# Advanced Technologies for Rocket Single-Stage-to-Orbit Vehicles

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**A single-stage-to-orbit vertical takeoff/horizontal landing rocket vehicle was studied to determine the benefits of advanced technology. Advanced technologies that were included in the study were variable mixture ratio oxygen/hydrogen rocket engines and materials, structures, and subsystem technologies currently being developed in the National Aero-Space Plane program. The application of advanced technology results in an 85% reduction in vehicle dry weight. Compared to an all-air-breathing horizontal takeoff/horizontal landing vehicle using the same advanced technologies and mission requirements, the rocket vehicle is lighter in dry weight and has fewer subsystems. To increase reliability and safety, operational features were included in the rocket vehicle: robust subsystems, 5% additional margin, no slush hydrogen, fail operational with an engine out, and a crew escape module. The resulting vehicle grew in dry weight, but was still lower in dry weight than the air-breathing vehicle.**

## Nomenclature

$h$ = altitude, ft
$I_{sp}$ = specific impulse, s
$\dot{Q}$ = convective heat rate, Btu/ft$^2$s
$q_{max}$ = maximum dynamic pressure, lb/ft$^2$
$t$ = time, s
$\alpha$ = angle of attack, deg
$\gamma_r$ = relative flight-path angle, deg
$\Delta V$ = ideal velocity, ft/s

## Introduction

FULLY reusable orbital vehicles were considered in the early days of the Space Shuttle program, but the technology of the 1970s restricted the concepts to two stages. Both air-breathing and rocket-propelled first stages were studied that carried second stages with rocket propulsion.[1,2] The results of these studies indicated that the air-breathing concepts were lighter in gross weight and had more operational flexibility (built in ferry and offset launch), but the all-rocket systems were lower in dry weight and had less technical risk and development cost. The all-rocket two-stage systems were selected as the prime candidates for the phase A and B Shuttle studies. However, because of budget constraints, the present partially reusable system was developed.

After 20 years of technology development, the National Aero-Space Plane (NASP) program has rekindled the flame of developing fully reusable, single-stage capability. For this experimental airplane, technologies are being developed in the areas of air-breathing and rocket propulsion, metal matrix and carbon-carbon materials, reusable cryogenic tankage, and lightweight subsystems. Once these technologies have been demonstrated, a wide range of future operational launch vehicles can be envisioned.

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In this study, an all-rocket propelled single-stage-to-orbit (SSTO) vehicle is analyzed using the technologies that are currently being developed for the NASP program. This present study includes the identification of appropriate technologies, a systems analysis using these technologies, trade studies determining the effects of various technologies, the definition of an SSTO vehicle that has been strictly designed for performance (minimum weight), and a comparison with an air-breathing SSTO vehicle[3] that has been designed with the same philosophy, mission, and technologies. However, to have routine access to space, a design for operations and safety philosophy must take precedence. Thus, the rocket SSTO vehicle is updated to include fail-operational, long-life, and safety features.

## Mission

The mission is defined by the second design reference mission for the advanced manned launch vehicle study.[3] This mission is to deliver 10,000 lb of payload from the Vandenberg Western Test Range to polar orbit (100 n.mi., 90-deg inclination) in a 12-ft-diam × 20-ft-length (3000 ft$^3$ volume minimum) payload bay. For a due east mission to and from Space Station Freedom, a 30,000-lb payload capability was assumed that defined the landing loads and vehicle trim requirements. The on-orbit maneuvering velocity increment $\Delta V$ was defined as 850 ft/s with the propellant tankage sized to provide an additional 350 ft/s. The environmental control and life support system was sized for a crew of three for a period of 24 h with the capability of trading payload for an additional 48 h.

## Technology

To demonstrate the effects of advanced technology on the rocket vehicle, vehicles have been designed for two technology levels—near term and advanced. Near-term technologies are considered those that are either 1990 state of the art or have been demonstrated sufficiently that little development is inherent in direct application to vehicle development as early as 1992. The advanced level consists of additional technologies to be demonstrated by the NASP program that will provide a technology readiness between 1994 and 1999.

Near-term technologies for structures consist of aluminum lithium cryogenic propellant tanks and composite intertank, aft skirt, and secondary fairings. Metallic panel or direct-bond ceramics are used for large-area entry heating thermal protection with carbon-carbon used for leading-edge and nose cap areas. Rocket propulsion is based on a lightweight derivative of the Space Shuttle main engine using liquid hydrogen and oxygen propellants. At the subsystem level, significant

changes from the Shuttle system are employed. Hydraulics are replaced with all-electric systems in which electromechanical actuators are used for both the engine gimbal and aerosurface controls. Orbital maneuvering, reaction control, and fuel cell power systems utilize hydrogen and oxygen. Advanced avionics and fault-tolerant, self-check subsystem components are used.

Advanced technologies are defined as those being developed in the NASP program. Titanium aluminide monolithic and composite materials are used as the main structural materials and also function as thermal protection on acreage areas of the body and wing with the addition of internal insulation. Carbon-carbon is utilized in the stagnation regions. Slush hydrogen and triple-point oxygen are used to reduce tankage volume requirements. Nonintegral hydrogen tanks are constructed from thermoplastics, and oxygen tanks retain the use of aluminum lithium. At this advanced technology level, an advanced variable-mixture ratio engine[4] was baselined. Subsystems are similar to those for the near-term technology level but are lighter in weight by incorporating advanced materials. Two types of subsystems have been defined in the NASP program. For the experimental NASP airplane, minimum weight and capability systems have been defined, whereas for future applications of NASP technology, more robust and long-life subsystems have been defined for operational vehicles. Comparisons of near-term and far-term technology levels are presented in Tables 1 and 2.

## Configurations

The rocket SSTO vehicle is a derivative of the second stage of a two-stage advanced manned launch system (AMLS) fully reusable concept.[3,5] The present rocket SSTO vehicle lifts off vertically, enters, and lands much like the Space Shuttle Orbiter. As shown in Fig. 1, the rocket SSTO vehicle body is shaped to efficiently package propellants by its low fineness ratio, and the crew cabin and payload bay are mounted on top of the vehicle so that there is no interference with the tankage or load paths. The payload is carried on the back of the vehicle in an external canister for rapid integration and removal in the operations processing flow. Crew access to the payload canister is through a tunnel leading from the forward crew cabin while in orbit. Tip fins on the wing are used for lateral-directional control rather than having a large vertical tail for stability like the Space Shuttle Orbiter. The wing, elevon, and body flap are positioned and sized to provide a hypersonic trim angle-of-attack range from 25 to at least 40 deg, subsonic neutral stability, and a maximum landing speed of 165 kt at an angle of attack of 15 deg.

The main propulsion for the near-term technology level is a scaled, lightweight derivative (25% dry weight reduction) of the current Space Shuttle main engine (SSME) with a two-position nozzle (sea-level expansion ratio equal to 55 and a high-altitude expansion ratio equal to 150). The advanced technology rocket is a hydrogen/oxygen variable mixture ratio (VMR) with an initial oxygen/hydrogen ratio ($O/F$) of 14:1 that transitions to 7:1.[4] As shown in Table 2, the VMR engine has a higher sea-level thrust-to-weight ratio and bulk density at an $O/F$ of 14:1 than the SSME derivative at the same technology level but has a lower specific impulse. The advanced SSME reflects a 50% weight reduction on the current SSME through the use of advanced metal matrix composites and other technology applications.

**Table 1 Technologies for advanced manned launch system vehicle options**

| Key technologies | Space Shuttle, reference | Near-term technology | Advanced technology |
|---|---|---|---|
| Structures | Al structures<br>Al tanks<br>Limited composites<br>Ceramic thermal protection system (TPS) | Composite structures<br>Reusable Al-Li tanks<br>Durable metallic or ceramic TPS | $Ti_xAl$ composite structures and TPS<br>Reusable thermoplastic hydrogen tanks<br>Reusable Al-Li oxygen tanks |
| Propulsion | SSME | Lightweight SSME derivative | Variable mixture ratio rocket<br>Scramjet propulsion |
| Subsystems | Hydraulic power<br>Monoprop auxiliary power unit<br>Hypergolic orbital maneuvering unit (OMS)/reaction control system (RCS)<br>Fuel cells | Electromechanical actuators<br>All electric<br>Lightweight fuel cells, batteries<br>Cyrogenic/gaseous OMS/RCS<br>Fault tolerant/self-check | Lightweight subsystems using advanced materials<br>Actively cooled inlets and nozzles |

**Table 2 Rocket propulsion technology**

| Mode | Advanced scaled SSME, 109% | Variable mixture ratio[4] 1 | Variable mixture ratio[4] 2 |
|---|---|---|---|
| $O/F$ ratio | 6 | 14 | 7 |
| Nozzle | Dual position | Retracted | Extended |
| Expansion ratio | 55/150 | 59.6 | 119.2 |
| Vacuum thrust, lb | 270,900/285,600 | 257,600 | 188,000 |
| Vacuum $I_{sp}$, s | 439.8/462.5 | 308 | 467 |
| Chamber pressure, psia | 3211 | 4700 | 3145 |
| Sea-level thrust, lb | 232,900/na | 232,800 | — |
| Sea-level thrust/weight | 69/na | 79 | — |
| Total propulsion weight, lb | 3360 | 2960 | |

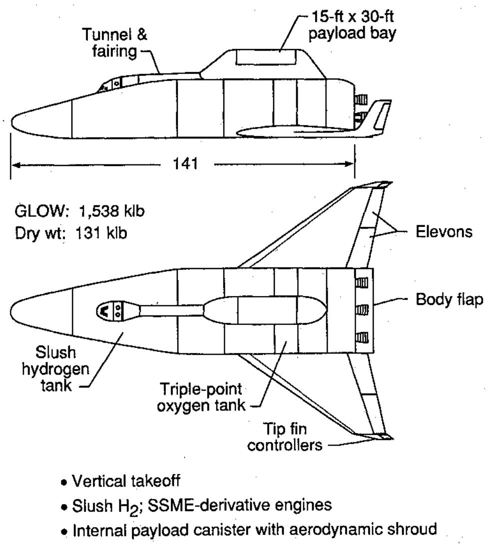



**Fig. 1 Advanced technology single-stage rocket vehicle.**

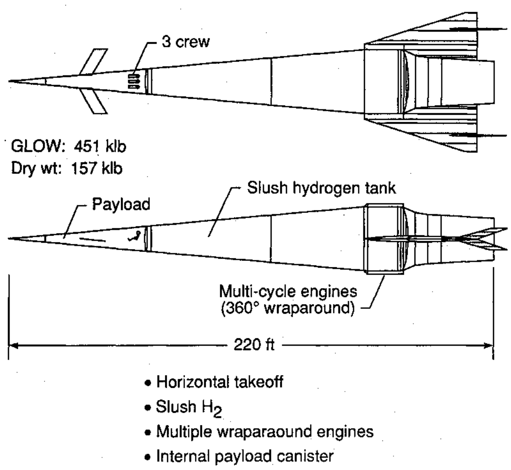



**Fig. 2 Advanced technology air-breathing conical accelerator SSTO vehicle.**

A cursory comparison of the rocket SSTO vehicle is made with the air-breathing SSTO vehicle defined in Ref. 3 that has the same design-for-performance (minimum weight) philosophy, mission, and technology level. The air-breathing SSTO vehicle (Fig. 2) is essentially a 5-deg half-angle cone on which the flow is compressed on the entire forebody. It has engines wrapped completely around the body, which maximizes thrust, corrects off-axis thrust vectors, and allows differential throttling for control. Wing vertical fins were used instead of a conventional tail because of the problem of attaching the tail to the nozzle that encompasses the entire rear of the vehicle. Details of this vehicle are presented in Ref. 6.

## Analysis

Trajectory/performance, aerodynamic heating, and structures analyses are used to provide a foundation for the technology comparisons.

### Trajectory

The rocket SSTO vehicle performs a typical rocket ascent trajectory with an initial vertical liftoff, gravity turn, and optimal pitch history to reach orbital insertion. The Program to Optimize Simulated Trajectories (POST) was used to minimize the required propellant weight to achieve orbit.[7] The aerodynamics for the rocket vehicle were predicted with the aerodynamic preliminary analysis system (APAS)[8] and the engine data from Table 2. The ascent trajectory was constrained by a normal force equal to that experienced during the 2.5-$g$ landing flare maneuver. Also, the axial acceleration was constrained to 3 $g$ to limit the sustained load experienced by the crew and payload.

The VMR engine performance was maximized by determining the Mach number at which the $O/F$ ratio was transitioned from 14:1 to 7:1 to provide minimum vehicle dry weight. The transition point was determined by trading specific impulse with propellant bulk density. As shown in Fig. 3, dry weight is a minimum at a transition point at Mach 1.4. At lower Mach numbers, the mode 2 extended nozzle would be subject to separation effects from the back pressure.

The resulting trajectory (Fig. 4) shows that the angle of attack has a reasonable range between −2.5 and 10 deg to be trimmed with engine gimballing. The maximum dynamic pressure is approximately 600 psf. This peak dynamic pressure is a factor of more than 3 less than the sustained flight-path dynamic pressure flown by the air-breathing launch vehicle.

A key feature thought to be inherent in air-breathing vehicles is a robust ascent abort capability as compared with present rocket systems. In the event of an engine module failure, the air-breathing vehicle has the capability to terminate the flight plan and return to the launch site under conditions no more severe than those of the nominal flight plan.[2] Unlike limited abort capabilities in present rocket systems, Ref. 9 demonstrates that the rocket SSTO vehicle can have a full range of single-engine-out opportunities without violating vehicle loading constraints of the nominal ascent and entry trajectories. Figure 5, which is taken from Ref. 9, summarizes the major events of an abort trajectory that allows the rocket SSTO vehicle to burn off all of its propellants and safely return to the launch site (RTLS) following shutdown of one main engine. Figure 6 shows the flexibility in the vertical-launched rocket vehicle abort scenario that includes an RTLS with two engines out, abort to orbit (ATO), and downrange abort to Easter Island, the current downrange for Space Shuttle launches from Vandenberg.[9]

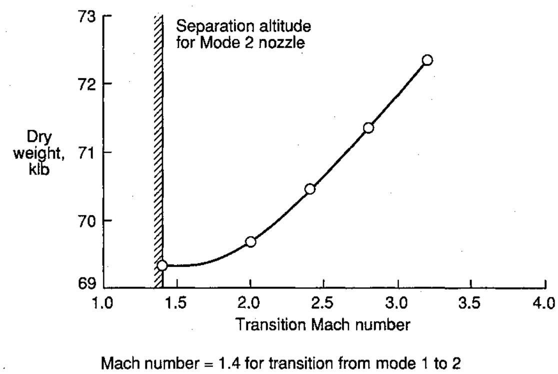



**Fig. 3 Variable mixture ratio engine transition.**

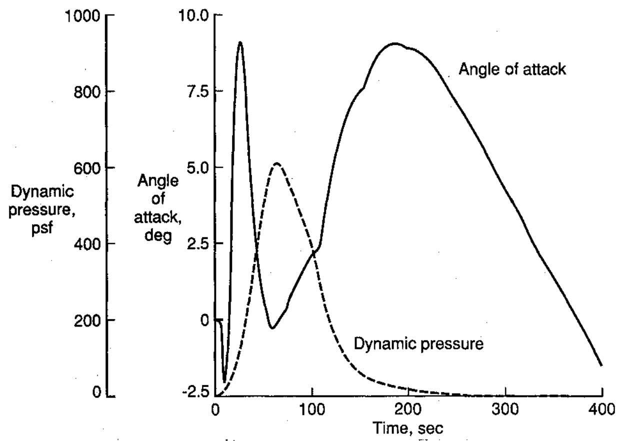



**Fig. 4 Rocket vehicle ascent trajectory.**

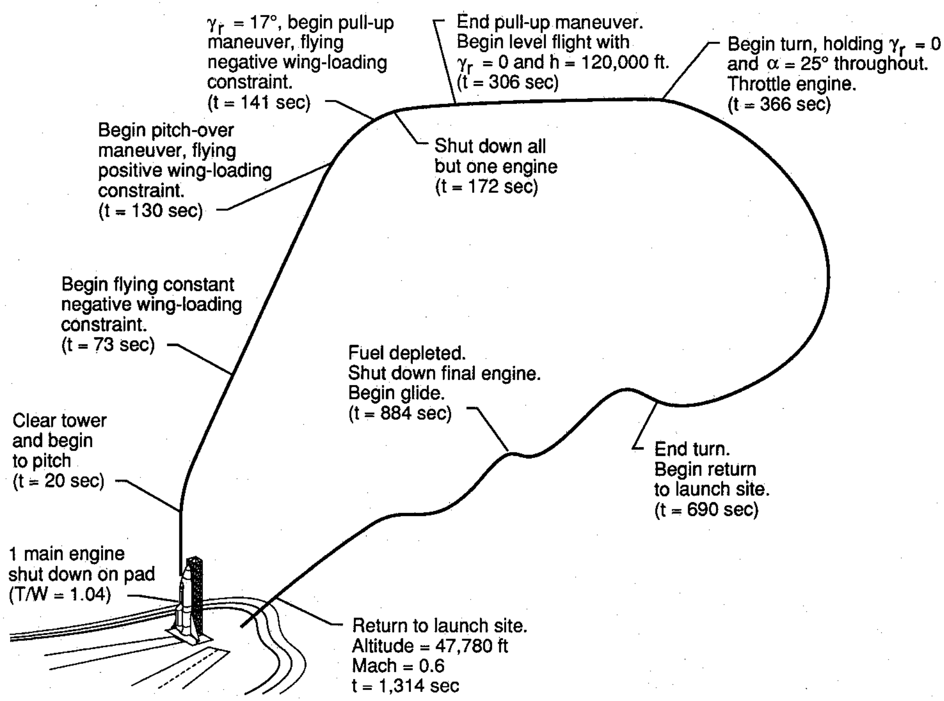



**Fig. 5 Rocket vehicle abort trajectory.**

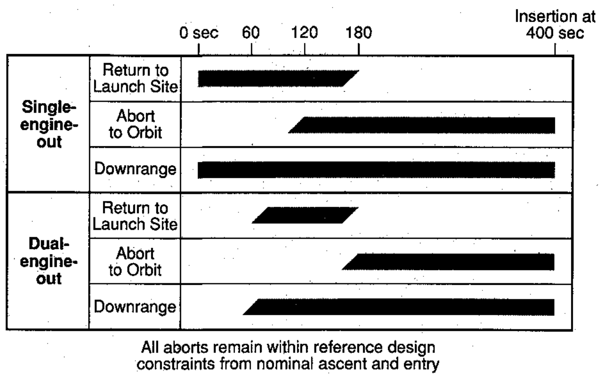



**Fig. 6 Abort opportunities.**

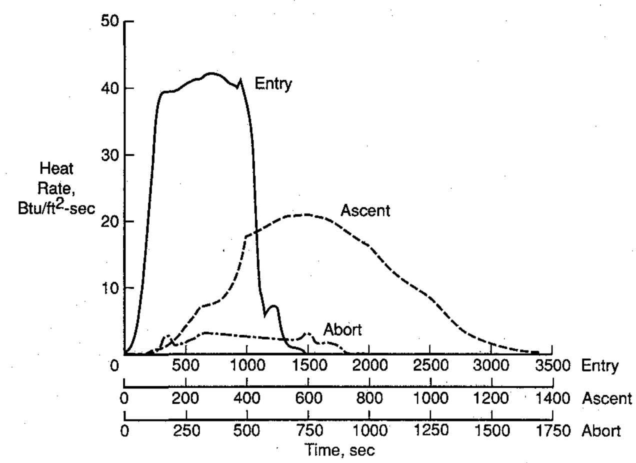



**Fig. 7 Rocket vehicle reference heating comparison.**

### Aerothermodynamics

Aerodynamic heating levels for the rocket vehicle on ascent, entry, and abort were predicted with the Fay-Riddell method in Miniver[10] (Fig. 7). The highest heating levels occurred during entry with a value of approximately 40 $Btu/ft^2 s$. The Miniver code was also used to predict the heating on the windward centerline of the rocket SSTO vehicle for the entry trajectory. The resulting surface temperature environment is shown in Fig. 8. This figure also illustrates that the carbon-carbon and titanium materials being developed by the NASP program can be used without the addition of any external thermal protection system. However, internal insulation is required to protect the crew cabin and other temperature sensitive regions. Leeward surface predictions indicate that the temperatures are less than 600°F and that an external thermal protection system is not required.

For the air-breathing SSTO vehicle, peak heating occurs during the ascent phase of the mission. The flight environment is much more severe because higher velocities must be maintained lower in the atmosphere to capture air for the propulsion system. Compared with the rocket vehicle, the heat rate on the air-breathing vehicle is a factor of 3 greater on the acreage regions, 30 greater in the stagnation regions, and 1000 greater on the cowl lip condition with impingement by the bow shock (maximum performance condition). Thus, the air-breathing vehicle requires heat pipe technology on the nose cap and leading edges and active cooling panels using hydrogen in the engine inlet and nozzle regions.

### Structures

A structural weight analysis was conducted using a finite element solver to compute local panel stresses and a panel solver to determine panel thickness based on material minimum gauge thickness or structural failure sizing criteria such as yield, ultimate, tension, and panel buckling.[11] Because stresses change with panel thickness, this technique is iterated to a final solution. The structural/panel sizing analysis is conducted for four load cases: ascent, entry, abort, and landing slapdown (Table 3). The maximum axial load shown in Table 3 represents a 3-*g* limit on ascent, and the maximum normal load for all trajectories was constrained to the 2.5-*g* pullup maneuver at landing. The safety and nonoptimum factors, structural materials, and construction techniques were based on NASP studies (Table 4).

The resulting segment unit weights for all of the materials, graphite/polyimide, titanium aluminide monolithic, and titanium aluminide composite, are shown in Fig. 9. Comparing the titanium aluminide monolithic with the composite shows that, for the regions with low loads, the monolithic is

lighter in weight because the minimum gauge of the three-directional composite layup is 57% heavier. In the higher load regions, the composite, with an increase in strength/density, has a definite advantage. Because of these results, the lowest weight regions predicted with the monolithic and composite materials were combined to provide the lowest weight structure, as shown in Fig. 9. This combination of titanium aluminides results in a 21% reduction over graphite/polyimide. The advantage of the titanium aluminides is even greater because the graphite/polyimide requires an external thermal protection system.

## Results

The effects of the incorporation of advanced technologies are shown in Fig. 10. The relative effects of each technology are deceiving because the vehicle sensitivity is decreased with the addition of each technology application. Also, with the application of all of the advanced technologies, the rocket SSTO is less sensitive to vehicle growth. The dry weight from near-term technology to advanced technology reduces dry weight from 427 to 71 klb (83% reduction). In addition to advanced technology, this rocket vehicle includes a design-for-performance (experimental vehicle) philosophy where each step in technology is applied to lower vehicle weight.

One of the main thrusts of the AMLS studies is a design-for-operations and safety philosophy. The results of adding operational, long-life, and safety features to the design-for-performance vehicle are shown in Fig. 11. The advanced subsystems defined for this vehicle include fault-tolerant, robust designs defined in the NASP application studies that detail the differences between an experimental and operational system. These differences include redundancy, orbital mission stay time, payload interfaces, and service life. Margin has been increased for all subsystems, including propulsion, from 10 to 15%, and slush hydrogen and triple point oxygen have been removed to eliminate additional operations overhead. The rockets are nominally operated at 80% thrust to increase engine life and provide fail-operational capability even with an engine out on the pad. With one engine out, the other four engines can be throttled up to provide 100% of the required thrust. Finally, a complete self-contained crew-escape module was added that has abort motors for jettison of the entire crew flight station. The system includes a heat shield and deployable flaps for stability, and would be recovered by a parachute landing in the

**Table 3 Vehicle loads for structural sizing**

| Structural loads | Axial, lb | Normal, lb |
|---|---|---|
| Ascent | | |
| Liftoff ($t$ = 30 s) | +1,190,000 | 200,000 |
| $q_{max}$ ($t$ = 50 s) | +1,170,000 | 224,000 |
| Entry | | |
| Subsonic pullout | — | 224,000 |
| Abort | | |
| Ascent maneuver | +960,000 | ±224,000 |
| Landing | — | 179,200 |

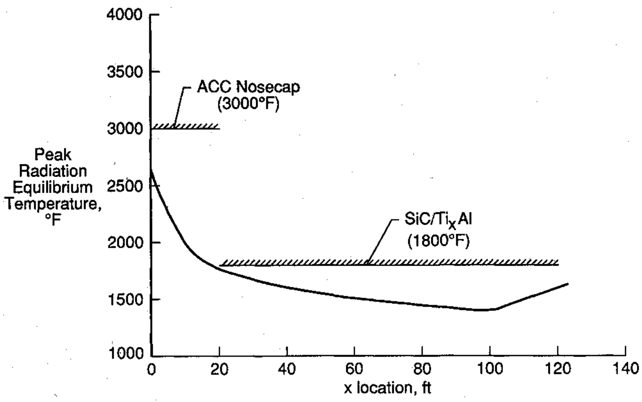


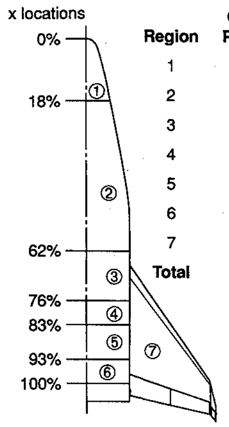

**Fig. 8 Rocket vehicle windward centerline entry heating.**

**Table 4 Structural sizing parameters**

| | Safety factor | Nonoptimum factor | Material | Construction |
|---|---|---|---|---|
| External structure | 1.5 | 1.5 | Nose and leading edge—advanced carbon-carbon<br>Acreage—SiC/Ti$_x$Al | Honeycomb |
| Cyro tanks | 1.5 | 1.4 | Slush H2—Thermoplastic<br>triple-point-oxygen-Al Li | Nonintegral |

**Table 5 Single-stage-to-orbit comparisons**

| | Rocket | | |
|---|---|---|---|
| | Performance | Operations | Airbreather |
| Dry weight, klb | 90 | 131 | 157 |
| Gross weight, klb | 1108 | 1538 | 451 |
| Propellant costs, $ | 185k | 259k | 411k |
| Body length, ft | 125 | 141 | 220 |
| $q_{max}$, lb/ft$^2$ | 600 | | 1500–2400 |
| $\dot{Q}_{max}$, Btu/ft$^2$s | 40 | | 150–50,000 |
| Subsystems | Rocket | | Rocket<br>Low-speed cycle<br>High-speed cycle |
| | Electrical mechanical actuators | | Hydraulics<br>Auxiliary power units |
| | Launch pad | | — |
| | Passive thermostructures | | Passive thermostructures<br>Leading edge and nose heat pipes<br>Inlet and nozzle active cooling |
| Abort | RTLS, abort-to-orbit, alternate sites | | RTLS, abort-to-orbit, alternate sites (greater flexibility) |
| Orbital, intercept | Marginal | | Yes |
| Loiter, recall | No | | Yes |




| Region | Graphite Polyimide | $Ti_3Al$ Monolithic | $Ti_3Al$ Composite | $Ti_3Al$ Combination |
|---|---|---|---|---|
| 1 | 1.69 | 1.14 | 1.16 | 1.14 |
| 2 | 1.87 | 1.23 | 1.81 | 1.23 |
| 3 | 1.87 | 1.27 | 1.76 | 1.27 |
| 4 | 2.54 | 2.13 | 2.40 | 2.13 |
| 5 | 4.55 | 5.38 | 3.93 | 3.93 |
| 6 | 3.48 | 5.04 | 3.14 | 3.14 |
| 7 | 2.31 | 2.44 | 2.16 | 2.16 |
| Total | 2.37 | 2.22 | 2.21 | 1.89 |

**Fig. 9 Rocket vehicle unit weights (lb/ft²).**

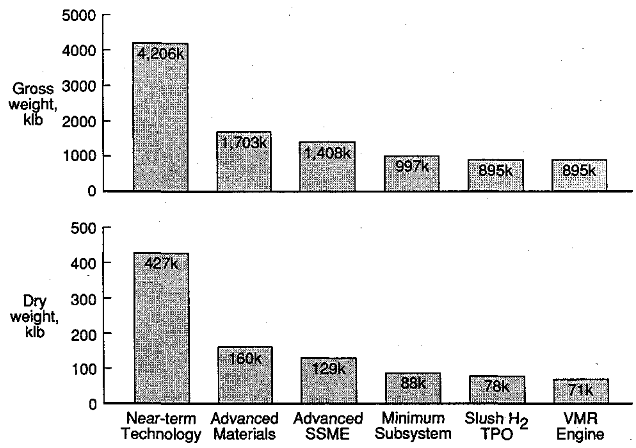



**Fig. 10 Design-for-performance rocket SSTO vehicle.**

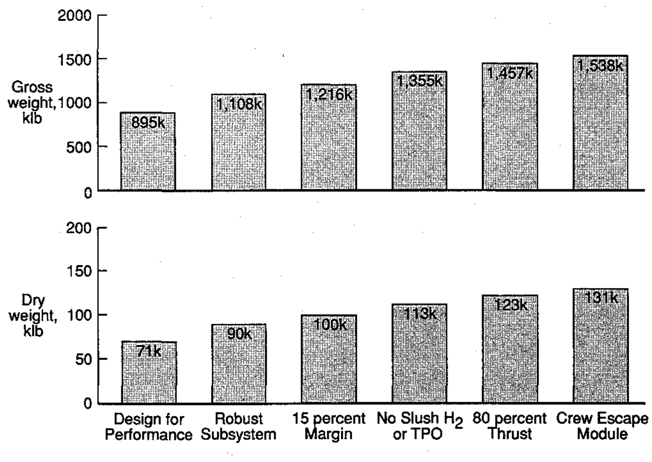



**Fig. 11 Design-for-operations rocket SSTO vehicle.**

ocean.[5] With these operational, long-life, and safety features, the rocket vehicle is still lighter in dry weight than the performance-driven air-breathing vehicle in Refs. 3 and 6. (see Table 5).

This updated vehicle can be compared with the air-breathing vehicle in Ref. 6 because both vehicles were designed to the same mission, technologies, and design philosophy, which is to design an experimental vehicle. As shown in Table 5, the design-for-performance rocket SSTO vehicle is 43% shorter and lighter in dry weight than the air-breathing vehicle. With the additional operational features, the rocket vehicle is still 36% shorter and 17% lighter. Although the rocket SSTO is greater in gross weight, the propellant costs are actually less because the rocket gross weight is dominated by the liquid oxygen that has a cost of $.03 per pound as compared to $1.53 for liquid hydrogen. As shown in Table 5, the rocket vehicle has a lower number of required subsystems because of the more benign flight environment and the utilization of one propulsion system throughout the flight regime. On the other hand, the air-breathing vehicle does not require a launch pad and has a greater range of flight operations including self-ferry capability with its air-breathing systems. A definitive comparison of rocket vs air-breathing propulsion for launch vehicles is beyond the scope of this paper because a detailed operations analysis and life cycle cost for a specific mission is required.

## Conclusions

A single-stage-to-orbit vehicle with rocket propulsion was designed with two levels of technology—near-term technology and advanced technology. Advanced technologies include materials, propulsion, minimum required subsystems, slush hydrogen, and triple point oxygen. By using these advanced technologies to minimize weight, the vehicle dry weight was reduced by 83% compared with the near-term technology vehicle. Compared with an all-air-breathing vehicle using the same advanced technologies and mission, the rocket vehicle was approximately 43% lighter in dry weight. This study shows that, for payload delivery to orbit missions, the rocket vehicle is lower in weight and has fewer subsystems. On the other hand, orbital missions that require cruise segments, loiter, recall, offset launch, or go-around capability will require air-breathing propulsion.

The rocket vehicle was also designed for operations in which fail-operational, long-life, and safety features were included. The resulting vehicle increased in dry weight by 85%, but was still lower in dry weight than the design-for-performance air-breathing vehicle.

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