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DESCENT GUIDANCE AND MISSION PLANNING FOR SPACE SHUTTLE

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ABSTRACT

The Space Shuttle descent mission planning, mission design, deorbit targeting, and entry guidance have necessarily become interrelated because of the nature of the Orbiter's design and mission requirements. The desired descent trajectory has been formulated in a drag acceleration/relative velocity state space since nearly all of the vehicle's highly constraining flight limitations can be uniquely represented in this plane. This paper presents a description of these constraints along with the flight requirements that affect them, a discussion of the guidance logic which allows the Orbiter to follow the designed trajectory, and a summary of the impacts of contingency aborts and flightcrew interaction. The mission planning and guidance techniques have remained essentially unchanged through the Shuttle flight test program and subsequent operational flights. No problems or anomalies have been observed in these areas.

INTRODUCTION

The experience gained in developing the Gemini and Apollo entry mission plans, flight software, and trajectory monitoring procedures has provided insight into the problems encountered during the atmospheric descent of a manned spacecraft. The Shuttle Orbiter shares many requirements and constraints with these earlier vehicles. A flightpath must be maintained that causes no violations of the spacecraft's thermal or load limits yet ensures atmospheric capture and stable flight. Allowance must be made for uncertainties in atmospheric properties, navigational accuracies, and aerodynamic characteristics. The vehicle and crew must be able to function autonomously because of communication blackout and limited ground coverage. Finally, the spacecraft must be delivered to a specified location and energy state with the required precision.

Although the general nature of these requirements for manned reentry vehicles is similar, because of the Orbiter's basic design, nearly all of its flight constraints are significantly more limiting than those of previous spacecraft, and its mission is more complex. In addition to the normal end-of-mission functions, the Shuttle's entry system must support the needs of transoceanic abort landing (TAL) and abort once around (AOA) contingencies. These factors imply a wide range of vehicle weights and center-of-gravity (c.g.) locations and have made it necessary to implement a complex guidance scheme with greater flexibility than that of either the Gemini or the Apollo vehicle.

The development of the guidance logic and the selection of a basic flight profile are closely related through the Shuttle descent mission planning. Therefore, the effects of both mission requirements and guidance system characteristics are addressed.

ENTRY CONFIGURATION

During the early phases of entry (before active guidance), attitude control in all vehicle axes is maintained by the Orbiter reaction control system (RCS). To avoid unacceptable aerothermodynamic heating, especially on the upper surface and wing leading edge, a 40° angle of attack is flown during the high-speed flight regime (Mach > 14). Even though this value is far on the back side of the lift-to-drag ratio (L/D) curve, it still results in a much higher L/D than for previously flown manned reentry vehicles. Figure 1 shows the overall aerodynamic characteristics on a typical Orbiter entry trajectory (ref. 1).

When sufficient atmospheric dynamic pressure has been achieved, attitude control is transferred to the aerodynamic control surfaces (aerosurfaces). At a navigation-sensed dynamic pressure of 10 psf, the roll RCS jets are deactivated and differential elevon deflections control motion about that axis. When the dynamic pressure exceeds 20 psf, control by the elevator in the form of symmetric elevon deflections replaces the pitch jets. As is indicated later, the primary maneuvers performed during entry are rotations about the vehicle velocity vector. These maneuvers amount to coordinated roll and yaw rates about the spacecraft body axes. Because of the large angle of attack, the vertical stabilizer is not an effective aerosurface during high-speed flight; therefore, the maneuvers require a combination of aft yaw RCS jets and ailerons. The yaw jets operate throughout entry.

In addition to providing active vehicle control (i.e., the Orbiter is statically unstable during much of its flight), the flight control system must compensate for variations in pitching moment due

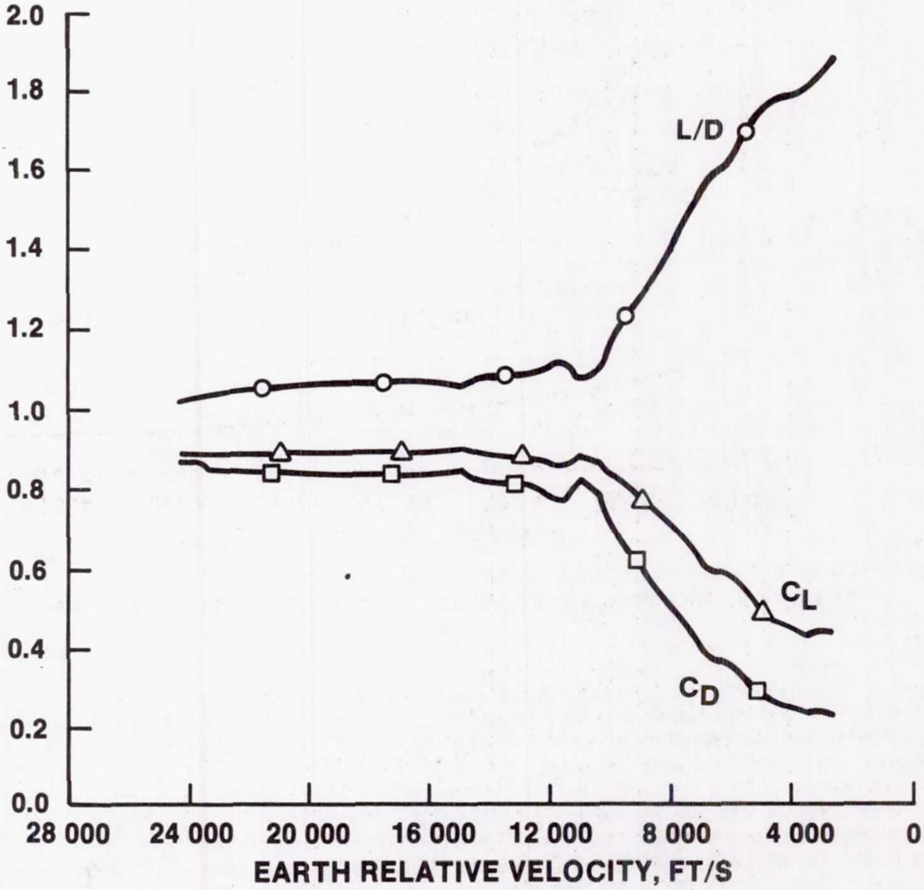

FIGURE 1.- TYPICAL ORBITER AERODYNAMIC CHARACTERISTICS.

to shifts in the spacecraft center of gravity and aerodynamic moments. To maintain the elevons in a thermally benign position where they are aerodynamically effective for lateral control, the large aft body flap is used for pitch trim. The ailerons trim out any lateral c.g. effects.

ENTRY CORRIDOR

Entry imposes on a returning vehicle certain physical conditions, the severity of which depends on the particular trajectory flown. In general, for a given entry velocity, a steep flightpath angle implies high surface temperatures and aerodynamic load factors, whereas a shallow flightpath angle can result in poor trajectory control (phugoids) or atmospheric skipout. The width of the entry corridor is a function of such vehicle capabilities as thermal and structural constraints and aerodynamic characteristics. Figure 2 shows the entry corridors for the Apollo command module (CM) and the Shuttle Orbiter (ref. 2). Both are defined by the flightpath angle and the inertial velocity at entry interface (400 000 feet altitude). It is apparent that the Shuttle thermal limits impose severe restrictions on the entry corridor and place stringent requirements on entry targeting and guidance.

DEORBIT TARGETING

The Shuttle orbital maneuvering system (OMS) performs a single deorbit burn to arrive at entry interface. The result is a specific combination of velocity, flightpath angle, and range to go, which depend on the orbital altitude and burn characteristics. To cover the range of Shuttle operational orbits (as high as 500 nautical miles), a target line is generated in the V-γ plane representing a set of acceptable entry interface (EI) conditions. The intersection of this target line with the appropriate deorbit curve defines the target state. The range to the target is controlled by properly

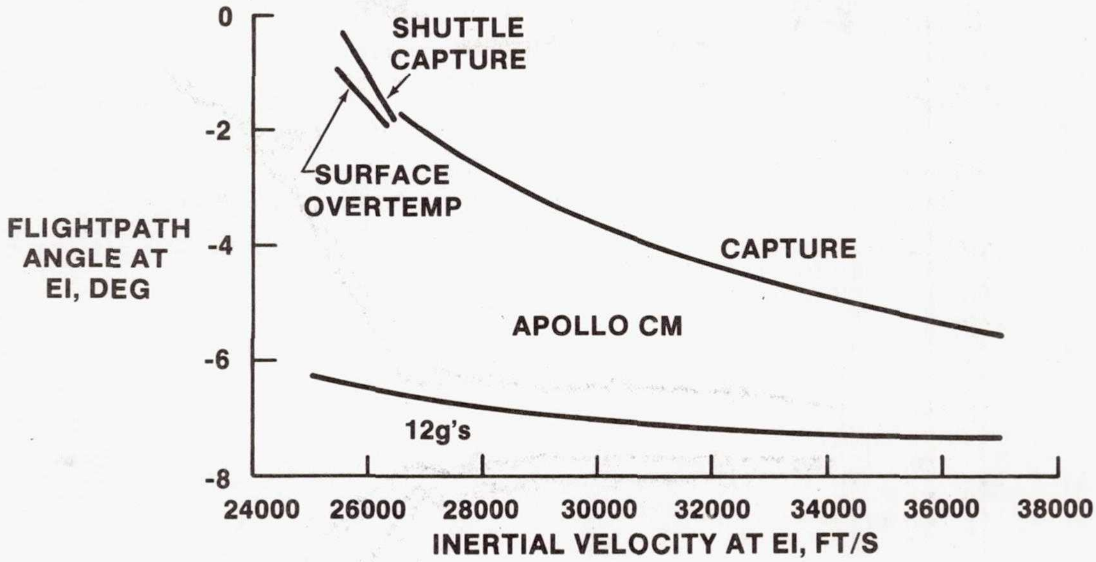

FIGURE 2.- APOLLO COMMAND MODULE AND SHUTTLE ORBITER ENTRY CORRIDORS.

timing the burn. The segment of the entry from EI to active guidance initiation is normally flown at a wings-level attitude (steep target). In the event of a fuel-critical deorbit or an OMS underburn, a bank angle as great as 90° can be commanded (shallow target). This prebank has the effect of steepening the early trajectory by dumping lift. Typical steep and shallow target lines and the transfer-orbit curves are shown in figure 3. The onboard deorbit guidance actually targets the line rather than the intersection, so that any deviation from the ideal transfer still results in acceptable entry conditions. The target lines themselves represent EI states which allow the trajectory to converge to preplanned entry profiles (to be discussed later). For steep targets, the line is adjusted to optimally trade surface temperatures against high backface temperatures; the latter temperatures are caused by the large heat loads generated during long, shallow glides.

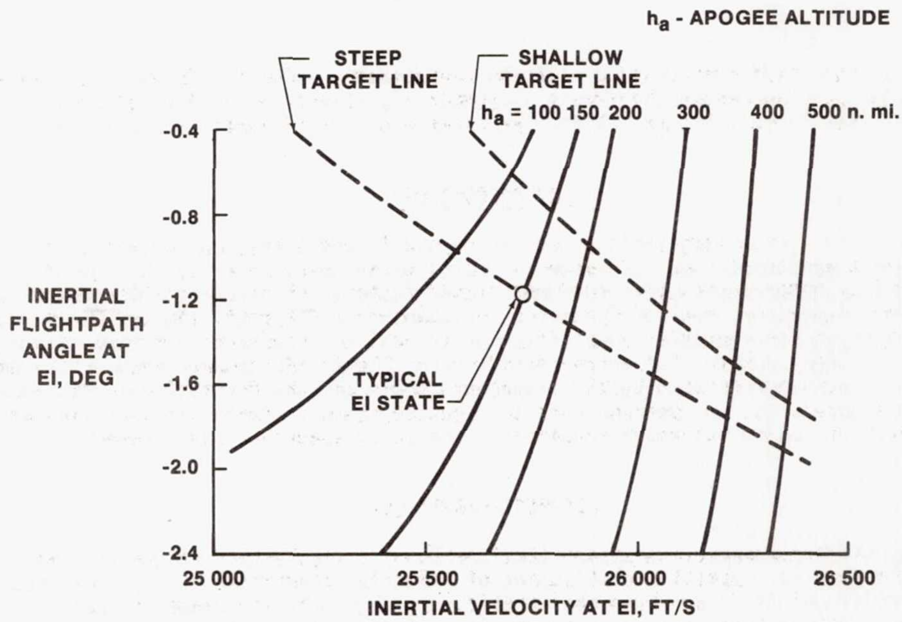

FIGURE 3.- STEEP AND SHALLOW TARGET LINES.

TRAJECTORY CONSTRAINTS

Once the Orbiter has achieved the desired EI state, it is still necessary to actively guide the vehicle to the landing site while remaining within trajectory and vehicle limits. The various constraint boundaries become binding at different flight conditions, and their interaction can be complex. To visualize the profile that must be flown, the constraints must be formulated as functions of the proper trajectory variables.

For thermal and flight control system considerations, the Orbiter angle of attack (and therefore its aerodynamic characteristics) has been scheduled as a function of Earth relative velocity. Figure 4 shows the profile used in the majority of Shuttle flights. The ramp beginning at a velocity of 14 500 ft/s delivers the Orbiter to the terminal area energy management (TAEM) interface (2500 ft/s) on the front side of the L/D curve, where more conventional aircraft-type control is employed.

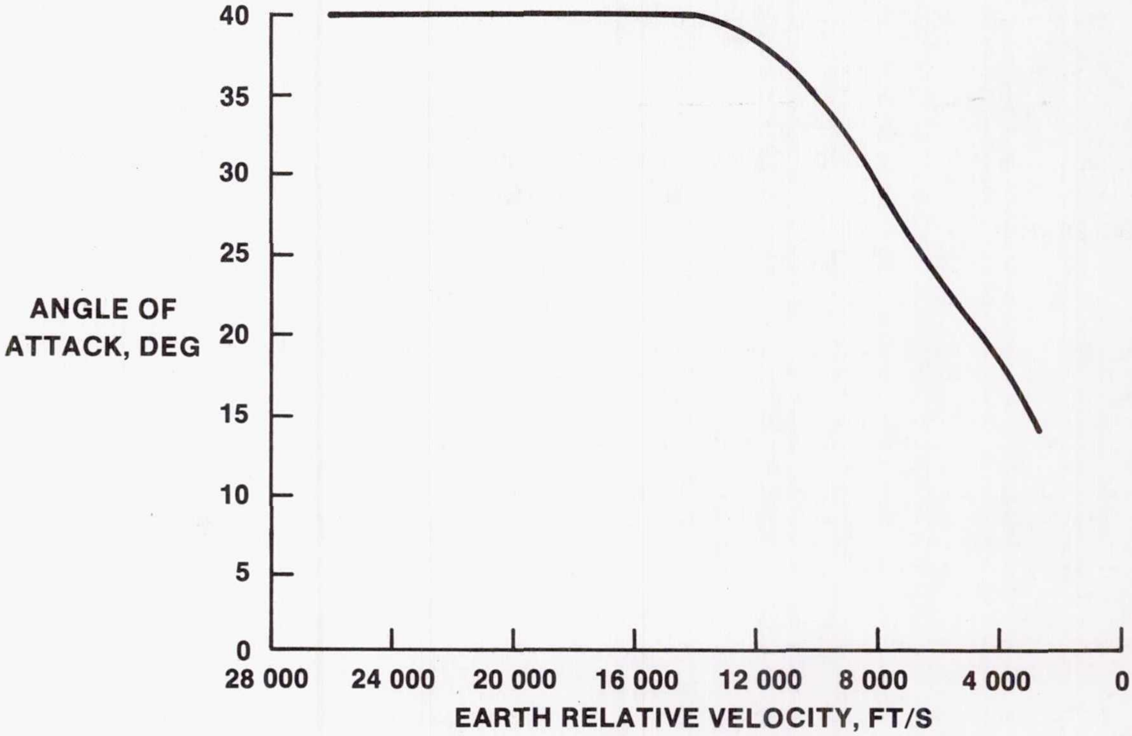

FIGURE 4.- ORBITER ANGLE OF ATTACK PROFILE.

The most critical constraints during early entry are the thermal protection system (TPS) surface temperatures. For a fixed angle-of-attack profile, large dynamic pressures and relative velocities will elevate surface temperatures. Since the aerodynamic flow field over the Orbiter's surface is complex, mathematical models representing heat rates on specific vehicle locations or control points are used for trajectory design (ref. 3). Figure 5 depicts the positions of several control points. Depending on the particular flight condition and the maximum allowable temperature at each point, any of these locations may represent the limiting constraint on the trajectory.

To ensure stable, nonoscillatory flight, a design requirement has been implemented to guarantee that the Orbiter flightpath angle is always decreasing, that is, that the trajectory is constantly becoming steeper. The limiting case, where $\dot{\gamma} = 0$, defines the equilibrium glide boundary. Physically, this value corresponds to the flight condition in which the vertical component of the vehicle lift acceleration plus the centripetal acceleration induced by the high velocity are balanced by gravity. For a given bank angle, the constraint can be expressed as a function of dynamic pressure and inertial velocity since they determine the magnitudes of lift and centripetal acceleration, respectively. The value of the minimum allowable bank angle resulted from trade studies evaluating the horizontal lift component necessary for Orbiter crossranging requirements.

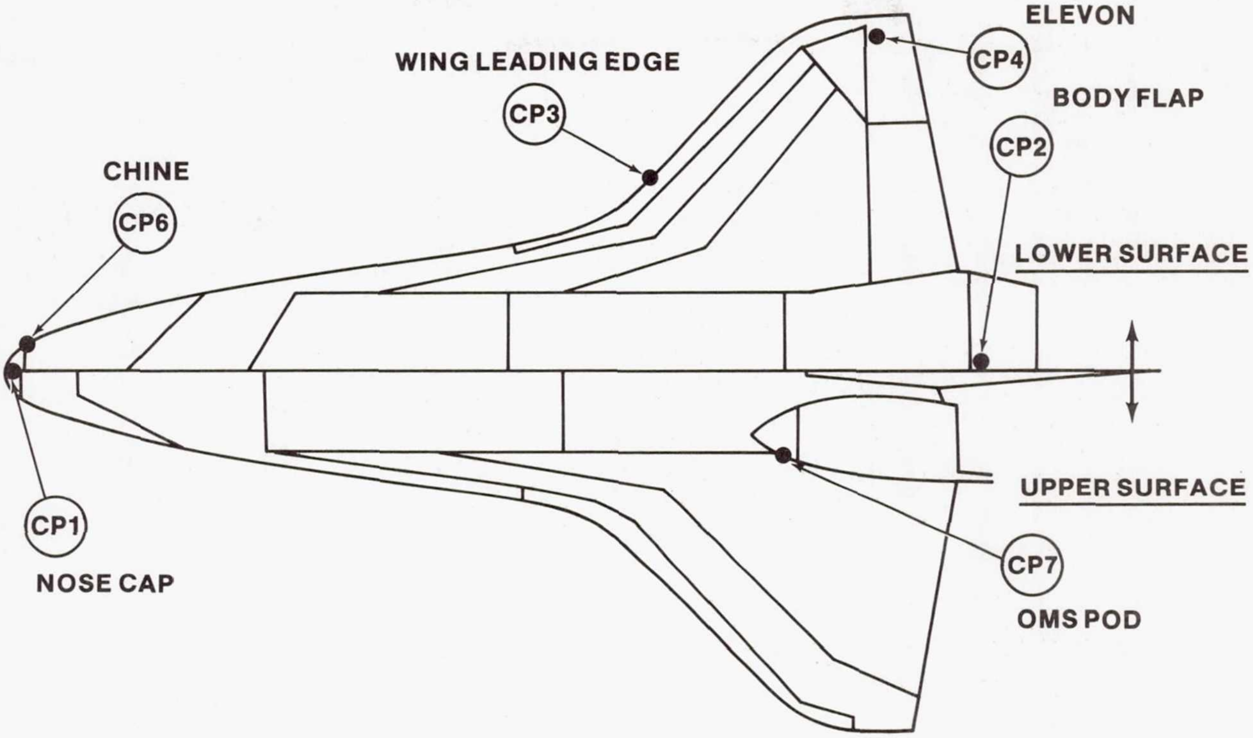

FIGURE 5.- CONTROL POINT GEOMETRY.

The Shuttle Orbiter is also much more limited in its maximum allowable load factor than were previous reentry vehicles. Gemini and Apollo spacecraft operated at 4g to 7g with a design limit of 12g on the Apollo CM (refs. 4 and 5). In contrast, the Orbiter was designed with a maximum normal load factor of 2.5g and a trajectory-shaping goal of 1.5g. The actual load factor encountered depends only on the normal acceleration magnitudes or, equivalently, on angle of attack and dynamic pressure. During lower speed portions of the entry (3500 to 2500 ft/s), dynamic pressure becomes a constraint because of its effects on wing loading and aerosurface hinge moments.

All of these constraints could be portrayed in a dynamic pressure/velocity state space. Use of dynamic pressure as a guidance control parameter would involve derivation from sensed vehicle accelerations and attitudes and would require lift and drag coefficient models for all valid angles of attack and Mach numbers. Since considerable uncertainties existed in the preflight predictions of these quantities, the constraint boundaries were reformulated into a drag acceleration/Earth relative velocity state space. This formulation requires only an estimate of the Orbiter lift-to-drag ratio, which is probably the most reliable aerodynamic parameter to predict and can also be directly measured during flight. In addition, a drag acceleration profile uniquely defines the range flown during entry. Figure 6 depicts the surface temperature, equilibrium glide, load factor, and dynamic pressure constraints in this plane for typical mission parameters. To accomplish a safe entry, the Orbiter must fly the corridor between these constraint boundaries.

The corridor width, and therefore the safety margins of the entry flightpath, depends on specific mission characteristics. The Space Shuttle must operate over large variations of orbital inclination, vehicle weight, and center-of-gravity location. Inclination affects the relationship between inertial and Earth relative velocity and shifts the equilibrium glide constraint in the D-V plane; the corridor narrows for increasing inclination. Vehicle weight is the driver on the location of all the surface temperature boundaries. An increase in weight narrows the corridor as the Orbiter must fly a trajectory consistent with larger aerodynamic forces to produce equivalent accelerations. The change in these constraint boundaries can be seen in figure 7. As the c.g. shifts, the body flap must deflect to trim the vehicle and thereby alters the airflow and thermal distribution on that surface. An aft c.g. deflects the body flap down into the airflow and increases the temperature of the associated control point as shown in figure 8. In practice, the elevon and predicted body flap positions are balanced so that neither surface temperature is excessively more restricting than the other.

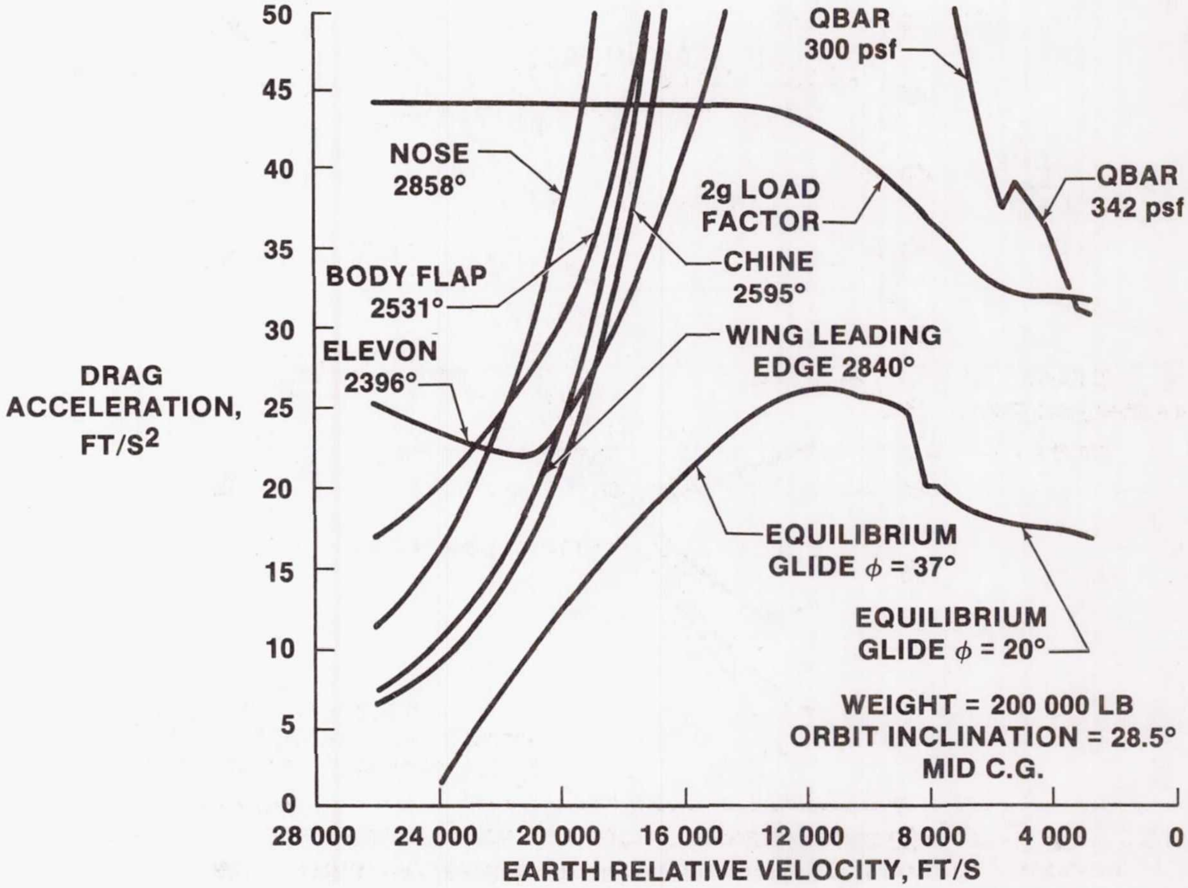

FIGURE 6.- REPRESENTATIVE CONSTRAINT BOUNDARIES.

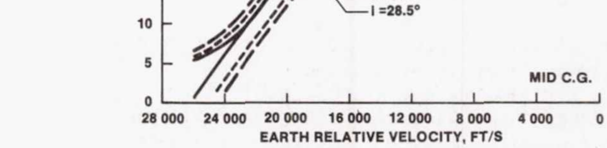

FIGURE 7.- EFFECTS OF WEIGHT AND INCLINATION ON CONSTRAINT BOUNDARIES.

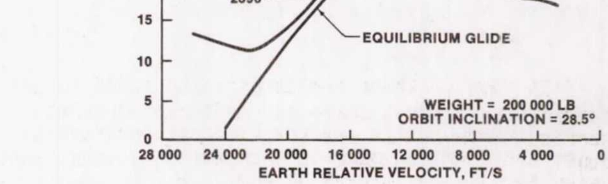

FIGURE 8.- EFFECT OF CENTER OF GRAVITY ON CONSTRAINT BOUNDARIES.

The combination of the effects of these mission parameters can be seen in the constraint boundaries of a "worst case" entry. As shown in figure 9, essentially no corridor remains.

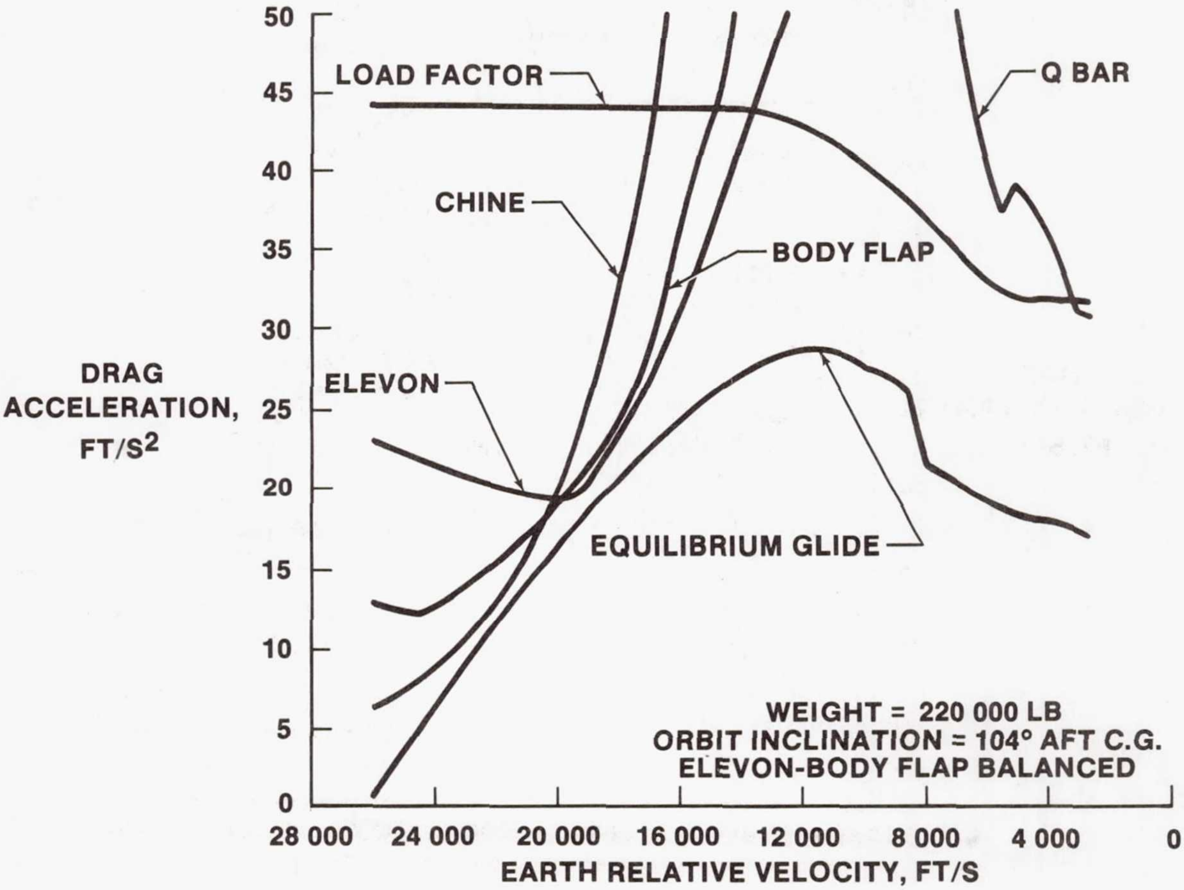

FIGURE 9.- "WORST CASE" CONSTRAINT BOUNDARIES.

GUIDANCE LOGIC

The engineering challenge addressed in designing the entry guidance was to devise a method for directing the Orbiter along a trajectory which remained within the highly confining constraint corridor using primarily the onboard navigation while still allowing enough flexibility to arrive at the landing site with the proper energy reserve. Achievement of this objective was made possible by the realization that the drag acceleration/relative velocity plane was the proper state space in which to view the constraints and define the entry range. It then became natural to implement the guidance logic in this plane also (ref. 6). Figure 10 depicts a typical drag profile, which represents the desired entry trajectory for the boundaries in figure 6.

ENTRY PROFILE

To remain within the constraint corridor, the guidance has been divided into four phases. The temperature control phase is initiated at a vehicle load factor of 0.176g and continues as long as surface temperatures are the binding constraints. At a relative velocity of 17 000 ft/s, a pseudo-equilibrium glide phase is entered for a short time to deliver the vehicle to the flight region in which load factor limits deceleration. A constant-drag phase designed to produce a 1.5g total load factor is then followed until the Orbiter pitch down and associated L/D increase requires a lower deceleration level. The transition phase completes the entry and delivers the spacecraft to the desired energy state at TAEM interface. All guidance phases are defined by simple geometry in the D-V plane, and 15 constraints mathematically describe the entire entry profile. It is the task of descent mission planning to select this profile based on its capability to accommodate nominal and all foreseen stress requirements.

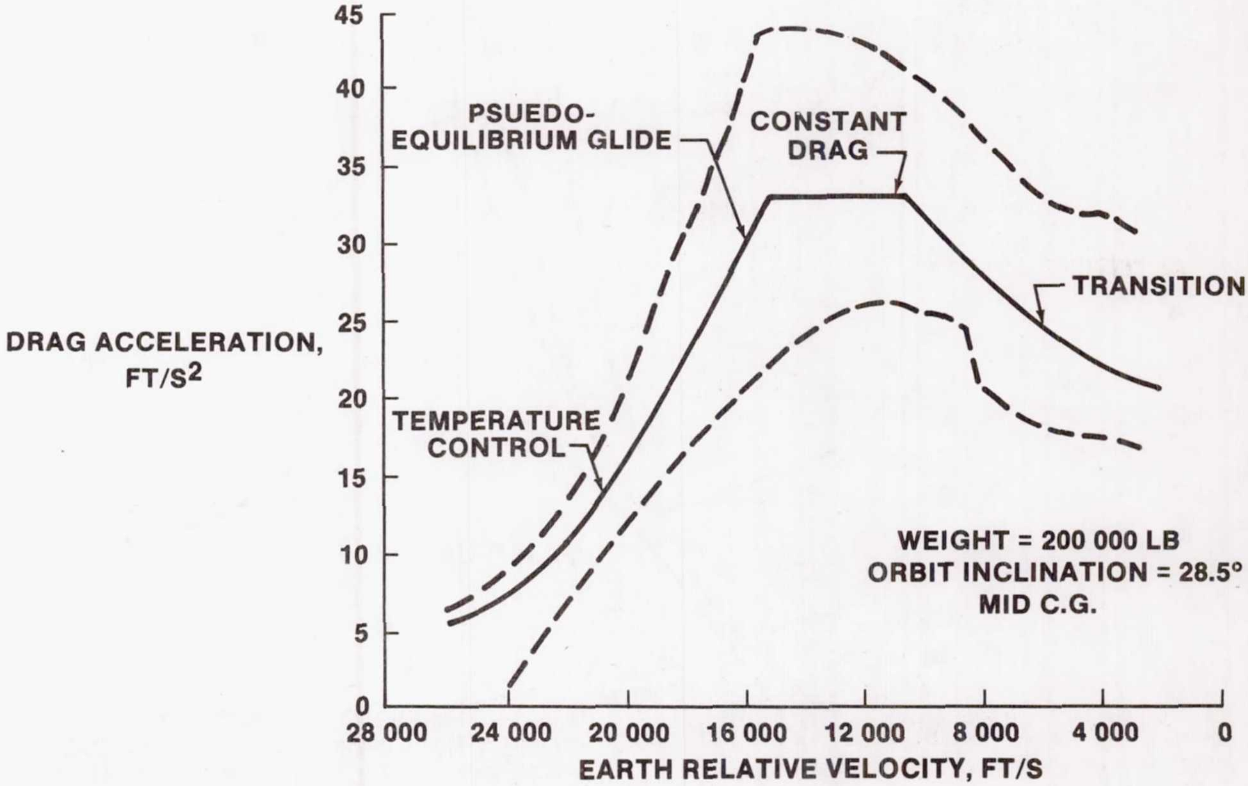

FIGURE 10.- DRAG PROFILE AND CONSTRAINTS.

The flightpath resulting from the profile of figure 10 is shown in figure 11 along with typical Apollo and Gemini descents (refs. 7 and 8). It is obvious that an extended high-altitude glide is the direct result of the thermal and load factor limitations. This long flight time produces a backface temperature constraint which is not uniquely defined in the D-V plane. The TPS was sized on the basis of a reference heat load, and any increase in this value has a direct bearing on the temperature of the Orbiter's aluminum structure. Procedures such as on-orbit shading of the lower surface before entry help alleviate this heat soak, but, in practice, the constraint on backface temperature is more binding than the equilibrium glide boundary.

TRAJECTORY CONTROL

Once a reference profile with the proper range potential has been designed, a method of commanding flight control and correcting for deviations must be devised. Recall that the only vehicle characteristic necessary to define a path in the D-V plane is the vertical component of the lift-to-drag ratio, L/D_V. Conversely, a reference L/D_V corresponding to the reference drag profile can be computed. Since the total vehicle L/D is scheduled with velocity (through angle of attack), this L/D_V is achieved by rotating the lift vector about the velocity vector through a stability bank angle with magnitude

$$\phi_S = \cos^{-1}\left[\frac{L/D_V}{L/D}\right].$$

Also, because the in-flight L/D can be measured directly by the onboard navigation, the vertical component can be precisely controlled.

To compensate for deviations from the drag profile, a drag error feedback term was introduced into the commanded L/D_V equation. It is usually desirable to include a lead term in a feedback control

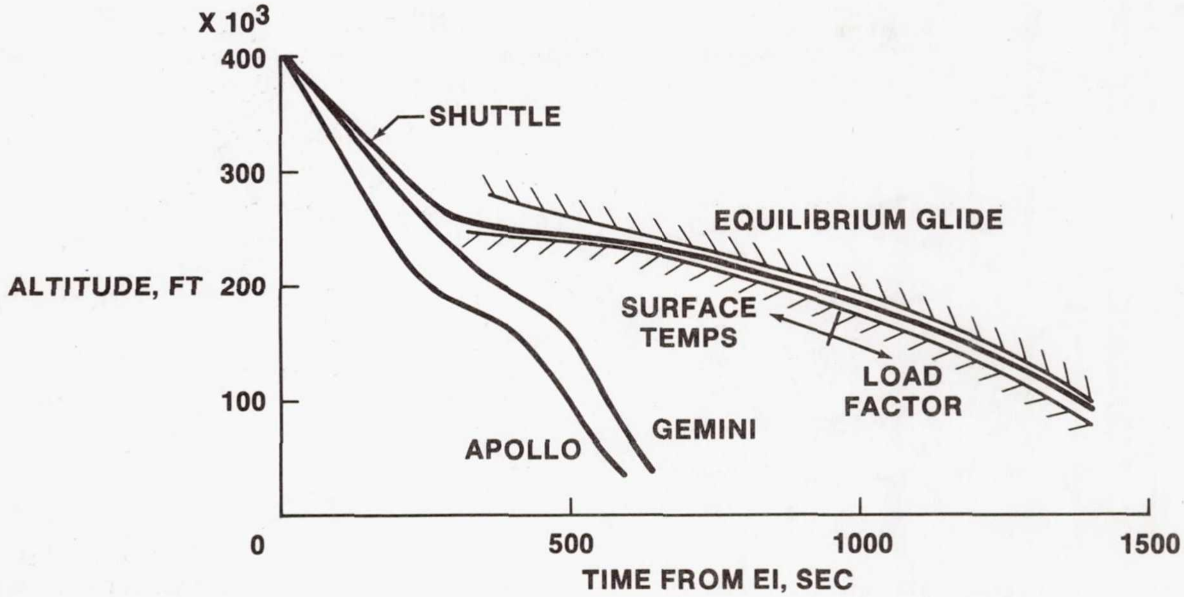

FIGURE 11.- FLIGHTPATH COMPARISIONS.

system, but accelerometer noise and small vehicle attitude changes make the time derivative of drag an unsuitable measurement without significant filtering. After appropriate manipulation, altitude rate ($\dot{h}$) can be used as a measure of the drag rate due to trajectory effects only, and a reference $\dot{h}$ profile can be analytically constructed from the reference drag profile. The final form of the vertical L/D command equation is

$$L/D_{V_{COMMAND}} = L/D_{V_{REF}} + k_D\,(D - D_{REF}) + k_{\dot{h}}\,(\dot{h} - \dot{h}_{REF})$$

where k_D and $k_{\dot{h}}$ are appropriate system gains. Again, this expression is implemented through a stability bank angle command.

RANGE PREDICTION

As has been stated earlier, the reference drag profile uniquely defines the range remaining to be flown from a given velocity. This range prediction, based on approximations to the equations of motion, is compared with the navigation-based range-to-go value to form an error term used to adjust the current drag profile as follows: increase it if the Orbiter is too close to the target, decrease it if it is too far. Thus, in effect, an outer feedback loop which continually updates the original reference profile is formed. Operationally, it is desirable to preserve as much ranging capability as possible late in the entry to allow for postblackout navigation updates and runway redesignations. Therefore, only the current guidance phase of the profile is adjusted for ranging and, consequently, the Orbiter is forced back toward the center of the ranging footprint (ref. 9).

CROSSRANGE CONTROL

Because a bank angle must be maintained to achieve the proper vertical trajectory, the horizontal component of lift can be used to turn the flightpath. The relatively high Orbiter L/D allows a much larger crossranging capability than with previous vehicles, approximately 750 nautical miles. This capability greatly aids operational factors such as the number of return opportunities into a given landing site and abort-once-around contingencies. To target for the proper crossrange, the guidance computes the azimuth error between the velocity vector and the line of sight to the runway. If this angle becomes greater than a stored deadband schedule, a bank reversal is commanded.

The trajectory is essentially uncontrolled during a reversal, and some lofting occurs because of the Orbiter's maximum roll rate of only 5 deg/s. This lofting would cause the drag level to drop below the reference profile; consequently, compensation has been added to the guidance pitch channel by which the angle of attack and, therefore, the drag coefficient is allowed to increase for driving the vehicle back to the reference. This modulation also decreases the effect of any unforeseen atmospheric density gradients. Typical altitude rate, roll, and angle-of-attack histories are shown in figure 12. The result is very tight drag trajectory control as shown in figure 13.

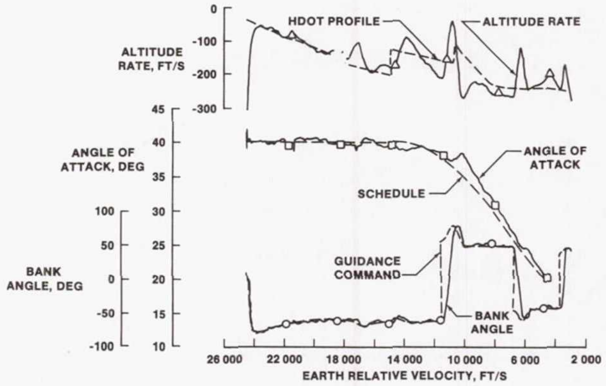

FIGURE 12.- FLIGHT DATA PARAMETERS FROM STS-5.

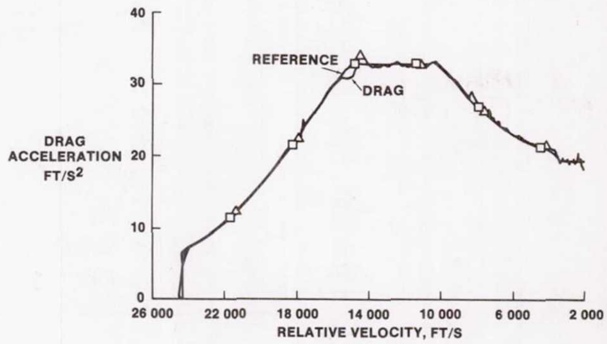

FIGURE 13.- DRAG AND REFERENCE PROFILE, STS-6.

CONTINGENCY ABORTS

The guidance, in addition to providing trajectory control for nominal and dispersed end-of-mission entries, must allow intact vehicle recovery for mission emergencies and aborts. The logic has been adapted for two contingencies: abort once around and transoceanic abort landings.

An AOA results from main propulsion system (MPS) failures during ascent which prevent nominal orbit insertion or Orbiter system failures which dictate immediate return to Earth. The latter usually involves a rather standard entry, although thermal loads may be more severe since there has been no time to dissipate ascent heating and the vehicle weight is usually higher. To compensate, the guidance drag profile is lowered. An MPS failure implies that the Orbiter may achieve entry interface with a shallow flightpath angle (perhaps necessitating entry prebank) with high heat loads resulting from the long-range, shallow trajectory. Still, the AOA falls into nearly the same region as dispersed end-of-mission entries, and no modifications to the guidance software have been necessary to support it.

A TAL is caused by one- or two-engine MPS failures during ascent and involves targeting for and flying to a downrange landing site. The TAL concept originated when flightcrews noticed during ascent simulations that entry-type energy-range conditions were often achieved. Although this observation is essentially true, the flight conditions during a TAL are similar to a very steep, low-energy entry, which would place extreme thermal stresses on the Orbiter. Figure 14 shows the vehicle drag and drag profile resulting from a TAL simulation. The entry is so steep that even lift-vector-up flight produces a large drag pulse and the associated high surface temperatures. Although this pulse is of short duration, large portions of the TPS would probably be damaged. Still, subsequent convergence to the profile is quite rapid and thus the other constraint margins can be maintained. Ranging to the new landing site is accomplished in the normal manner.

FLIGHT DECK DISPLAYS AND CREW INTERACTION

The flightcrew can monitor entry by means of computer-driven cathode-ray tube (CRT) operations displays. Figure 15 shows the configurations for the segment of flight from a velocity of 20 000 ft/s to 13 500 ft/s. The central portion of the display depicts a velocity versus range plot of the entry constraints (solid lines). From left to right, these are 2.5g load factor, nominal trajectory, equilibrium glide for 37° bank angle, and equilibrium glide for 0° bank angle. The dashed lines represent constant-drag levels with the numerical value shown above each line. The numbers in the lower section of the display are the vehicle altitude rates necessary to parallel the nominal profile. The square depicts the current guidance-commanded drag level, and the Shuttle symbol is the navigation estimate of the vehicle range to go. The dots and triangles mark the past values of these quantities snapped at 30-second intervals. In addition, reference drag command, roll command, dynamic pressure, and other guidance and flight control parameters are displayed digitally. Figure 15 represents a situation in which the Orbiter was low in drag and too far from the landing site, but has converged to

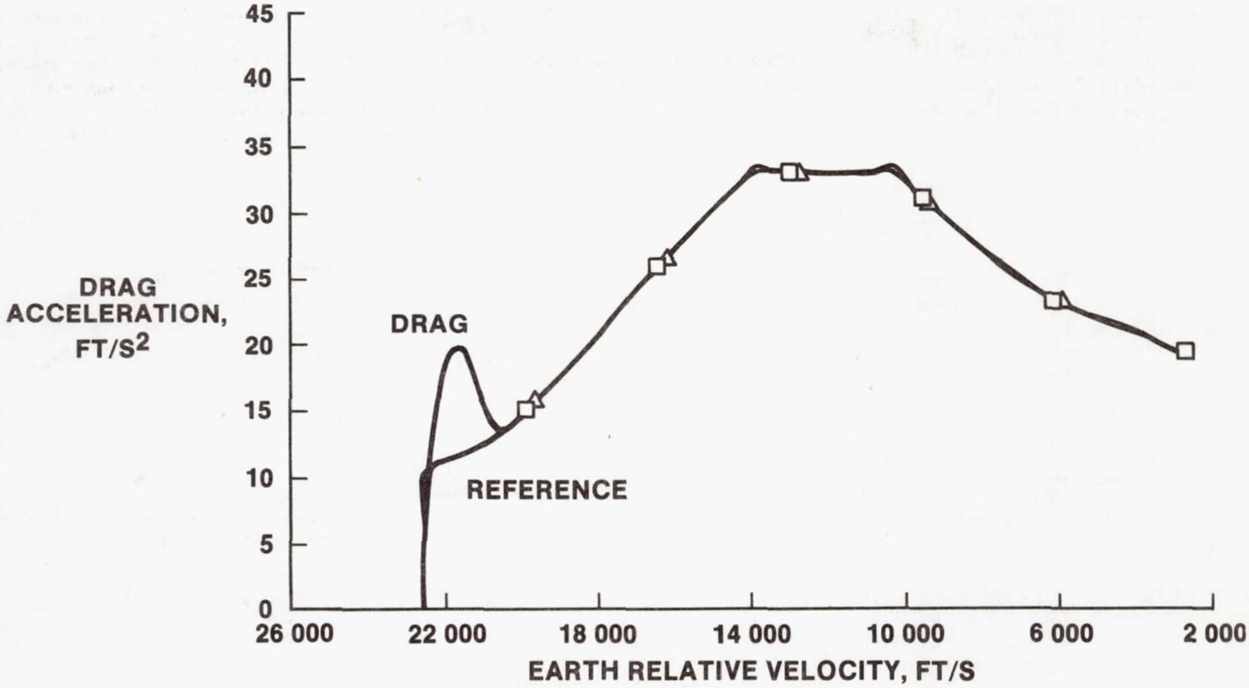

FIGURE 14.- TAL DRAG AND REFERENCE PROFILE.

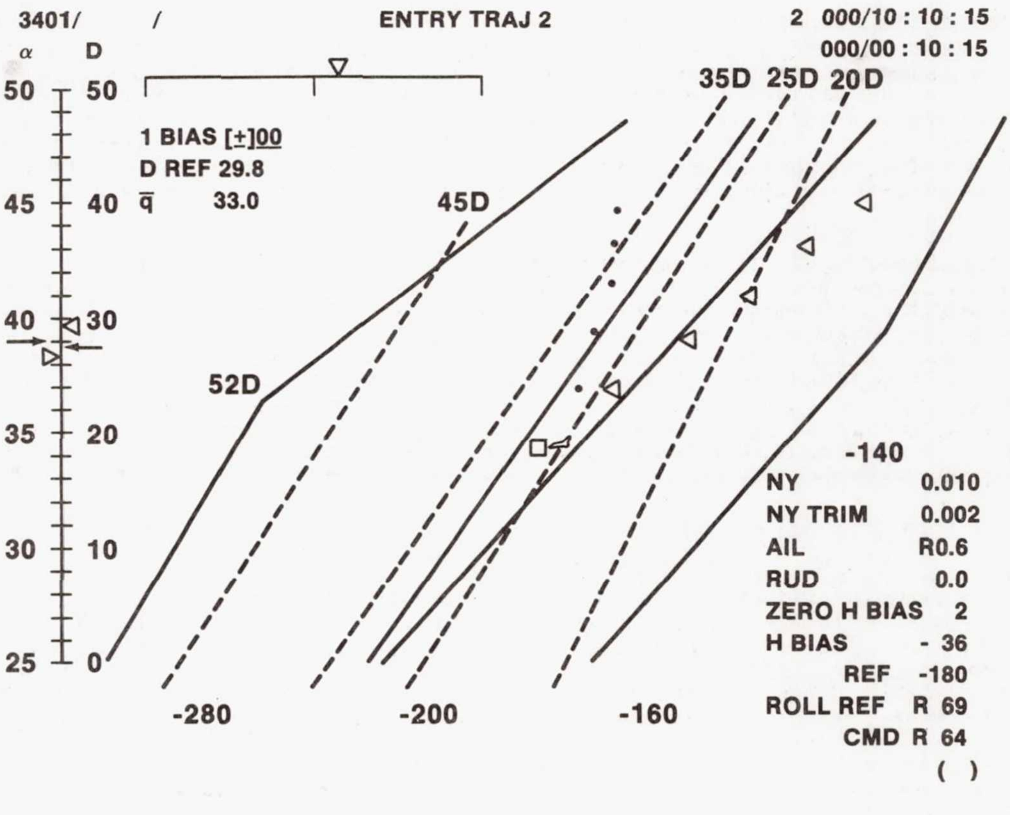

FIGURE 15.- ENTRY CRT DISPLAY.

the guidance command. In addition to the CRT's, the error needles of both cockpit attitude-direction indicators are driven by the guidance outputs.

Normally, the guidance commands are fed directly into the flight control system, but they can be interrupted if the crew enables the control stick steering (CSS) mode. In this configuration, guidance will continue to drive the flight deck displays but inputs to flight control are made by way of the commander's or the pilot's rotational hand controller.

FLIGHT RESULTS

Figures 12 and 13 represent typical flight data obtained from the onboard recorders during entry. No unexpected guidance or trajectory behavior has been seen during flight. During several entries, manual or automatic test maneuvers have been executed for the purpose of determining the Orbiter's dynamic and thermal characteristics more accurately. In all cases, the guidance system reestablished the vehicle on the proper trajectory in the predicted amount of time.

CONCLUSIONS

The Space Shuttle entry guidance meets the objectives of accommodating a large variety of mission characteristics while maintaining the vehicle within highly confining physical constraints and delivering it to the target with the required accuracy. The guidance logic and the mission planning activities are based on a reference drag profile shaped to allow for flight safety margins. Attitude commands to the flight control system are provided by correcting for deviations from this profile in a closed-loop manner. The Shuttle flight test program and subsequent operational flights have proven the soundness of interrelating deorbit targeting, guidance, mission planning, and mission design through the drag acceleration plane. No guidance-related anomalies have occurred during flight, and no modifications or improvements to the system are seen as necessary at this time.

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