Abort Capabilities of Rocket-Powered Single-Stage Launch Vehicles

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Application of advanced technologies to future launch vehicle designs would allow the introduction of a rocket-powered, single-stage-to-orbit (SSTO) launch system early in the next century. A fully reusable SSTO vehicle would be quite desirable from an operational standpoint; hence, this paper utilizes a vehicle design that incorporates the enabling technology advances in structure, propulsion, and subsystems that are essential. This paper examines the abort capabilities of an advanced SSTO launch vehicle that has five main engines. In the event of a single or dual main engine shutdown, it was determined when the vehicle could execute return-to-launch-site, abort-to-orbit, or down-range abort maneuvers. Throughout each abort maneuver, vehicle loads are kept within nominal ascent and entry design values.

Nomenclature

Az_r	= relative azimuth angle (measured clockwise from north), deg
a_x	= longitudinal acceleration, g
C_m	= pitching moment coefficient
F_z	= aerodynamic normal force, lb
g	= acceleration of gravity, 32.2 ft/s^2
h	= altitude, ft
L/D	= lift-to-drag ratio
Q	= total heat load, Btu/ft^2
$\dot{Q}$	= stagnation point heat rate, Btu/ft^2•s
q_∞	= dynamic pressure, psf
T	= time, s
T/W	= thrust-to-weight ratio
V_r	= relative velocity, ft/s
α	= angle of attack, deg
γ_r	= relative flight-path angle, deg
ΔV	= change in relative velocity, ft/s
ϕ	= bank angle, deg

Introduction

WITH the advent of the Challenger accident, increased emphasis has been placed on the abort capabilities of the space transportation system (STS). Some changes have been implemented; however, Shuttle abort capabilities remain limited because of the nature of the vehicle design. Separation of the Space Shuttle Orbiter during the boost phase (the first 120 s of flight) would be very difficult; thus, any attempt for crew recovery or intact Orbiter recovery during a failure mode would occur after the solid rocket boosters separate. For about 150 s after staging, a return-to-launch-site (RTLS) abort is planned in the event of a main engine shutdown. This RTLS maneuver is quite complicated because the engines must thrust during the maneuver; hence, the external tank must remain attached to the Orbiter throughout much of the maneuver and must be separated under high dynamic pressure conditions. If main engine shutdowns occur later in the flight, either a trans-Atlantic landing (TAL) or an abort-to-orbit (ATO) maneuver is possible.[1] Judging by the impact of the Challenger accident, any future manned launch system should place great emphasis on abort capability throughout the entire flight regime (from launch to orbital insertion).

At present, a variety of advanced technologies in major disciplines are being studied as a part of the Space Shuttle and National Aerospace Plane programs. Application of these technologies to future launch vehicle designs would allow the introduction of a winged, rocket-powered, single-stage-to-orbit (SSTO) launch system early in the next century. A fully reusable SSTO vehicle would be quite desirable from an operational standpoint; however, such a vehicle cannot be designed without accompanying technological advances in structure, propulsion, and other subsystems. The conceptual design of such a vehicle has recently been completed. Often in the past, vertical-takeoff, rocket-powered vehicles (like the Shuttle) have been assumed to have a limited abort capability (especially when compared with air-breathing vehicles). This paper will demonstrate that intact vehicle recovery is possible throughout the flight regime for a vertical-takeoff, rocket-powered SSTO vehicle in the event of a noncatastrophic, single-engine-out abort. A range of noncatastrophic, two-engine-out abort opportunities will also be determined. The results presented will indicate the areas of the flight regime where RTLS, down-range abort, and ATO maneuvers are possible.

Analysis

In the design of a future manned launch system like the advanced SSTO vehicle addressed here, a determination of the aerodynamic wing loads, dynamic pressure loads, acceleration loads, and heating loads that will be encountered in various abort scenarios is important to determine if changes are required in the baseline vehicle to allow a full range of abort opportunities. The approach used in this paper is similar to that of the Space Shuttle Orbiter in which the landing loads determine the design of the wing, the nominal entry heating determines the design of the thermal protection system, and the ascent dynamic pressure and acceleration loads determine the design of the fuselage. The design constraints for the advanced SSTO vehicle are summarized in Table 1. Throughout the nominal ascent and entry, the longitudinal acceleration a_x is held to the current STS limit of 3 g. The wing is designed to carry a normal load F_z equivalent to that of a 2.5 g subsonic flare maneuver by the empty vehicle prior to landing (with a safety factor of 1.5), and this constraint is maintained throughout ascent and entry. This wing loading constraint is maintained for all subsonic and supersonic abort maneuvers during which the wing is assumed to carry all of the normal

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Table 1 Trajectory constraints

Constraint	Value	Comments	Design maneuver	Constrained maneuvers
Normal force, lb	243,300	Wing load for a 2.5g flare with 1.5 safety factor	Landing	Landing, ascent, abort
	434,000	Equivalent hypersonic wing load	Abort	Abort
Axial acceleration, g	3	Space transportation system payload and crew limit	Ascent	Ascent
$\dot{Q}$, Btu/ft^2 s	53	Maximum stagnation point heat rate	Re-entry	Re-entry, abort
Q, Btu/ft^2	46,000	Total stagnation point heat load	Re-entry	Re-entry
q_∞, lb/ft^2	700	Maximum dynamic pressure	Ascent	Ascent, abort

load. For hypersonic maneuvers, however, the body carries a portion of the normal load approximately equal to the ratio of the body planform area to the reference wing area. A preliminary aerodynamics package was used to determine what percent of the F_z load is carried by the body at various angles of attack, and 44% was chosen as a conservative upper bound. Hence, for Mach numbers > 4, the F_z constraint can be increased because of the hypersonic aerodynamic characteristics. The dynamic pressure q_∞ is maintained below 700 psf during ascent and entry. Throughout the nominal entry heating profile, the minimum reference stagnation point heat rate $\dot{Q}$ attainable is 53 BTU/ft^2·s and the total heat load Q is 46,000 BTU/ft^2. Maintaining Q and $\dot{Q}$ within these constraints during abort will allow the use of the same thermal protection system (TPS) that was designed by entry conditions. Using these design constraints, a full range of single-engine-out abort scenarios was constructed.

All of the trajectory analyses for the abort study presented in this paper were performed using the three-degrees-of-freedom version of the Program to Optimize Simulated Trajectories (POST). POST is a generalized point mass, discrete parameter targeting and optimization program that allows the user to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. Simulation flexibility is achieved by decomposing a trajectory into a logical sequence of simulation segments or phases. Each phase can then be modeled and simulated in the manner most appropriate for that particular flight regime.[2] Throughout each abort trajectory, POST was used to construct trajectories that would not violate the design loading conditions of wing normal force, acceleration, dynamic pressure, and heating listed in Table 1.

A variety of other tools were used in the design and analysis of the advanced SSTO vehicle. The vehicle geometry was modeled using the solid modeling aerospace research tool (SMART) geometry package.[3] All of the aerodynamic data that were utilized by POST were obtained from the aerodynamic preliminary analysis system (APAS).[4] The weights and sizing analyses were performed using an in-house sizing program in conjunction with the PATRAN finite element analysis program.[5] In the design of the baseline vehicle, the ascent and entry loads obtained from POST were used by PATRAN to calculate structural unit weights, which were then used by the weights and sizing program to provide vehicle system weights. For each abort trajectory, vehicle structural loads were kept within nominal ascent and entry loads, which were inputs to the PATRAN weights analysis.

None of the abort trajectories performed for this study account for the thrust vector losses due to engine gimballing. The aerodynamic data base used in this level of analysis did not include any pitching moment C_m data; hence, the effect of pitching moment on engine gimbal requirements was not calculated. However, a cursory analysis was performed to determine the maximum gimbal angle required to track the vehicle center of gravity. The worst case was found to be when a single engine is burning during the later portion of the RTLS trajectory when the vehicle is 35% full of propellant. For this worst case, the maximum gimbal angle required is 6.8 deg, which remains within reasonable limits. (The Space Shuttle Orbiter has a ±10 deg gimbal range.) A complete abort analysis that includes the effect of pitching moment on engine gimballing requirements is beyond the scope of this paper; however, such an analysis could affect the arrangement of the engines on the vehicle or the engine shutdown sequence.

Vehicle Concept

The advanced SSTO vehicle examined in this study employs a variety of advanced technologies currently under study as a part of the Space Shuttle and National Aerospace Plane programs. Figure 1 shows this SSTO vehicle and summarizes some of the technologies utilized. The vehicle uses slush hydrogen and oxygen for propellants to increase propellant

Table 2 Mission and design parameters

Gross weight	964,970 lb
Dry weight	72,870 lb
Payload weight	10,000 lb
Body length	125.8 ft
Wing span	73.0 ft
Liftoff T/W ratio	1.3
Number of engines	5
Number of crew	2
Target orbit	100 nmi circular
Destination inclination	90 deg
Launch site	Vandenberg Air Force Base

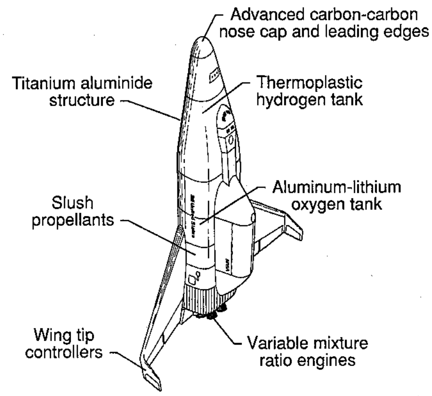

Fig. 1 Technology assumptions for the advanced SSTO vehicle.

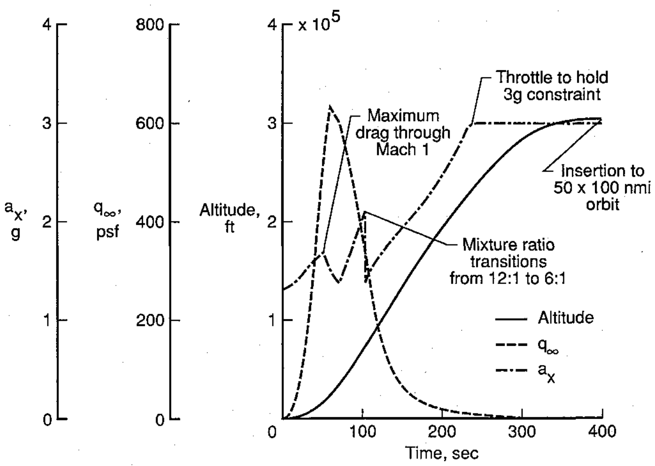

Fig. 2 Nominal ascent trajectory parameters.

bulk density and decrease tank size. Vehicle structural assumptions include the use of advanced carbon-carbon for the nose cap and wing leading edges, titanium aluminides for the wings and fuselage, and thermoplastics and aluminum/lithium for the hydrogen and oxygen tanks, respectively. Advanced technologies are also applied to the vehicle subsystems. The main propulsion system utilizes five advanced variable mixture ratio rocket engines that nominally operate at a throttle setting of 100%. Up to Mach 2.4, each engine burns oxygen and hydrogen in a ratio of 12:1 by weight with a nozzle expansion ratio of 40. At that point, each engine transitions to a 6:1 mixture ratio, and the nozzle is extended to provide an expansion ratio of 150.

Nominal Mission

Table 2 summarizes the major mission and design parameters of the advanced SSTO vehicle. The baseline mission is to deliver and return a 10-klb payload to a polar orbit (100 nmi circular, 90-deg inclination) from a launch out of the Western Test Range at Vandenberg Air Force Base (VAFB). The vehicle is nominally designed to support a crew of two for a one-day mission. An additional on-orbit ΔV capability of 500 ft/s is provided to allow missions to higher orbits. As shown in the table, the gross liftoff weight is 964 klb and the dry weight (without propellant, fluids, or payload) is 73 klb.

The nominal ascent trajectory is presented in Fig. 2. As shown in the figure, the initial thrust-to-weight ratio T/W is 1.3. As propellant is burned, the vehicle accelerates until it enters the transonic flight regime at high dynamic pressure (600 psf $< q_\infty <$ 700 psf) at 50 s. The large increase in drag causes the vehicle to decelerate for a short period of time. The vehicle then accelerates until engine transition from a mixture ratio of 6:1 to 12:1 occurs at 104 s. The vehicle then accelerates until the longitudinal acceleration limit a_x, of 3 g is encountered at 240 s. The engines are then throttled to maintain this limit until the fuel is depleted, and orbital insertion occurs at 400 s into a transfer orbit with a 50-nmi perigee and 100-nmi apogee.

Results

Return-to-Launch-Site Aborts

One of the major goals of this study was to demonstrate that a range of single- and two-engine-out RTLS aborts is possible that does not violate the acceleration, wing normal force, dynamic pressure, and heating loads listed in Table 1. Within these constraints, it was demonstrated that the advanced SSTO vehicle has a single-engine-out RTLS abort capability if one of its five engines must be shut down anytime from launch until 180 s into the nominal ascent. The vehicle also has a two-engine-out RTLS abort capability from 60 s to 180 s into the nominal ascent. It should be noted that none of the abort trajectories examined require the dumping of propellant; hence, no unique hardware is required for that purpose. In each case, all propellant is burned through the remaining engines in the appropriate mixture ratio.

Abort from Launch Pad

Figure 3 provides an example of an RTLS trajectory. The figure summarizes the major events of an abort trajectory that demonstrates that the advanced SSTO vehicle can execute an RTLS abort when a main engine must be shut down immediately after launch. If one engine is shut down on the pad, the vehicle still has a sufficient thrust-to-weight ratio to climb (T/W = 1.04). After the tower is cleared, the vehicle begins to

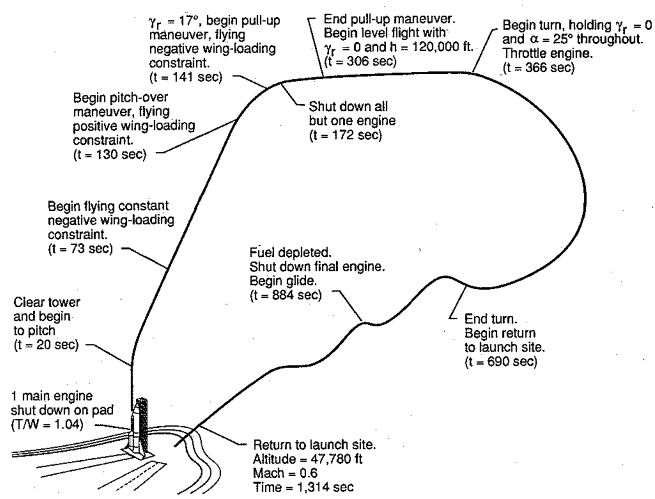

Fig. 3 RTLS abort from pad for the advanced SSTO vehicle.

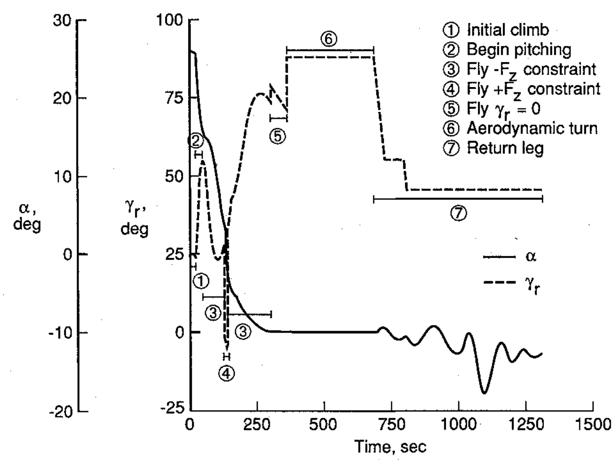

Fig. 4 Angle of attack and flight-path angle for single-engine-out abort from pad.

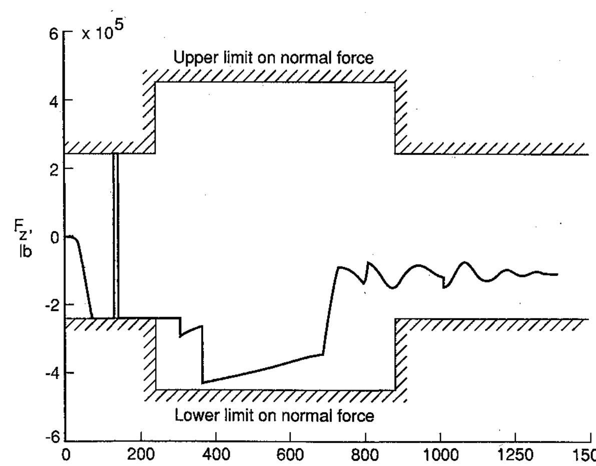

Fig. 5 Wing normal force for single-engine-out abort from pad.

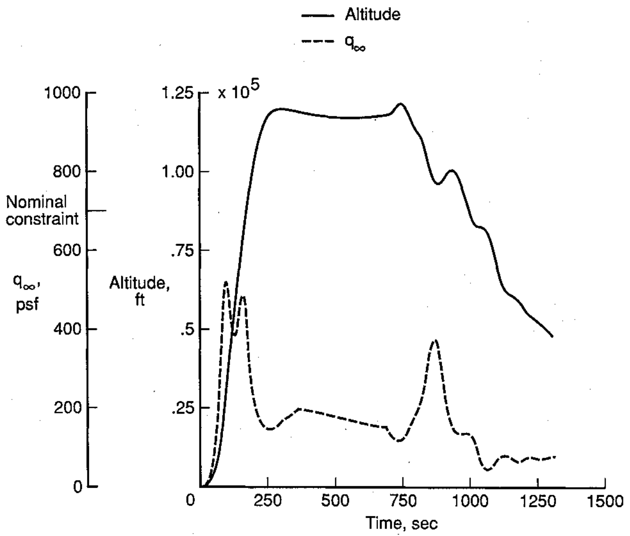

Fig. 6 Altitude and dynamic pressure for single-engine-out abort from pad.

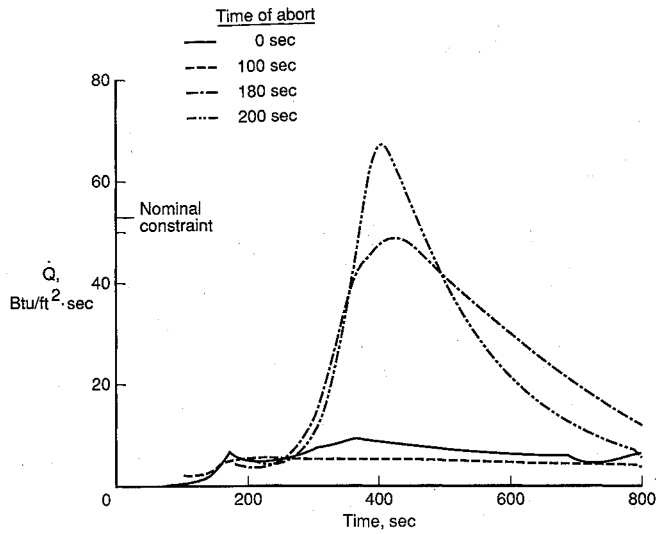

Fig. 9 Reference stagnation point heat rate for single-engine-out RTLS aborts.

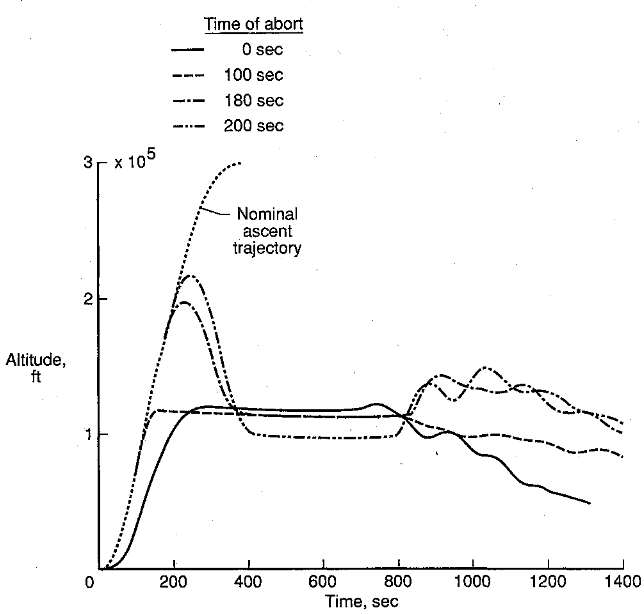

Fig. 7 Altitude profiles for single-engine-out RTLS aborts.

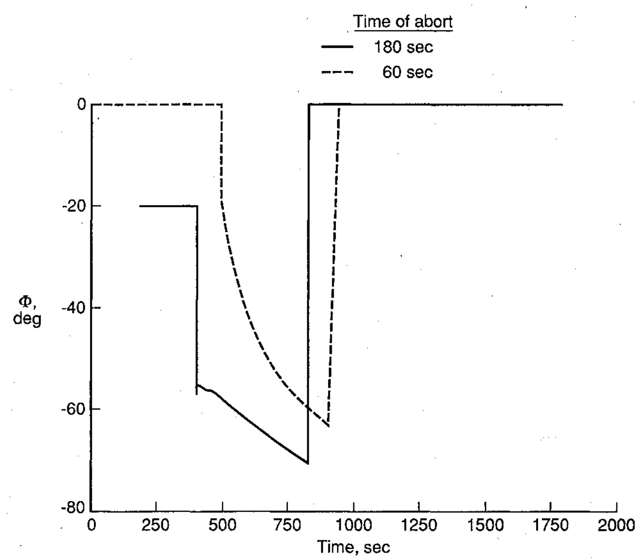

Fig. 10 Bank angle profiles for single-engine-out RTLS aborts.

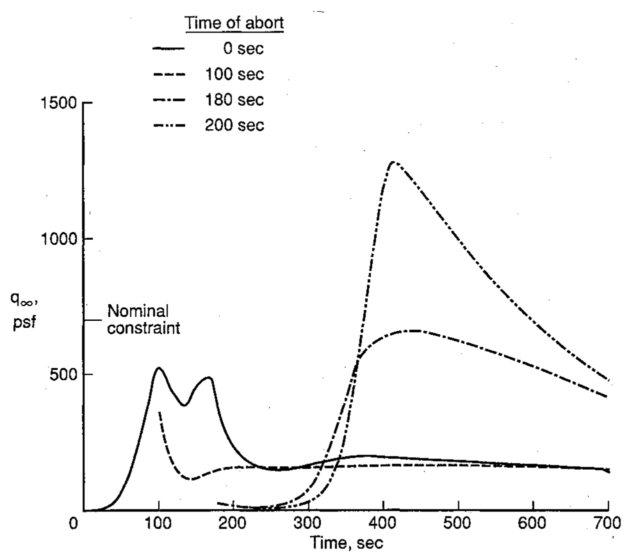

Fig. 8 Dynamic pressure for single-engine-out RTLS aborts.

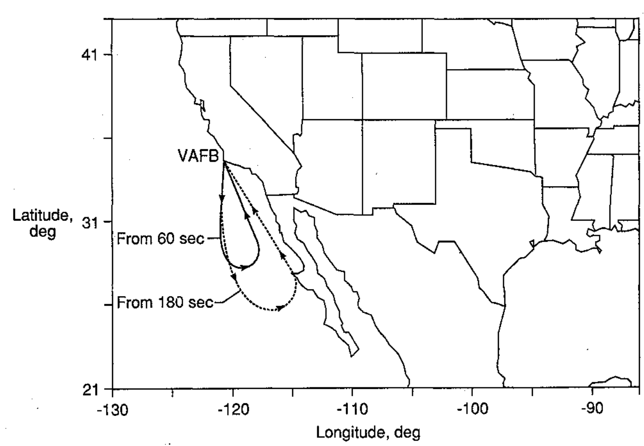

Fig. 11 Ground traces for single-engine-out RTLS aborts.

pitch until the wing loading constraint value ($F_z = -243{,}300$ lb) is reached, as shown in Figs. 4 and 5. The angle of attack is then modulated to follow this wing loading constraint at a positive α to allow the vehicle to efficiently gain needed altitude. A pitchover maneuver is then executed by flying at a negative α for a short period of time. Then α is increased in order to pull up at a relative flight-path angle γ_r of 0 deg to begin level flight at an altitude h of approximately 120,000 ft (Fig. 6). During this pull-up maneuver, all but one of the main engines are shut down. After 366 s, the vehicle begins a level aerodynamic turn. Throughout this turn, α is again modulated to keep γ_r at 0 deg to maintain altitude. At the end of this turn, the longitudinal acceleration a_x reaches its maximum value of 2.7 g. When the azimuth angle Az_r reaches 343 deg, the vehicle begins its return to the launch site. After 884 s, the final engine depletes the remaining fuel and is shut down. Following an unpowered glide back to the launch site, the vehicle returns at an altitude of 50,000 ft, as shown in Fig. 6. It is assumed throughout this study that returning to the launch site at an altitude of 25,000 ft provides a sufficient altitude margin to accomplish a safe landing.

During the abort trajectory, the maximum Mach number attained is 5.3, the maximum dynamic pressure (520 psf) remains below the 700 psf encountered during the nominal ascent, and the maximum heat rate (9.3 BTU/ft$^2\cdot$s) remains far below the nominal entry maximum of 53 Btu/ft$^2\cdot$s.

Other Abort Cases

The trajectory presented in the previous section is not completely optimized with respect to the altitude and velocity at which the vehicle returns to VAFB. Performance margins remain in various flight regimes. For example, no banking is performed prior to 300 s. Some RTLS aborts from further into the nominal trajectory will require immediate banking to offset the fact that the vehicle travels further down range from the launch site. From Fig.5, it is evident that a normal force F_z margin exists during the aerodynamic turn maneuver, which occurs from 366 to 690 s. RTLS aborts from later in the nominal trajectory will require flying this constraint to achieve a more efficient turn. There is also excess performance in the return leg of the RTLS abort from the launch pad (i.e., the vehicle could return to the launch site with a much higher than necessary altitude and Mach number). Later RTLS abort trajectories will require climbing to higher altitudes than those shown in Fig. 6 and will require flying at or near the maximum value of the lift-to-drag ratio L/D.

For the abort study, trajectories were constructed for single-engine-out RTLS aborts ranging from 0 to 200 s into the nominal ascent at intervals of 20–40 s. Aborts from different points in the nominal trajectory often require modification of the strategies employed in the RTLS abort from the launch

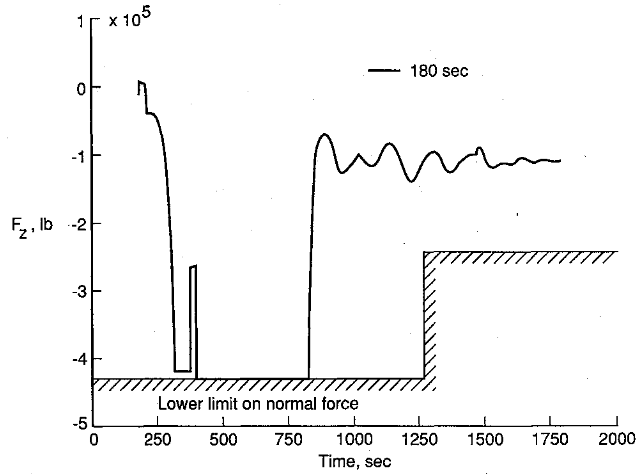

Fig. 12 Wing loading for RTLS abort from 180 s.

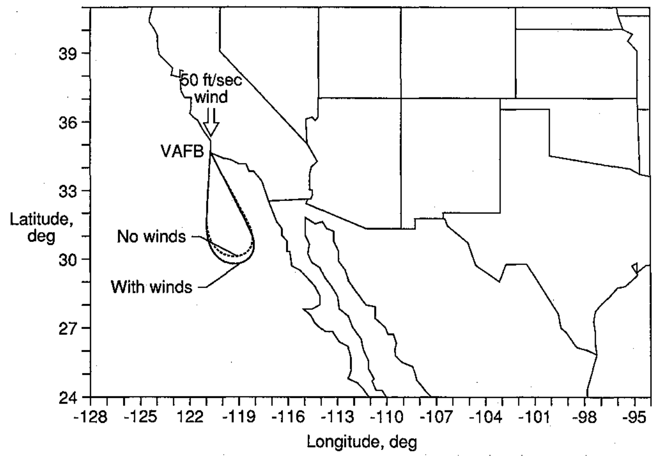

Fig. 13 Effect of winds on ground trace of RTLS abort from 0 s.

pad that is described in Fig. 3. Profiles of important parameters for single-engine-out RTLS abort trajectories from 0, 100, 180, and 200 s are given in Figs. 7–9.

For RTLS aborts from 0 to 60 s, the pull-up maneuver described in Fig. 3 is accomplished smoothly by flying the subsonic and supersonic F_z constraint. For aborts from 60 s to about 120 s, this pull-up maneuver occurs at Mach numbers exceeding 4; hence, the F_z constraint can be relaxed to its hypersonic value and γ_r can transition more rapidly and abruptly to 0 deg for the aerodynamic turn. For RTLS aborts from between 120 and 180 s, the altitude from the nominal ascent trajectory is such that the vehicle must climb to altitudes between 150,000 and 200,000 ft, execute a dive maneuver, and then pull out at an altitude sufficient to achieve an efficient aerodynamic turn in a benign dynamic pressure and heating environment. For aborts from between 180 and 200 s, this dive maneuver can not be executed in sufficient time to return to the launch site without violating nominal q_∞, $\dot{Q}$, or F_z constraints.

As mentioned earlier, RTLS abort trajectories from early in the flight regime have normal force margins that must be fully utilized for RTLS aborts from further into the nominal ascent. Figure 10 demonstrates that no banking is required until 500 s after launch for the single-engine-out RTLS abort from 60 s, whereas the RTLS abort from 180 s requires immediate transition to a bank angle Φ of 20 deg during the dive and pull-out maneuver and later transition (at 380 s) to higher bank angles to perform the main aerodynamic turn. The ground traces of these two abort trajectories are given in Fig. 11. From the F_z profile of the RTLS abort from the launch pad given in Fig. 5, it is evident that a rather large wing loading margin exists throughout the aerodynamic turn maneuver. Figure 12 demonstrates that for the RTLS abort case from 180 s, this normal force margin must be utilized almost entirely to achieve the required banking efficiency to return to the launch site. RTLS aborts from early in the nominal trajectory also have large performance margins in the return leg of the abort (i.e., the optimum α profile need not be flown to return to the launch site at the required altitude and velocity) that must be utilized during the return leg of aborts from later in the nominal ascent. Figure 7 indicates that, for RTLS aborts from 180 to 200 s, the vehicle must immediately gain altitude after the completion of the turn and fly at or near the maximum L/D. For the other abort cases shown in the figure (from 0 and 100 s), this maneuver is not necessary to return to the launch site with sufficient altitude for landing maneuvers.

Another important difference between the strategies employed in the various RTLS abort trajectories occurs in the engine shutdown schedules. For single-engine-out abort trajectories from 0 to 100 s into the nominal ascent, the remaining four engines continue burning to achieve sufficient velocity for the aerodynamic pull-up and turn maneuver. Just

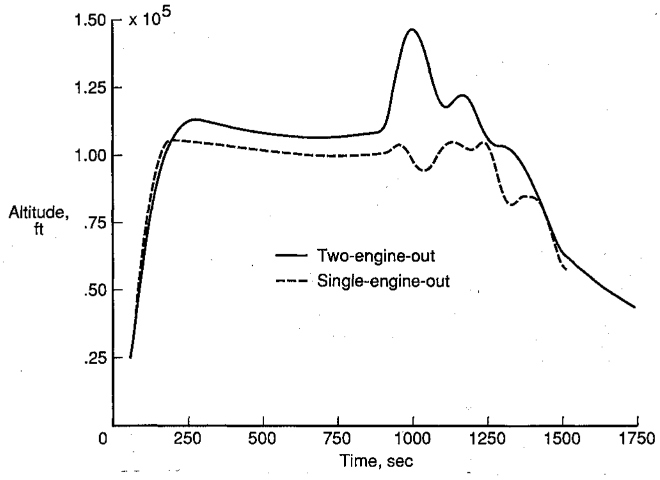

Fig. 14 Two-engine-out and single-engine-out RTLS aborts from 60 s.

prior to the pull-up maneuver, all but one of the engines are shut down. This engine is throttled during the aerodynamic turn and return leg, and it remains on until the fuel is depleted. For single-engine-out abort trajectories from > 100 s, all but two of the engines are immediately shut down. These two engines are required to allow sufficient thrust to pull out of the dive maneuver and attain a 0 deg flight-path angle in order to begin the aerodynamic turn. The two engines are gradually throttled back, and then one is shut down shortly after beginning the turn. The remaining engine again remains on and is throttled until the fuel is depleted.

In order to limit the time required to construct RTLS trajectories, the engine throttle capability was initially assumed to be 50%. However, the RTLS abort case from the launch pad was successfully reconstructed within the vehicle loading limits assuming no throttling capability. RTLS abort trajectories from later into the nominal ascent do require some throttling to limit a_x to 3 g at the end of the aerodynamic turn; however, this requirement does not exceed 70–75%.

Effect of Winds

None of the abort cases discussed thus far consider the effect of unfavorable winds on the RTLS trajectory. To consider properly the effect of winds on the RTLS abort from 180 s, an optimal nominal ascent trajectory was run assuming a constant wind velocity of 50 ft/s from the north. (No launch would be attempted reasonably at greater wind velocities.) The new conditions obtained at 180 s into the flight were then used as inputs to a new RTLS abort trajectory, which also assumed a constant wind velocity of 50 ft/s from the north. With some minor adjustments to the α profile of the vehicle, the vehicle can return to the launch site with an altitude of 31,000 ft for landing maneuvers as compared to 40,000 ft with no winds. A single-engine-out abort case from the launch pad was also run assuming a constant wind velocity of 50 ft/s from the north. Once again, the advanced SSTO vehicle was able to return to the launch site at an altitude of 25,600 ft for landing, although the trajectory takes 380 s longer to complete. The ground traces of these two different abort cases from the launch pad are given in Fig. 13.

Two-Engine-Out Cases

All of the RTLS abort cases discussed thus far consider the loss of a single main engine. It has been shown that single-engine-out RTLS abort opportunities exist from launch to 180 s into the nominal ascent trajectory without violating the ascent and entry design constraints of the advanced SSTO vehicle. For the RTLS abort case from 180 s discussed earlier, two additional engines are immediately shut down when one engine is lost. Hence, the same trajectory constructed for the single-engine-out abort from 180 s would be applicable for a two-engine-out abort from 180 s into the nominal ascent. A number of trajectories were run to determine when the earliest opportunity exists to execute a two-engine-out RTLS abort maneuver. It was found that a two-engine-out RTLS abort can be executed from 60 s into the nominal ascent without violating the ascent and entry design constraints on the vehicle. The altitude profiles of the single-engine-out and two-engine-out abort trajectories from 60 s are given in Fig. 14. The two-engine-out abort case contains much less of a normal force margin in the aerodynamic turn and altitude margin in the return leg than the single-engine-out case. Thus, two-engine-out RTLS abort opportunities exist from 60 to 180 s into the nominal ascent trajectory without violating the vehicle design constraints.

Abort-to-Orbit Cases

All of the trajectories discussed thus far concern the return of the vehicle to the launch site in the event of an abort situation. As a part of the abort study, a series of trajectories were also run to determine when it is possible to abort to a feasible orbit in the event of an engine-out situation. The advanced SSTO vehicle was designed to have a cross-range capability of 1100 nmi; hence, this orbit need only be sufficient to allow the vehicle to perform one orbit before reentry occurs. For the purposes of this study, an orbit of 100 nmi circular was chosen. This represents a very conservative choice that will remain stable for days, thus allowing a number of reentry opportunities to the Kennedy Space Center or Edwards Air Force Base. As noted previously, the advanced SSTO vehicle was designed to deliver a 10-klb payload to an initial target orbit of 100 nmi circular with an additional orbital maneuvering system (OMS) ΔV capability of 500 ft/s required for mission

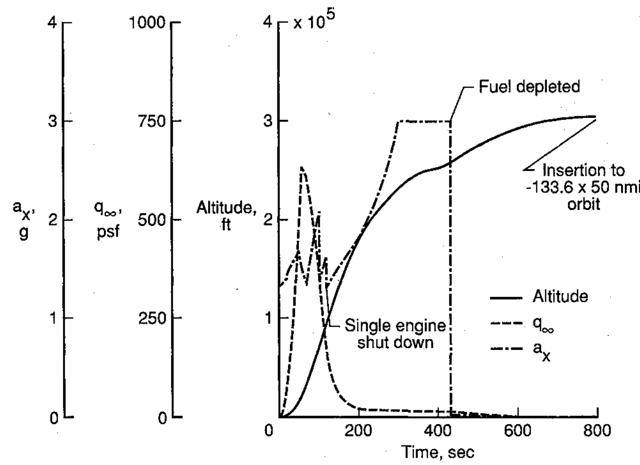

Fig. 15 ATO trajectory for single-engine-out abort from 120 s.

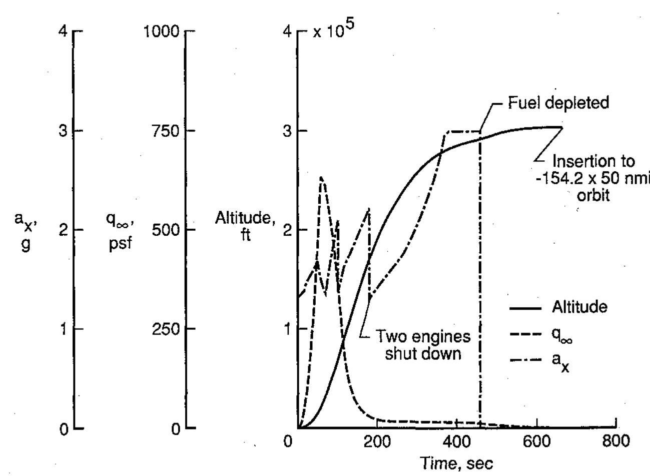

Fig. 16 ATO trajectory for two-engine-out abort from 180 s.

completion. This 500 ft/s of OMS propellant is in addition to the propellant provided for a reentry burn from a 100 nmi circular orbit. The ATO cases considered in this study use all or part of this 500 ft/s of orbital maneuvering propellant; thus, any mission requiring orbital maneuvering would not be possible in an ATO situation. The vehicle would merely obtain a 100-nmi circular orbit and remain there until a re-entry opportunity occurs.

Single-Engine-Out

The minimum time from which a successful ATO maneuver could be accomplished in the event of a single main engine shutdown is 120 s. This capability provides a 60-s overlap (from 120 to 180 s) during which the vehicle can execute either an RTLS or an ATO maneuver. When a main engine is shut down at 120 s into the nominal ascent, the vehicle T/W drops from 1.68 to 1.29 (Fig. 15). The pitch rates from the nominal ascent are then modified to allow the vehicle to gain needed altitude. At 430 s, the remaining fuel is depleted and all engines are shut down. The vehicle then coasts until γ_r is equal to 0 deg at 780 s. Insertion then occurs into an orbit with a -133.6-nmi perigee and a 50-nmi apogee (-133.6×50 nmi). A circularization burn is performed, and an additional burn places the vehicle in the nominal transfer orbit of 50 × 100 nmi. The vehicle then coasts until an altitude of 100 nmi is reached, and a final circularization burn is performed to place the vehicle in a 100-nmi circular parking orbit.

To perform this ATO maneuver from 120 s, 440 ft/s of the available 500 ft/s of additional OMS propellant is used. Hence, a 60 ft/s OMS ΔV capability remains as a margin to compensate for additional drag during the transfer and parking orbits.

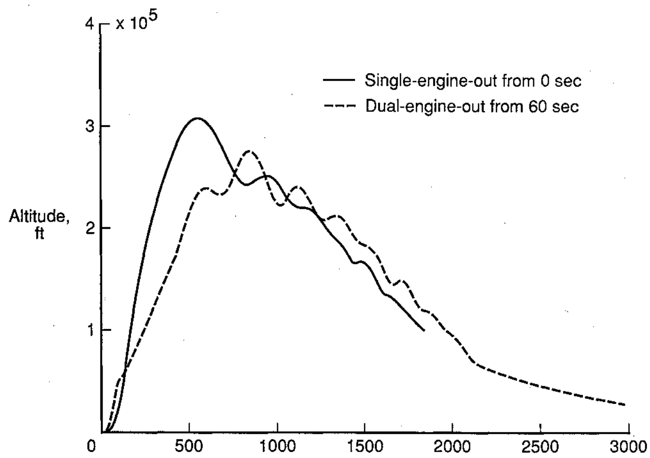

Fig. 17 Altitude profiles of downrange aborts to Easter Island.

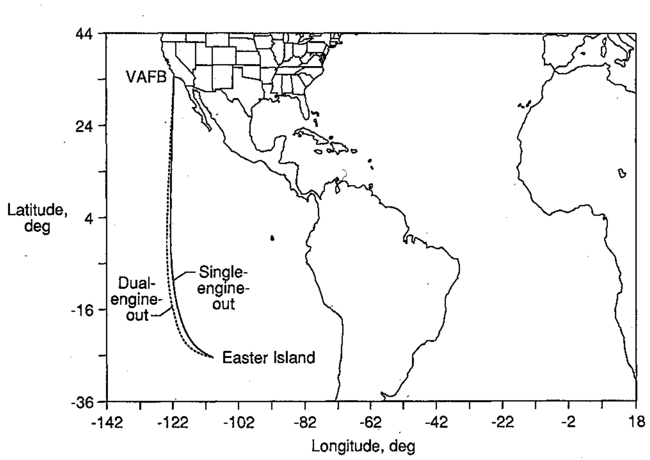

Fig. 18 Ground traces of downrange aborts to Easter Island.

Two-Engine-Out

The minimum time from which a successful ATO maneuver could be accomplished in the event of a dual main engine shutdown is 180 s. Thus, if two main engines must be shut down, an RTLS maneuver could be performed from 60 to 180 s after launch and an ATO maneuver could be performed after that time. When two main engines are shut down at 180 s into the nominal ascent, the vehicle T/W drops from 2.22 to 1.33 (Fig. 16). The pitch rates from the nominal ascent are then modified to allow the vehicle to gain needed altitude. At 460 s, the remaining fuel is depleted, and all engines are shut down. The vehicle then coasts until γ_r is equal to 0 deg at 660 s. Insertion then occurs into a -154.2×50 nmi orbit. From this point, the orbital transfer to a parking orbit of 100 nmi circular is similar to the single-engine-out case.

To perform this ATO maneuver from 180 s, 480 ft/s of the available 500 ft/s of additional OMS propellant is used. Hence, a 20 ft/s OMS ΔV capability remains as a margin to compensate for additional drag during the transfer and parking orbits.

Down-Range Abort

The advanced SSTO vehicle can execute either an RTLS abort or ATO maneuver anytime from launch until orbital insertion during the nominal ascent. Thus, there are no gaps in the engine-out abort capability of the vehicle that would require the existence of down-range landing sites. However, the existence of down-range abort opportunities would provide a useful alternative abort mode should an RTLS or ATO maneuver be judged less desirable.

Although a complete analysis of down-range abort opportunities is beyond the scope of this study, an attempt was made to determine the minimum time into the nominal ascent trajectory that a down-range abort to Easter Island (26.5°S, 109°W) would be feasible. Easter Island was selected as a down-range abort site for Space Shuttle launches from VAFB, and runway facilities currently exist that are capable of landing a Space Shuttle. A single-engine-out down-range abort to Easter Island is possible from the launch pad, and a two-engine-out down-range abort is possible from 60 sec into the nominal ascent. The altitude profiles and the ground traces for these two trajectories are given in Figs. 17 and 18. The philosophy used in constructing these two abort trajectories was to continue climbing to an altitude sufficient to allow a typical re-entry profile for the latter portion of the trajectory. Given the cross-range capability of the advanced SSTO vehicle and the flexibility provided by the remaining on-board propellant, a series of down-range abort opportunities should be possible for engine-out cases later into the nominal ascent trajectory. Should down-range aborts to Easter Island become impossible within the vehicle design constraints for engine-out cases later into the ascent, the island of Diego Garcia (7°S, 72°E) could be an attractive candidate for an additional down-range landing site because of its 12,000-ft runway facility.

Summary

The abort capabilities of an advanced-technology, rocket-powered, single-stage-to-orbit launch vehicle that has five main engines have been studied. In the event of a single or dual main engine shutdown, return-to-launch-site, abort-to-orbit, and down-range abort opportunities were assessed. As a result of the analysis performed, several observations can be made:

1) If a single main engine must be shut down between launch and 180 s into the nominal ascent, an RTLS abort maneuver can be performed. If a single main engine must be shut down between 120 s into the nominal ascent and orbital insertion, an ATO maneuver is possible. If a single main engine must be shut down immediately upon liftoff, a down-range abort can be accomplished to Easter Island, and the possibility exists for down-range aborts from later in the nominal ascent

trajectory. Thus, for a single-engine-out failure mode, a full range of abort opportunities exists, including a 60-s overlap in ATO and RTLS aborts.

2) If two main engines must be shut down between 60 s and 180 s into the nominal ascent, an RTLS abort maneuver can be performed. If two main engines must be shut down between 180 s into the nominal ascent and orbital insertion, an ATO maneuver is possible. If two main engines must be shut down at 60 s into the nominal ascent, a down-range abort can be accomplished to Easter Island, and the possibility exists for down-range aborts from later than 60 s into the nominal ascent trajectory. Thus, for a two-engine-out failure mode, a range of abort opportunities exists from 60 s into the flight until orbital insertion.

3) The advanced reference SSTO vehicle can execute all of the abort trajectories just summarized without violating design constraints on aerodynamic wing loads, dynamic pressure loads, acceleration loads, and heating loads from the nominal ascent and entry profiles. Hence, no additional structure or thermal protection system must be added to allow the advanced SSTO vehicle to have a large range of abort opportunities.

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