BOOSTER RECOVERY FOLLOWING PREMATURE SPACE SHUTTLE STAGE SEPARATION

M. J. Hurley, Design Specialist
Flight Technology, Space Shuttle

Convair Aerospace Division of General Dynamics
San Diego, California

INTRODUCTION

Abort criteria necessary to satisfy Space Shuttle program requirements include intact vehicle abort capability. Intact abort implies the ability of the booster and orbiter to separate and both continue flight to a safe landing, with a full payload aboard the orbiter. Obviously, the requirement to separate early along the ascent trajectory presupposes critical operational problems that are probably booster problems and may preclude booster recovery. On the other hand, some critical problems while mated can become manageable when separated (e.g., major loss of booster thrust) and should result in full booster recovery. All critical orbiter problems fall into this category; since stage separation without orbiter thrust is a capability of some separation system concepts, booster stage recovery following separation is a requirement.

STUDY CONFIGURATION

The study configuration is the North American Rockwell delta-wing orbiter and the General Dynamics B-9S delta-wing booster. The orbiter is launched piggyback on the booster and is located slightly ahead of the booster nose. Previous studies (e.g., Ref. 1 – 3) have demonstrated the ability of a modified four-bar linkage system to separate the stages anywhere along the ascent trajectory with a modest weight penalty. The capacity for booster recovery after separation was the objective of this study. It should be noted that the study results are equally applicable to the current, tandem-staged Space Shuttle concepts, providing that (1) stage separation does not require booster engine cutoff, and (2) the basic booster design parameters (e.g., wing loading and aerodynamic balance) are comparable.

STUDY CONFIGURATION

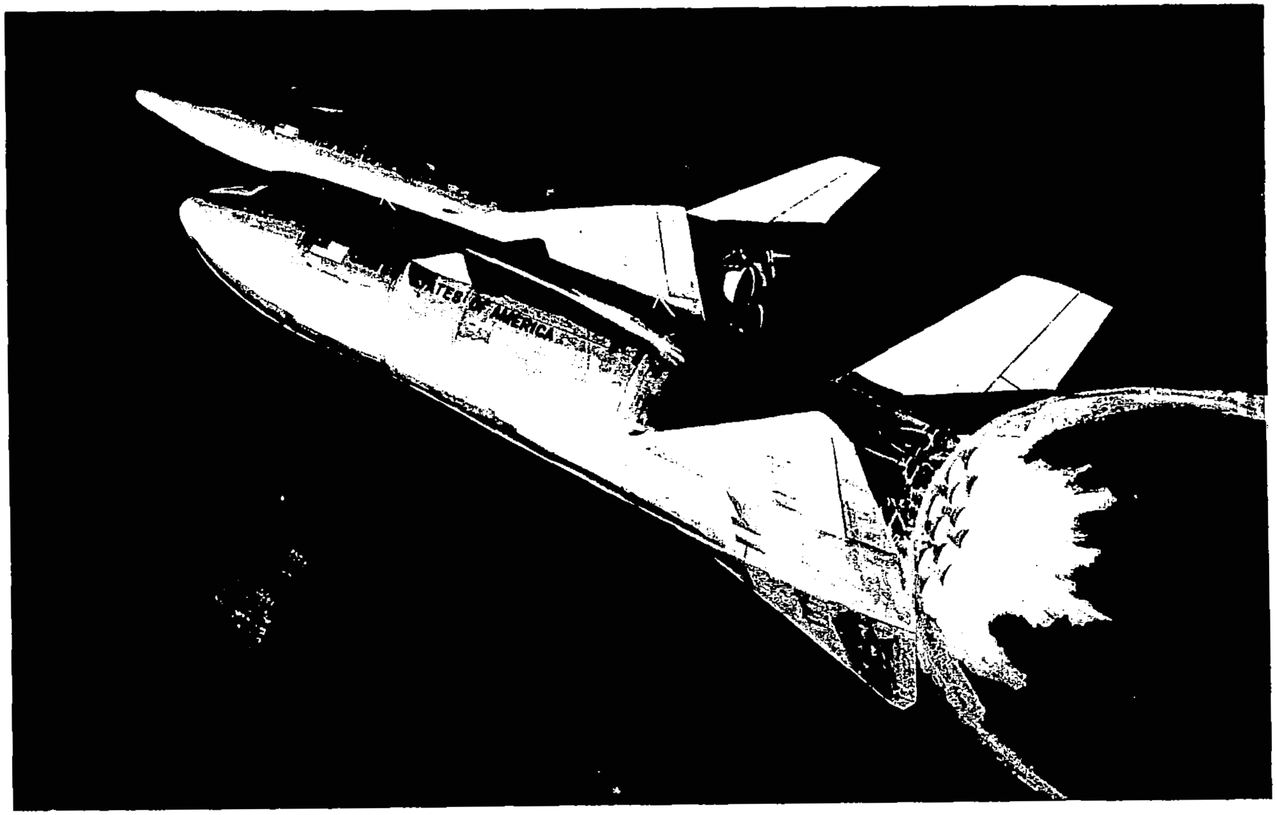


Figure 1

BURNOUT AND APOGEE CONSTRAINTS

Several recovery problem areas can be immediately uncovered in even a cursory overview of the postseparation physics. Without the orbiter mass in which to "sink" the energy derived from thrust acceleration, the resultant burnout conditions could* be at a much higher energy state, resulting in much more severe entry heating and loading problems, as well as downrange recovery problems due to the added velocity. The alternative of engine cutoff with substantial propellants still remaining in the booster tanks creates insurmountable problems on entry and landing. Even deviations from the nominal ascent trajectory immediately result in a host of off-nominal flight conditions (e.g., heating, loading) that must be carefully evaluated to ensure that design constraints are not appreciably** violated. In some instances, these constraints are not readily apparent and can be easily violated; for example, the thermal protection system and the cruise flyback systems are designed for the worst recovery trajectory – namely, the nominal trajectory – and any trajectory that substantially exceeds it in burn duration or velocity-time will be unacceptable.

This trajectory constraint diagram exhibits two of the major constraints on the apogee. Also presented is the nominal trajectory through the 200.4-second burnout point. Any apogee ($\gamma = 0$) point would violate either (or both) the entry heating or loading capabilities of the booster. It should be noted that the coast to apogee beyond the 200.4-second burnout condition will put the apogee point directly on the 4g boundary (the nominal condition). Velocity-time constraints (e.g., exceeding booster flyback range) cannot be included on velocity x altitude constraint space.

**Abort just before nominal separation (where the burnout conditions are near nominal) are also considered.*

***In a probabilistic sense, it is conceivable to use the design margin of the various subsystems in event of an independent failure, since the probability of a marginal subsystem (already a partial failure) and a primary critical failure is very small by design intent.*

TRAJECTORY CONSTRAINT DIAGRAM

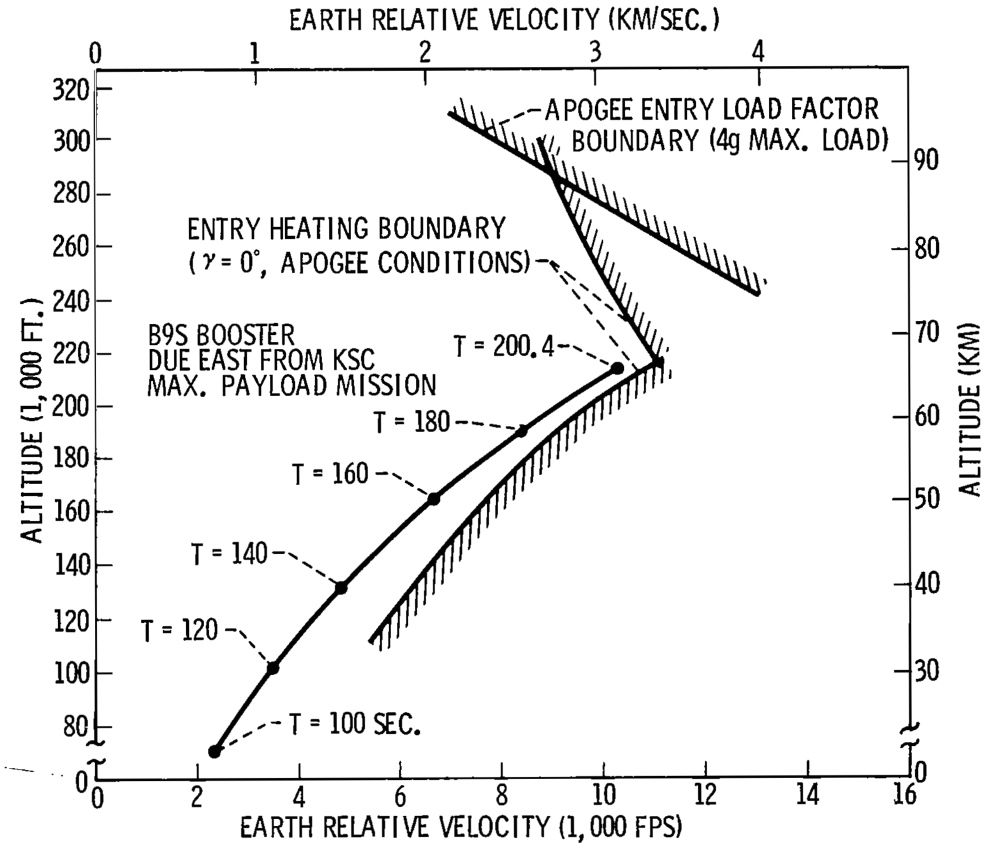


Figure 2

A secondary problem is with the engine system. To maintain a maximum of 3g longitudinally during engine firing as the booster approaches an empty condition, a number of engines must be throttled or cut off. The problem with cutting off one engine in the proximity of others that are still firing is illustrated opposite and is serious enough to require scrapping the engine bell after booster recovery. Since this procedure does not jeopardize vehicle recovery, it is an accepted mode of operation in event of an abort.

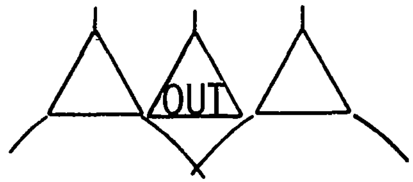
BOOSTER ENGINE BELL HEATING, ENGINE OUT CONDITIONS

NO ENGINE DEFLECTION

ESTIMATED HEATING RATE: 114 - 285 KW/M^2 (10 -25 BTU/SQ. FT.-SEC.)

EQUIVALENT RADIATION EQUILIBRIUM TEMPERATURE 1,217°– 1,517° K (1,730°– 2,270° F)

BASED ON ENGINE MANUFACTURER QUOTED LIMIT OF 1,356°–1,422° K (1,980°F–2,100°F) CONDITION IS MARGINAL & REQUIRES DETAILED ANALYSIS



EFFECT OF ENGINE DEFLECTION

HEATING RATE = 794 KW/M^2 (70 BTU/SQ. FT.-SEC.) BASED ON SATURN V/S-II STAGE TESTING

EXPECTED HEATING RATE IS TOO SEVERE FOR THE SHUTTLE ENGINE

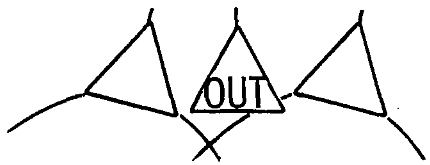


Figure 3

The general effect of aerodynamic heating can best be seen in this figure. The majority of heat transfer to the booster lower surfaces occurs during the entry phase; internal temperatures (e.g., the LH_2 and LO_2 tanks in the figure) tend to peak shortly thereafter. It was reasoned that if a loiter maneuver could be employed within the constraint region shown earlier so that the velocity vector magnitude was not increased and the altitude was increased (if desired) to reduce the prevailing heat transfer rate, then a recovery trajectory could be conceived that would result in temperatures lower or on the same order as the nominal trajectory.

TYPICAL BOOSTER LOWER SURFACE TANKAGE TEMPERATURE AND HEAT TRANSFER RATE HISTORIES

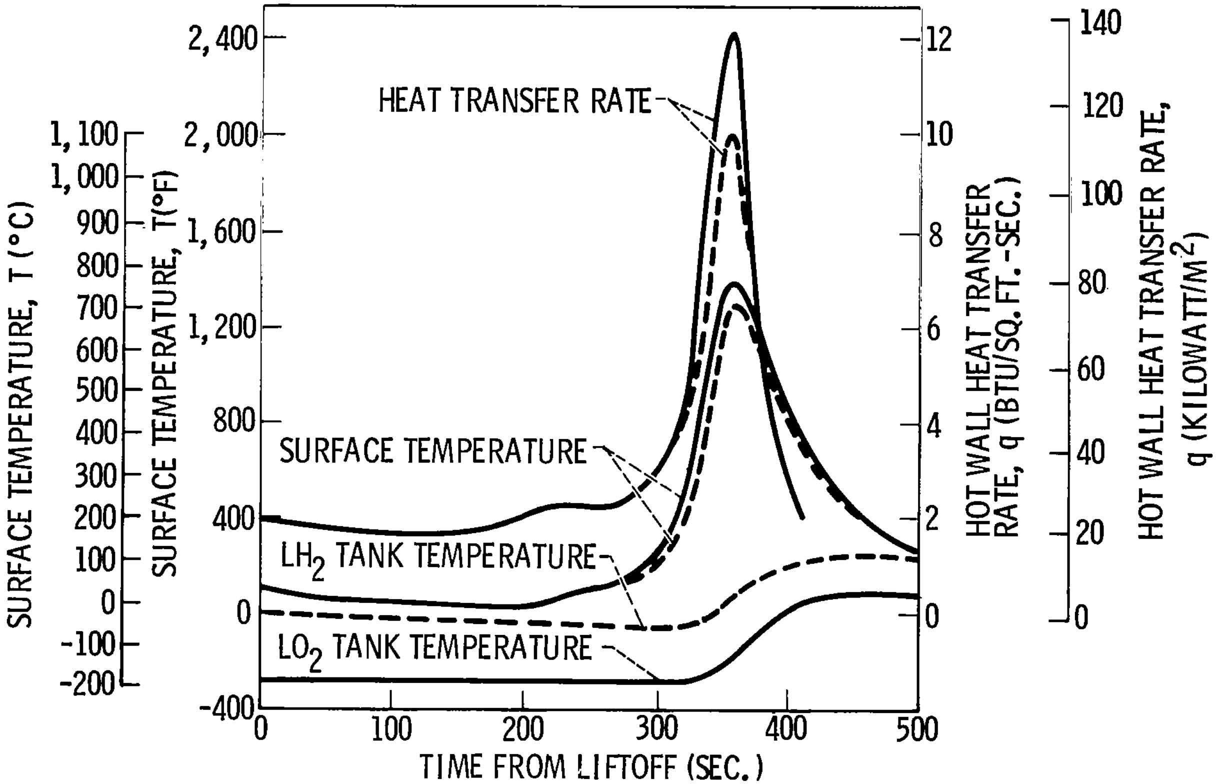
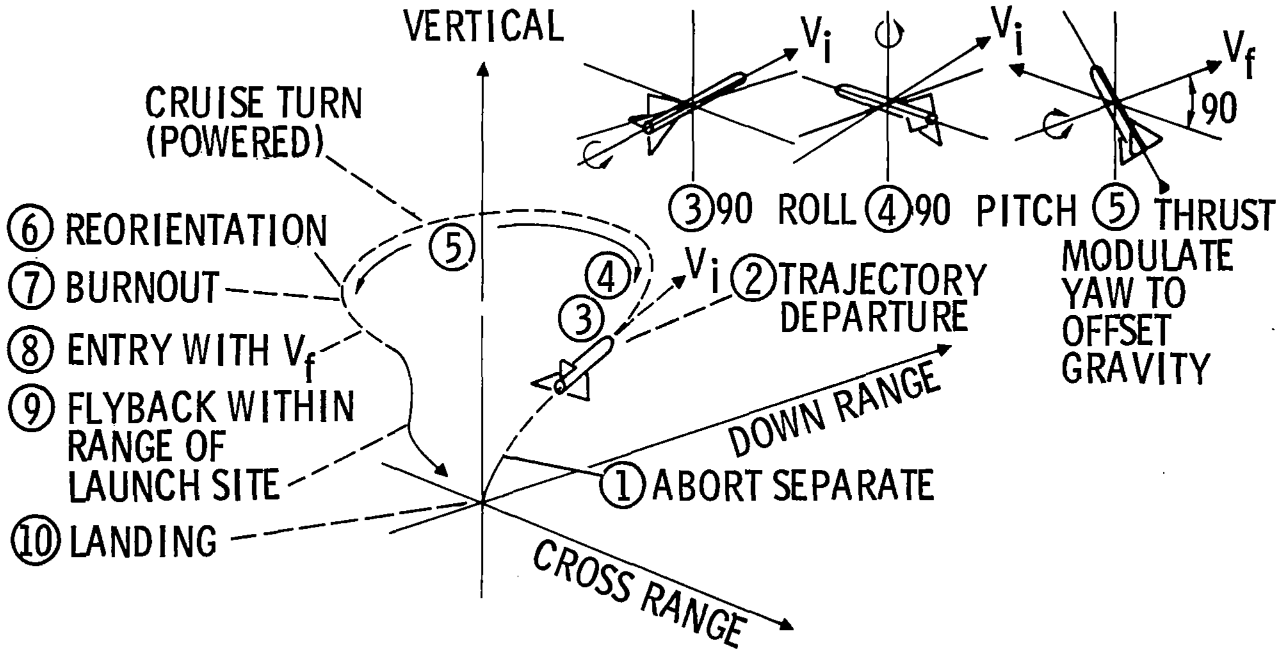


Figure 4

RECOVERY CONCEPT

Such a recovery trajectory is shown on this figure. Following abort separation (1), the booster continues on the nominal ascent trajectory until arriving within the constrained region. At that point (2), it departs from the nominal trajectory by (3) rolling 90 degrees counterclockwise about its longitudinal axis, (4) pitching 90 degrees nose-up to a 90 degree angle of attack, and (5) modulating the yaw angle with respect to the local horizontal to add to or detract from the gravity vector, thus controlling the vertical velocity component. By modulating the yaw angle, various higher altitudes may be achieved or altitudes in the near vicinity of the trajectory departure point (2) may be held. Once the flight path angle (γ) falls to zero, a vertical acceleration vector $\dot{V}_v = g$ could be achieved (by changing the yaw angle) so as to maintain the desired altitude. The component of thrust acceleration that lies in the horizontal plane will serve to torque the velocity vector to the left (back toward continental United States, if Kennedy Space Center is the launch site), thus both reducing downrange (by vectoring this into cross-range) and not adding to the initial departure velocity V_i. Since $\gamma > 0$, the final velocity attained at $\gamma = 0$ is $V_f < V_i$ due to the component of gravity that detracts from velocity. The resulting loiter trajectory (5) is a constant-altitude, constant-velocity powered (cruise) turn until burnout. At burnout (γ near 0), the booster begins its entry trajectory (8) at that apogee altitude and cruise velocity (V_f). Since the velocity is being continuously turned with the horizontal thrust acceleration vector component, the range plot will lie within the nominally provided flyback range. (An important feature is that entry loading and heating will also be less severe.) Following deployment of its airbreathing engines, the booster returns to the launch site (9) and lands (10).

BOOSTER RECOVERY TRAJECTORY FOLLOWING ABORT SEPARATION



WITHIN CONSTRAINTS
UP TO 30% THROTTLING OR CUTOFF ENGINES
BURN TIME ≤100 SEC. OVER NORMAL

Figure 5

ABORT TRAJECTORY CONSTRAINTS

Flying at 90 degrees relative to the free stream can produce additional problems to be resolved. The figure presents the wing loading constraint at 90 degrees angle of attack and is seen to completely enclose the constrained region. (Note that for the configuration investigated, the control constraint line to hold 90 degrees angle of attack fell just below the wing loading constraint.) Thus, if an abort resulted in stage separation before 130 seconds into the flight, the procedure would be to proceed along the nominal trajectory until the 130-second point is reached before departing from the nominal trajectory in accordance with the recommended recovery procedure (preceding figure). If an abort occurred after 130 seconds and resulted in stage separation, trajectory departure would occur immediately.

The requirements of a booster recovery following stage separation can now be simply expressed:

1. Stay within the nominal ascent trajectory until the sensitive regions (e.g., Mach 1.0 and maximum q) have passed, thus avoiding excessive aerodynamic loading and heating at maneuvering angles of attack. This requirement implies delaying trajectory departure until after 130 seconds into the flight.

2. Avoid high velocities when possible to avoid excessive heat transfer during the burn to propellant depletion.

3. Avoid holding inertial velocity orientations for appreciable durations so as not to aggravate the downrange problem during the burn to propellant depletion.

4. Minimize, when possible, the entry loading and heating so as not to aggravate a possibly crippled booster.

5. Maneuver, when possible, into a region that will put the intended landing site in close proximity.

ABORT TRAJECTORY CONSTRAINT DIAGRAM

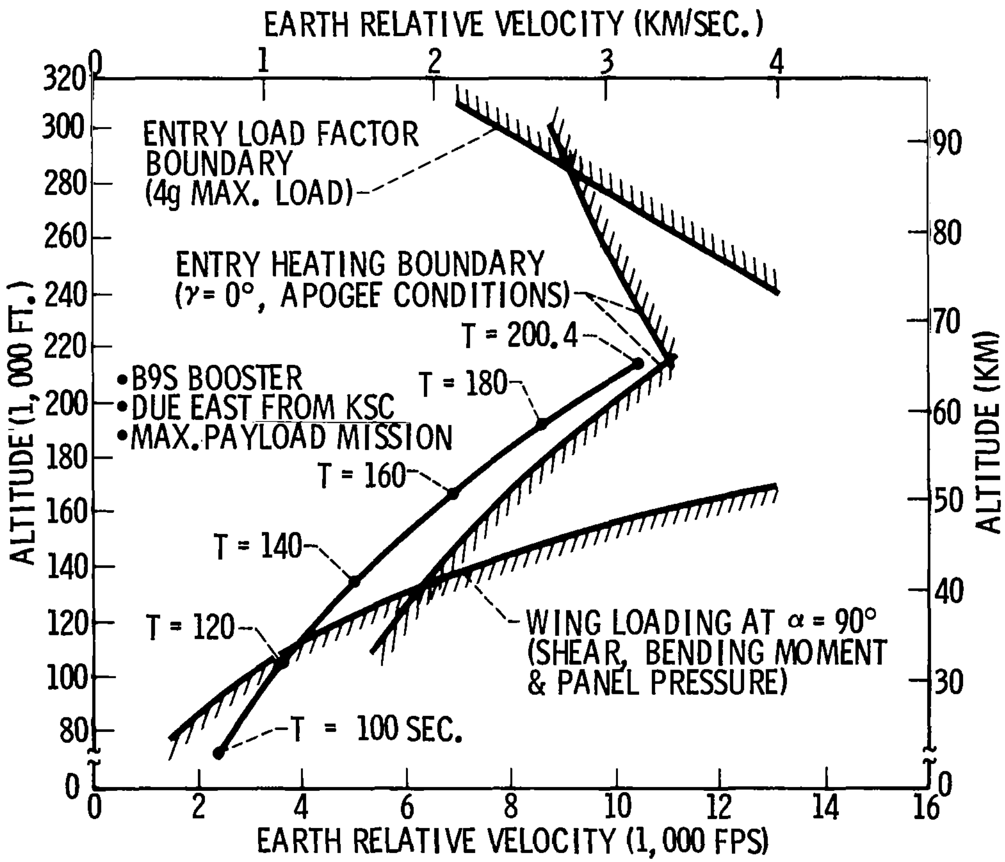


Figure 6

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This figure presents the additional burn time beyond the nominal 200.4-second burnout condition due to the propellant remaining, which was to have been spent carrying the orbiter. This time ranges from a maximum of 92 seconds when the orbiter is dumped at liftoff, to a minimum of zero seconds for an abort at booster engine cutoff (BECO). Up to 92 seconds additional burn time might be required if separation occurs before 130 seconds, depending upon the actual time of separation. However, should separation occur after 130 seconds, the additional burn time can be read directly from the figure and will be less than 54 seconds.

ADDITIONAL BURN TIME VERSUS ABORT INITIATION

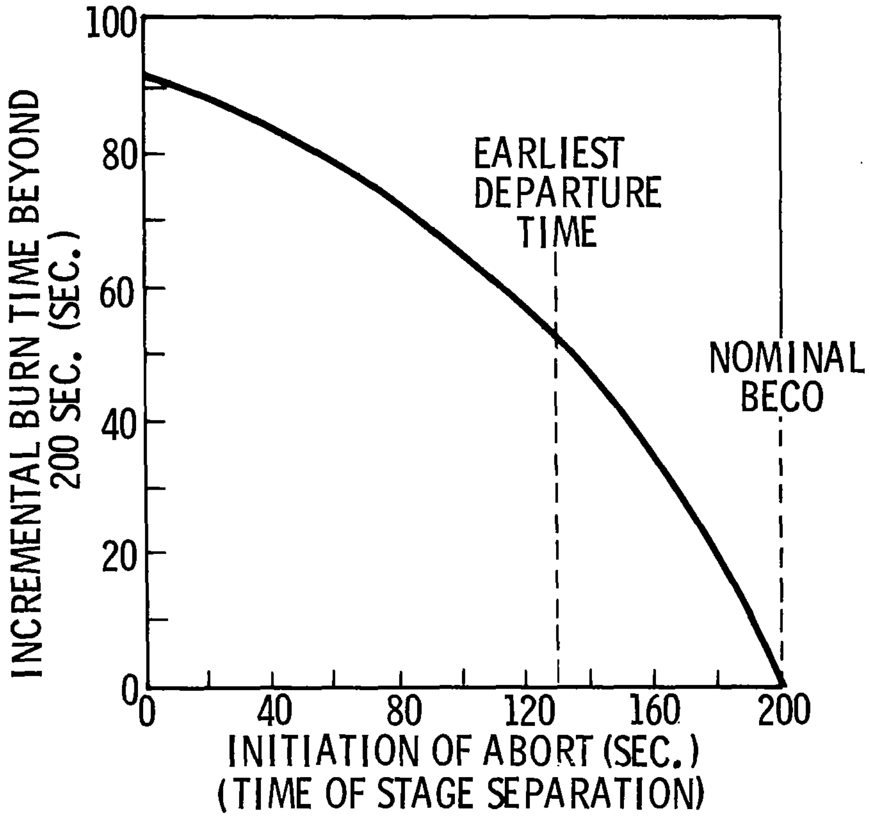

Figure 7

Two easily achievable operating procedures (using the recovery technique outlined) are superimposed on the constraint diagram. One procedure selects and maintains a constant yaw angle (no modulation), which produces burnout at apogee ($\gamma = 0$). The second procedure accomplishes continuous modulation of yaw angle to attain an altitude hold in the vicinity of the trajectory departure point. These procedures are merely extremes of trajectory management capability inherent in the recovery technique. Three distinct points (shown as "X") were selected at representative points in the region for detailed aerothermal analysis during the loiter and subsequent entry.

ABORT TRAJECTORIES FOR $T_{DEPARTURE} > 130$ SECONDS

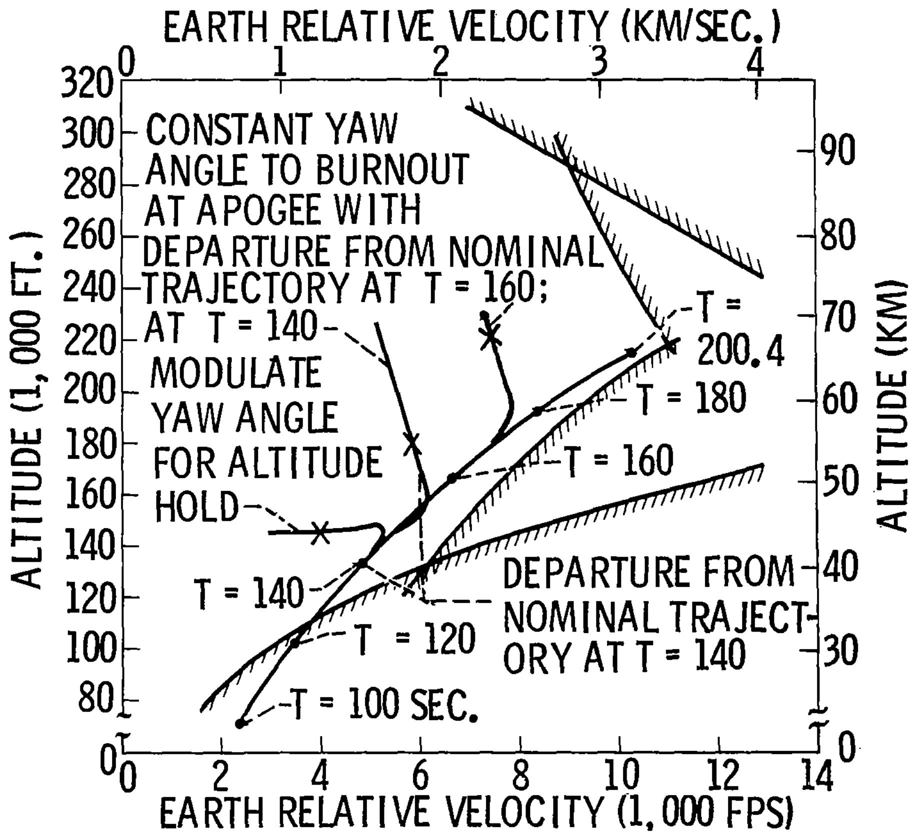

Figure 8

This figure demonstrates that the lower surface of the wing skin panel (Node 12) is lower in temperature than the nominal ("no abort") condition shown as a solid line. The aeroheating analysis included the ascent trajectory, a maximum-duration loiter at the "X" points, and subsequent entry heating. The results assumed an abort separation at time zero (post-liftoff) and included the full 92-second added burn time (beyond nominal burn) to propellant depletion; as such, the results are overly conservative. Although the 1,219-mps loiter is applicable to an abort separation at time zero and a trajectory departure of t = 140 seconds (see previous figure), the higher loiter velocities would generally be a consequence of abort separation after the earliest possible departure time (130 seconds) and the resulting loiter time would be correspondingly shorter.

LOWER SURFACE SKIN PANEL TEMPERATURES

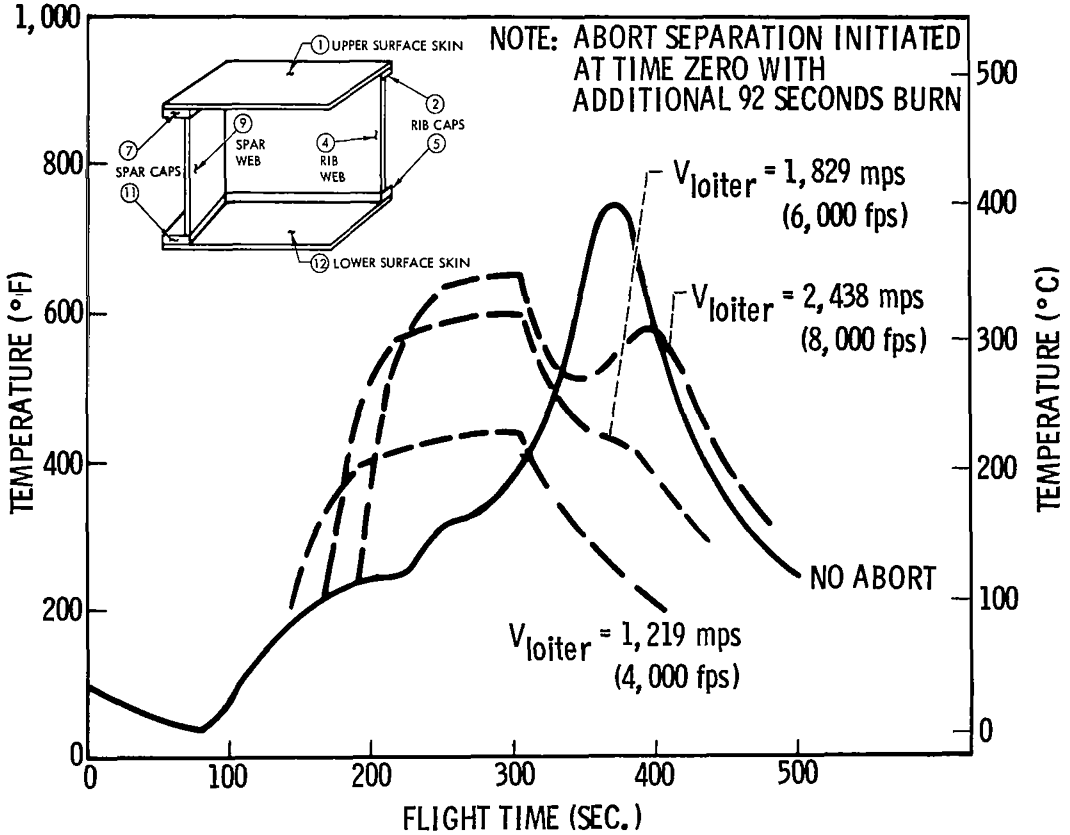

Figure 9

This illustration shows lower surface spar cap temperatures (Node 11) corrected to reflect the anticipated additional burn time commensurate with the indicated departure velocities. Again, it may be seen that the maximum spar cap temperature during abort is lower than in the "no abort" case.

LOWER SURFACE SPAR CAP TEMPERATURES

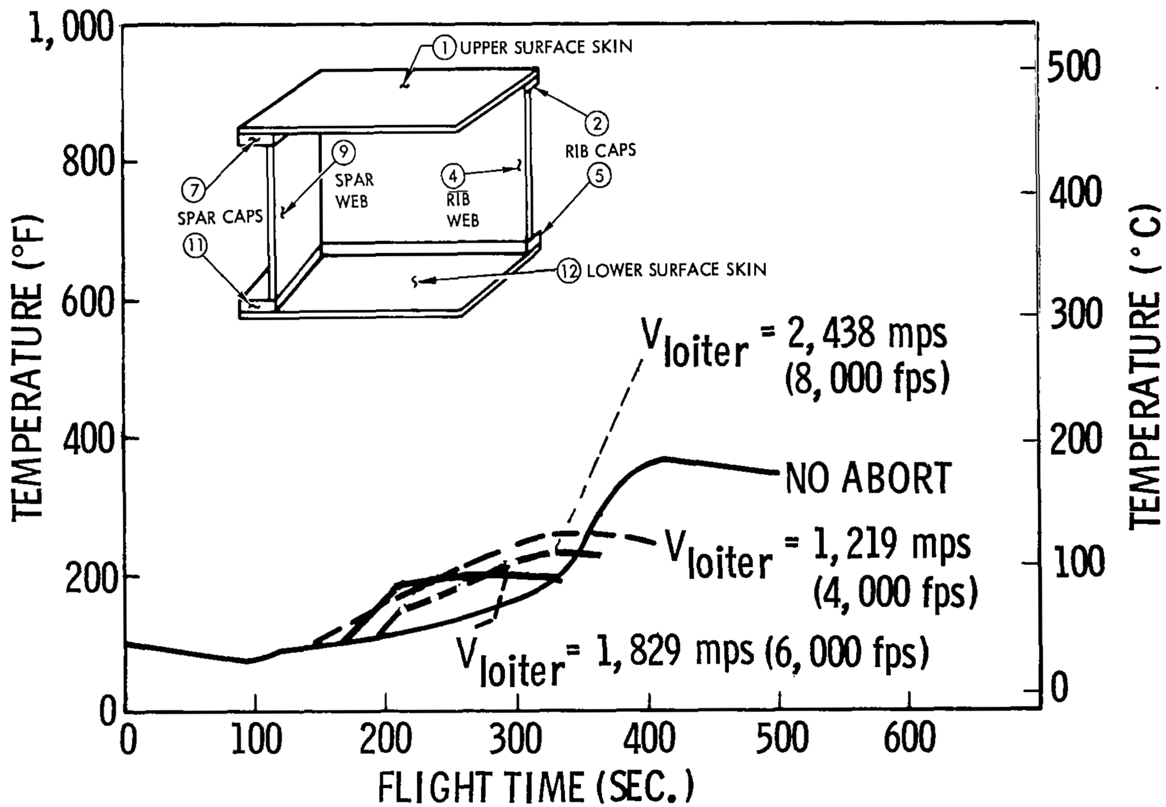

Figure 10

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STUDY RESULTS

Separation times of T_{abort} = 40, 80, 100, 160, and 190 seconds were simulated and the resulting trajectories plotted. The trajectories illustrate that the abort recovery procedure is well within the established flight constraints, except for abort separation near nominal BECO.

ABORT TRAJECTORIES FOR CONSTANT YAW ANGLES

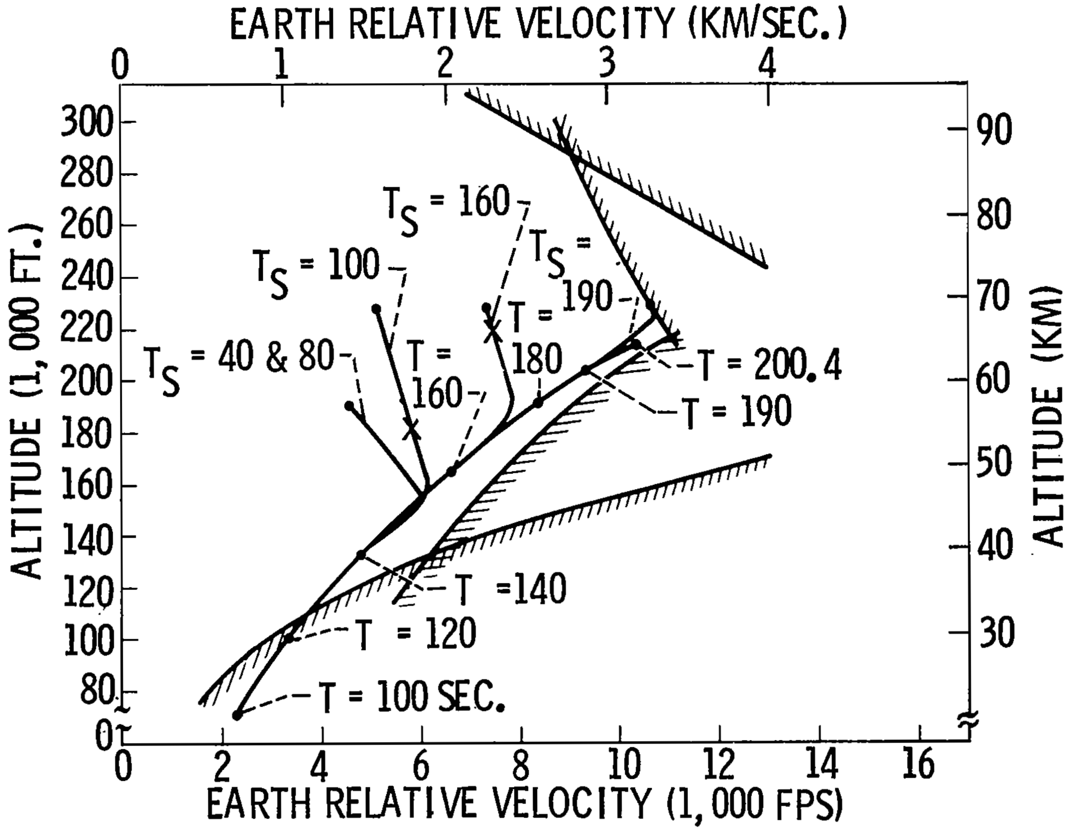

Figure 11

After deployment of its airbreathing engines, the booster returns to the launch site. The figure compares post-recovery flyback distance with time of abort separation. The reference flyback range is also shown. Except for abort separation immediately before normal staging, enough burn time remains to restrict the flyback range to within the baseline capability. Beyond 180 seconds into the trajectory, insufficient time is available to redirect the velocity vector; however, the excess energy is expended nearly colinearly with the velocity vector at separation, placing the booster beyond its design flyback range. An alternative landing site may be required for this condition.

REFERENCES

1. M.J. Hurley and M.J. Lanfranco, "Separation Dynamics of Multibody Clusters of Hinged and/or Linked Lifting-Entry Vehicles," presented to the Seventh Space Congress, Cocoa Beach, Fla., April 1970.
2. G.W. Carrie and M.J. Hurley, "Space Shuttle Separation System Analysis, A Capability Assessment," Convair Aerospace Report 76-549-4-172, 15 June 1971.
3. M.J. Hurley and G.W. Carrie, "Stage Separation of Parallel-Staged Shuttle Vehicles, A Capability Assessment," (to be published in proceedings of NASA Space Shuttle Aerothermodynamics Technology Conference, 15 and 16 Dec. 1971).

FLYBACK DISTANCE VERSUS TIME OF ABORT SEPARATION

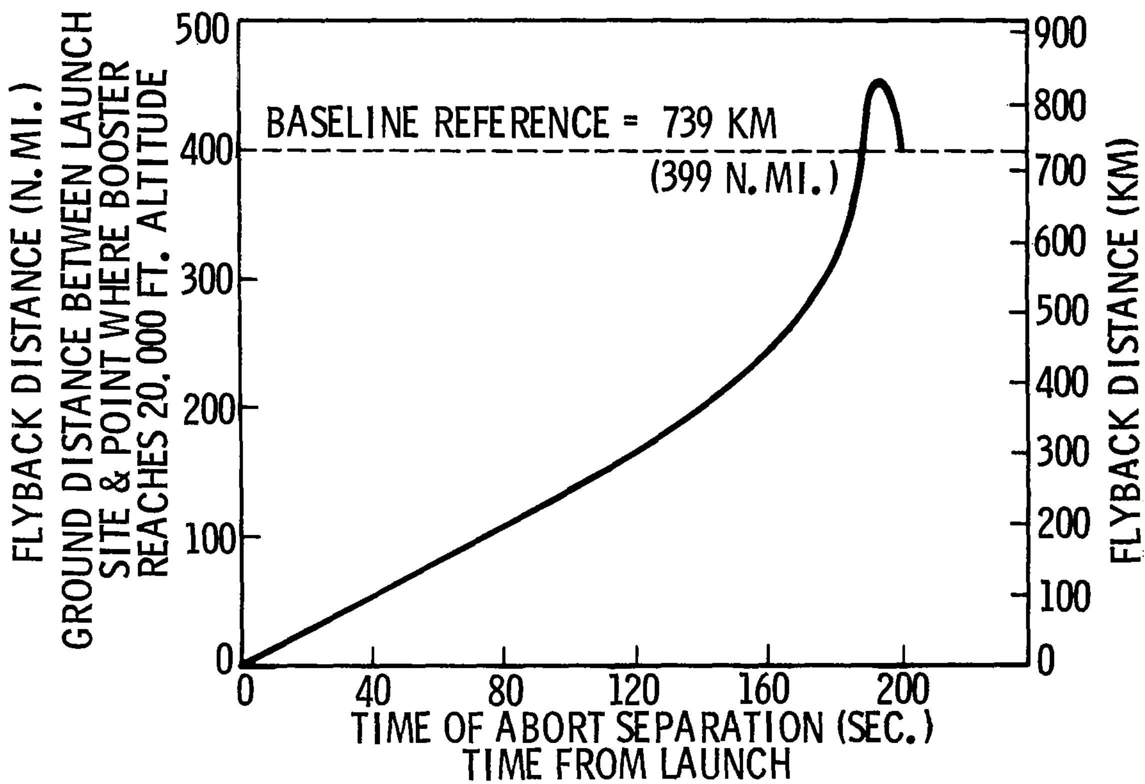

Figure 12