FIXED-BASE SIMULATOR STUDIES OF THE ABILITY OF THE HUMAN PILOT TO PROVIDE ENERGY MANAGEMENT ALONG ABORT AND DEEP-SPACE ENTRY TRAJECTORIES

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ABSTRACT

A simulation study has been made to determine a pilot's ability to control a low L/D vehicle to a desired point on the earth with initial conditions ranging from parabolic orbits to abort conditions along the boost phase of a deep-space mission. The program was conducted to develop procedures which would allow the pilot to perform the energy management functions required while avoiding the high deceleration or skipout region and to determine the information display required to aid the pilot in flying these procedures.

The abort conditions studied extend from a region of relatively high flight-path angles at suborbital velocities while leaving the atmosphere to a region between orbital and near-escape velocity outside the atmosphere. The conditions studied included guidance from suborbital and superorbital aborts as well as guidance following return from a deep-space mission.

In this paper, the role of the human pilot's ability to combine safe return abort procedures with guidance procedures has been investigated. The range capability from various abort and entry conditions is also presented.

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INTRODUCTION

A desirable requirement for manned space missions is that the pilot have a capability for guiding the vehicle to a predetermined landing area on completion of a successful mission or following an abort during the boost phase of the mission. References 1 through 4 are reports covering previous studies conducted in this general category.

This paper contains the results of a simulation study to determine a pilot's ability to control a low L/D vehicle to a desired point on the earth with initial conditions ranging from parabolic orbits to abort conditions along the boost phase of a deep-space mission. The program was conducted to develop procedures which would allow the pilot to perform the energy management functions required while avoiding the high deceleration and skipout regions and to determine the information display required to aid the pilot in flying these procedures. Emphasis was placed on allowing the pilot to make the decisions necessary to achieve a successful entry.

The abort conditions studied extend from a region of relatively high flight-path angles at suborbital velocities while leaving the atmosphere to a region between orbital and near-escape velocity outside the atmosphere. For the suborbital region of the mission, the primary concern following abort is the high deceleration period encountered upon reentering the atmosphere while for aborts at superorbital velocity the problem becomes one of changing the vehicle's flight path such that it will reenter the earth's atmosphere. The method employed in reference 1, by which an abort rocket was used for these flight-path angle changes, is extended in the present study to include the pilot in the control loop.

The conditions studied included guidance from suborbital and superorbital aborts as well as guidance following return from a deep-space mission. For subcircular entries following an abort and for the subcircular phase of parabolic entries, the reference trajectory, heading-error method of range control reported in reference 2, was extended to utilize the pilot's intelligence and learning capability to provide the guidance logic and control commands necessary for achieving a successful entry. For the parabolic phase of an entry, the pilot was given displays to enable him to perform pull-ups at superorbital speeds which allow large extensions in range.

DESCRIPTION OF SIMULATION

<u>General</u>.- A six-degree-of-freedom, static simulation of a space vehicle was performed in a fixed-base cockpit. The simulated vehicle was of the capsule type with a lift-to-drag ratio of 0.5.

Control of motions about the vehicle's body axes was achieved with reaction controls. Linear reaction control (output proportional to stick deflection) and damping systems were used for pitch and yaw and an off-on reaction system was used for roll control. In the atmosphere the vehicle was assumed to be trimmed, with an offset center of gravity, at an angle of attack of about 35° which corresponded to an L/D of 0.5. Thus, outside the atmosphere the pilot could control motions about all three body axes, but in the atmosphere he could control only the vehicle's roll, since the moments applied by the reaction jets were small in comparison with the moments produced by the offset center of gravity.

Control of the trajectory inside the atmosphere was achieved by varying the direction of the vehicle's lifting force. This was done by rolling the vehicle. Thus, if maximum lift was desired in an upward direction (to increase range), the roll angle was maintained at zero. If maximum lift was desired lateral to the flight path (for heading changes) the vehicle was rolled to a ±90° roll angle, while if lift was required in a downward direction (to shorten range) the roll angle was increased to ±180°. Hence, by varying the roll angle between ±180°, the vehicle's lift could be proportioned between the longitudinal and lateral planes.

The pilot was also supplied with an abort rocket which had a capability of giving an ideal velocity increment of 3,000 ft/sec. This rocket was positioned along the roll axis of the vehicle (through the center of gravity).

<u>Instrument display</u>.- The pilot's instrumentation included the basic trajectory variables such as altitude, velocity, vertical velocity, and acceleration. In addition, he was supplied with an attitude group of instruments to show the vehicle's orientation with respect to fixed axes on the earth.

Special instrumentation was also provided to aid the pilot in performing the maneuvers required following abort and to aid him in performing the energy management functions necessary to guide the vehicle to a desired landing area. The pilot utilized the instrument shown in figure 1(a) to reorient his vehicle following an abort. This instrument shows the orientation of the vehicle

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and the abort rocket (in the pitch plane) with respect to the local horizontal and the velocity vector.

An instrument used for terminal guidance is shown in figure 1(b). This instrument shows errors in the vehicle's range and heading with respect to a desired range and heading. The longitudinal guidance error gave the position of the vehicle at any altitude with respect to a precalculated reference trajectory of altitude as a function of range-to-go which terminated at the desired destination. This reference trajectory was computed for an entry at circular velocity with an entry angle of -1° and a constant L/D of about 0.2. This single reference trajectory was used for all entries. The cross-range error gave the lateral "miss-distance" at the desired destination assuming the vehicle continued on its present heading throughout the entry. This reference trajectory-heading error concept is described in reference 2. The pilot was also given a display (to be described in a later section) on a cathode ray type memory scope which was used during pull-ups at superorbital velocities. The use of this display and the previously described abort and entry guidance displays will be described in following sections of the paper.

RESULTS AND DISCUSSION

The simulation studies reported in this paper can be divided into two general areas; piloting procedures following an abort and piloting procedures following reentry. A discussion of each area will be given along with typical results obtained in the study.

Piloting Procedures Following Abort

Suborbital abort.- For aborts initiated at suborbital velocities (12,000 to 25,000 ft/sec), the primary concern was in orienting the vehicle properly for firing the abort rocket and then in reorienting the vehicle for reentry. It was shown in reference 1 that reentry deceleration following an abort at suborbital speeds could be minimized by firing an abort rocket nearly perpendicular to the velocity vector to decrease the entry angle. It was further shown that a near optimum time for firing was just before the rapid increase in dynamic pressure during reentry. This procedure is illustrated in figure 2 for a typical suborbital abort. This figure shows the position of the capsule and the abort instrument (fig. 1(a)) at different positions along the trajectory. At position (A) the capsule was on the booster. At position (B) the mission was aborted and a separation rocket was fired. This separation rocket burned for 3 seconds and gave the vehicle an ideal velocity increment of about 600 ft/sec. The capsule coasted to apogee (position (C)) and then began its descent. The pilot oriented his capsule as shown at position (D) and fired the abort rocket at an altitude of about 300,000 feet. He then continued the pitching maneuver to position (E) for reentry. Note that between positions (C) and (D) the capsule was rolled through 180° to orient the lift vector properly for reentry. The time between positions (D) and (E) is the critical phase of this maneuver since the vehicle must be oriented near the trim angle of attack before the dynamic pressure buildup. Otherwise the heat shield would not be in the air stream and the vehicle's lift could not be utilized for controlling the trajectory. Thus, the vehicle might enter backwards resulting in excessive deceleration and heating of unshielded parts. A typical pitching maneuver to establish a reentry attitude is shown in figure (3).

Superorbital abort.- For aborts at supercircular velocities, the primary concern is in altering the flight path so that the vehicle will reenter the earth's atmosphere. A dip-type trajectory, shown in figure 4, was assumed during the boost phase of the mission. Thus, at superorbital speeds the vehicle was traveling at an altitude of about 500,000 feet with a small positive flight-path angle. Thus, if a mission were aborted at superorbital speed, the flight-path angle would continue to increase (due to centrifugal force) and the abort rocket was needed to establish a flight-path angle which would effect a reentry. A typical superorbital abort showing piloted maneuvers is presented in figure 5. At position (A) the vehicle was on the booster. At position (B) the mission was aborted and the separation rocket was fired. The vehicle was then pitched perpendicular to the velocity vector at position (C) and the abort rocket was fired. The pitching maneuver was continued to position (D) so as to direct the vehicle's lift downward to aid in keeping the vehicle in the atmosphere. In superorbital orbits, the primary critical phase of the mission is between positions (B) and (C) since delays in firing the abort rocket reduce the chance of recapturing the vehicle in the atmosphere. A typical superorbital pitch maneuver is shown in figure 6.

Pilot's ability to perform abort maneuvers.- In order to compare a pilot's ability to perform the previously described critical phases of suborbital and superorbital abort maneuvers with a maximum allowable time, several abort maneuvers were performed by different pilots. For the suborbital case, the mission was aborted at a velocity of 12,000 ft/sec which represented critical launch trajectory conditions with respect to reentry deceleration. The abort rocket was fired at an altitude of 300,000 feet which allowed about 22 seconds after completion of the abort firing to acquire the trim angle of attack before a dynamic-pressure buildup. For the superorbital case, the mission was aborted at a velocity of 29,000 ft/sec. To assure reentry at this velocity and altitude (500,000 ft), with the available abort rocket capabilities, the pilot had about 17 seconds in which to reorient his vehicle and fire the abort rocket. As is shown in figure 7, the pilots experienced no difficulty in performing the necessary maneuvers within the prescribed time interval. The time required to perform these critical maneuvers would, of course, be a function of the abort rocket impulse and the pitching acceleration of the vehicle. For example, with a larger abort rocket, the pilot could delay the firing and still achieve a safe entry while the same would be true if the vehicle could be pitched more rapidly. However, a smaller weight penalty would probably occur by increasing the pitching acceleration rather than the abort rocket.

Piloting Procedures Following Entry

Entry following return from a deep-space mission.- For simplicity, the total range capability of the vehicle was divided into three general areas; short-, medium-, and long-range entries. Short-range entries were considered to be those less than 2,000 miles. Medium-range entries were between 2,000 and 4,000 miles and long-range entries were greater than 4,000 miles. Typical entries are shown in figure 8 illustrating the piloting procedures used in each range regime. The procedures described are for an entry angle of -6.5° which is at about the middle of the safe entry corridor. The procedures vary somewhat with initial entry angle as will be described in following sections.

Short ranges.- For these entries, the piloting procedure consisted of a pull-out at about 200,000 feet followed by a coasting phase at or near this altitude and a final descent along the reference trajectory to the desired destination. With sufficient experience, the pilot could maintain his deceleration at levels such that he would intersect the reference trajectory with the required energy to allow a descent. For example, with entries at the lower limit of the vehicle's range capability it was necessary to maintain a near maximum deceleration throughout much of the entry. An additional task for these entries, as for all entries, was to acquire and maintain the desired heading by utilizing available lift in the lateral direction. Typical down- and cross-range variations for a short-range entry are shown in figure 8.

Medium ranges.- The piloting procedure for these entries was similar to that for short ranges during the initial portion. The pilot would level off and maintain a constant altitude until the velocity dropped below about 30,000 ft/sec. This was done to dissipate energy and to reduce the possibility of a skipout. The pilot then initiated a climbout to an intermediate altitude of about 250,000 feet from which a coasting phase to the reference trajectory at near circular velocity could begin. A typical medium-range entry is shown in figure 8.

The pull-up maneuver was a critical phase of the entry since, if the vehicle climbed too rapidly, it would be unable to level off again due to the lack of atmosphere and hence lifting force. Thus, a skipout would occur. Therefore, the pilot made use of a memory scope display to aid him in the pull-up maneuver. This display is shown in figure 9. The memory scope was used as an x-y plotter for displaying the vehicle's altitude as a function of vertical velocity. Also shown on this display was a reference trace which represented a skipout boundary, since for points above the trace insufficient lift was available in a downward direction to overcome the vehicle's centrifugal force. Thus, by observing the vehicle's trace with respect to the reference trace, lift could be varied such as to keep the vehicle's trace just inside the boundary. To aid in visualizing the operation of this display, time histories of altitude and roll angle are also shown in figure 9.

Long ranges.- For long-range entries the pilot initiated a pull-up immediately after leveling off in order to remove the vehicle from the dense atmosphere and hence retain as much of its initial energy as possible. He then used the altitude-vertical velocity display to insure against a skipout. A typical long-range entry is shown in figure 8. By executing properly the pull-up maneuver, the vehicle would arrive at an altitude of 250,000 feet with a supercircular velocity. From this altitude a gradual ascent was begun to allow the vehicle to reach an altitude of about 300,000 feet from where a coasting phase to the reference trajectory was begun. By keeping the vertical velocity small (about 100 ft/sec) this climbout could be accomplished with no danger of a skipout. Due to the rarefied atmosphere above 250,000 feet, the vehicle could traverse great distances with little reduction in velocity.

Reentry following aborts.- The piloting procedure following reentry from aborted missions was similar to the terminal phase of the previously described entries. For most of these entries ($V < 26{,}000$ ft/sec) no skipout problem existed and the pilot simply reduced his down- and cross-range errors to zero and descended along the reference. For aborts at supercircular velocities the piloting procedure was similar to that used following the pull-up phase of long-range entries.

The piloting procedures have been described in terms of long-, medium-, and short-range entries. There is, of course, an overlapping between the three range procedures. For example, on an entry with a desired range of 2,200 miles, which is at the lower end of the medium-range regime, the pilot might use the following method. Rather than pull up to an altitude of 250,000 feet and begin an immediate descent, the pilot might level off at 230,000 feet and make a more gradual descent to the desired destination.

The piloting procedures naturally varied somewhat with initial entry angle since for different entry angles the initial pull-up occurs at different altitudes. Thus, for steep entry angles all lift was applied in an upward direction initially to prevent excessive deceleration while for shallow entry angles, lift was applied in a downward direction initially to "pull" the vehicle into the atmosphere. Following the initial pull-up, the coasting and descent phase of an entry was the same for all entry angles.

Range Capability

Results will be given showing the maximum-range capability of the vehicle for returns from a deep-space mission and following aborts at subcircular velocity. The range capability is defined as the area in which the vehicle can be controlled to within 10 miles of the desired destination at an altitude of 100,000 feet above the desired destination.

Return from a deep-space mission.- Maximum range attainable contours for a vehicle entering the atmosphere at escape velocities with different flight-path angles are given in figure 10. As would be expected, the vehicle's range capability is defined by the initial entry angle and increases as the initial entry angle is decreased.

Reentry following suborbital aborts.- The range capability following suborbital aborts was determined by the velocity at which the mission was aborted. Range contours for different abort velocities are shown in figure 11. The figure shows the range attainable from an altitude of 200,000 feet. At this altitude the abort firing is completed and the g buildup begun. The distance traveled to this point is largely a function of the assumed boost trajectory and is shown in figure 4 for different abort velocities. For abort velocities above 20,000 ft/sec, the abort rocket was not needed since the maximum reentry deceleration did not exceed 8g for these cases due to the shallow flight-path angles as shown by the early skip in figure 4.

SUMMARY OF RESULTS

The results of a simulation study to determine a pilot's ability to control a low L/D vehicle to a desired point on the earth, with initial conditions ranging from parabolic orbits to abort conditions along the boost phase of a deep-space mission, can be summarized as follows:

1. Following aborts at subcircular velocities, the pilots were able to perform the abort rocket firing-reentry orientation sequence required to overcome the deceleration problem associated with such aborts.

2. Following aborts at supercircular velocities (up to velocities of 29,000 ft/sec) the pilots were able to reorient the vehicle and fire the abort rocket in sufficient time to insure recapturing the vehicle.

3. The study has indicated that the human pilot with experience and a good display of flight information can perform the reentry guidance maneuvers required to navigate to a desired landing area over the abort and reentry conditions covered in the analysis. The information display included the following: basic trajectory variables, vehicle orientation with respect to some reference, distance from and the heading with respect to the desired destination, and an indication of the vehicle's position with respect to a skipout boundary during superorbital pull-ups.

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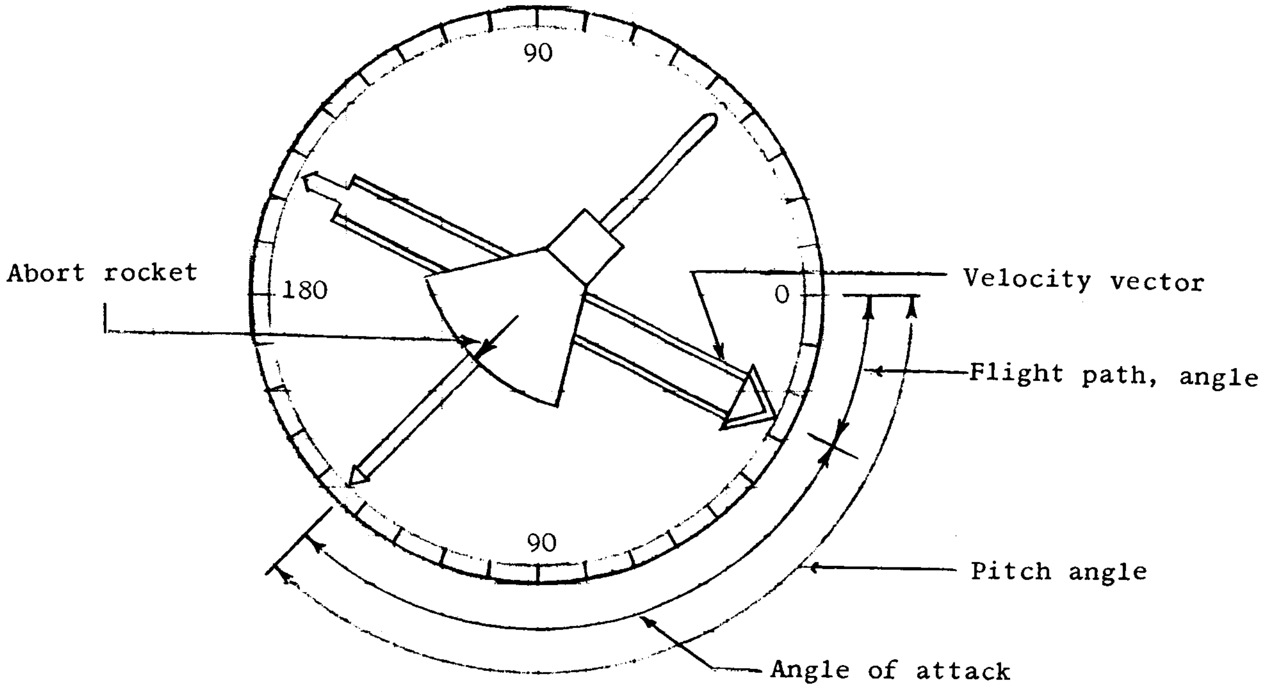
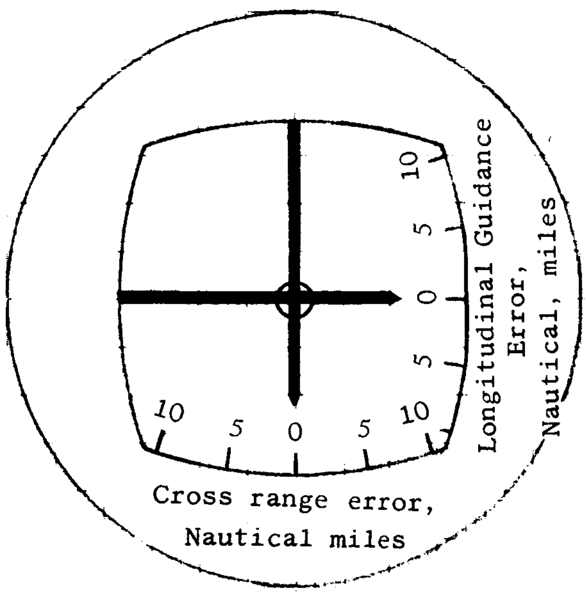


(a) Abort instrument showing capsules orientation in the pitch plane.



Sensitivity of error scales could also be set for full scale readings of 100 and 1000 nautical miles.

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(b) Instrument showing the longitudinal guidance error and the cross-range error.

Figure 1.- Abort and guidance instruments used in simulation.

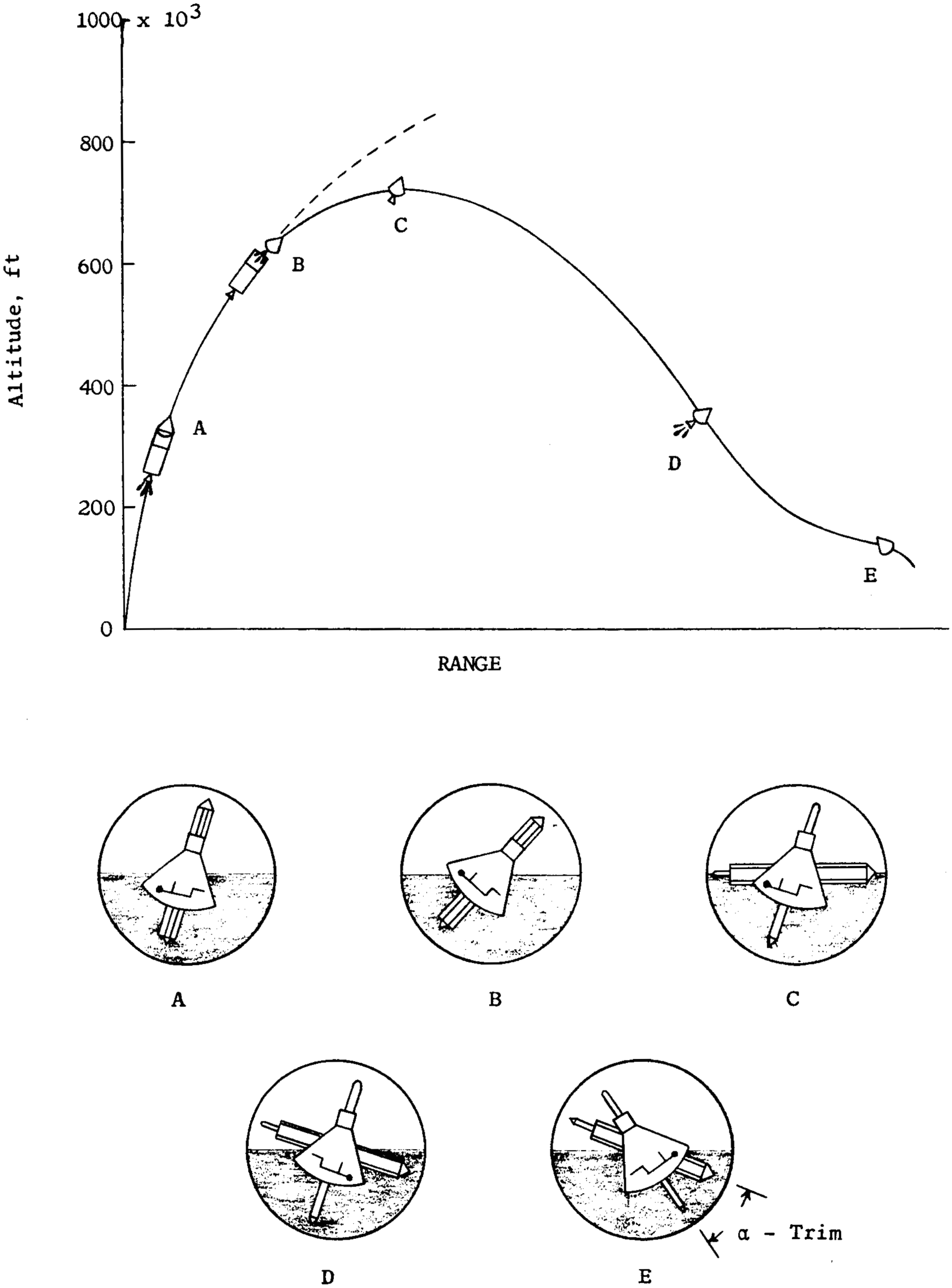

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Figure 2.- A typical suborbital abort illustrating piloting procedures and showing the abort instrument at positions along the trajectory.

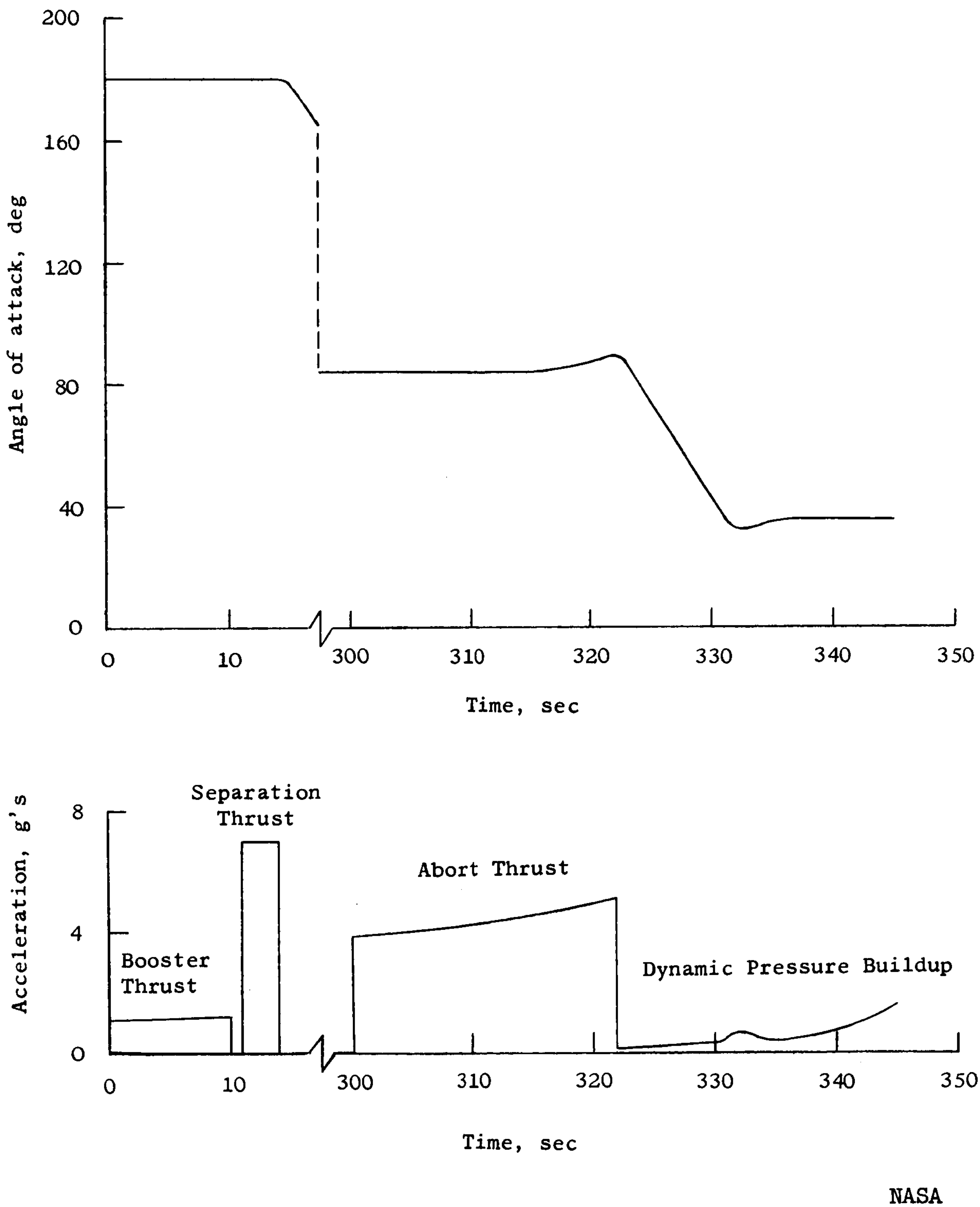

Figure 3.- A typical pitching maneuver following suborbital abort.

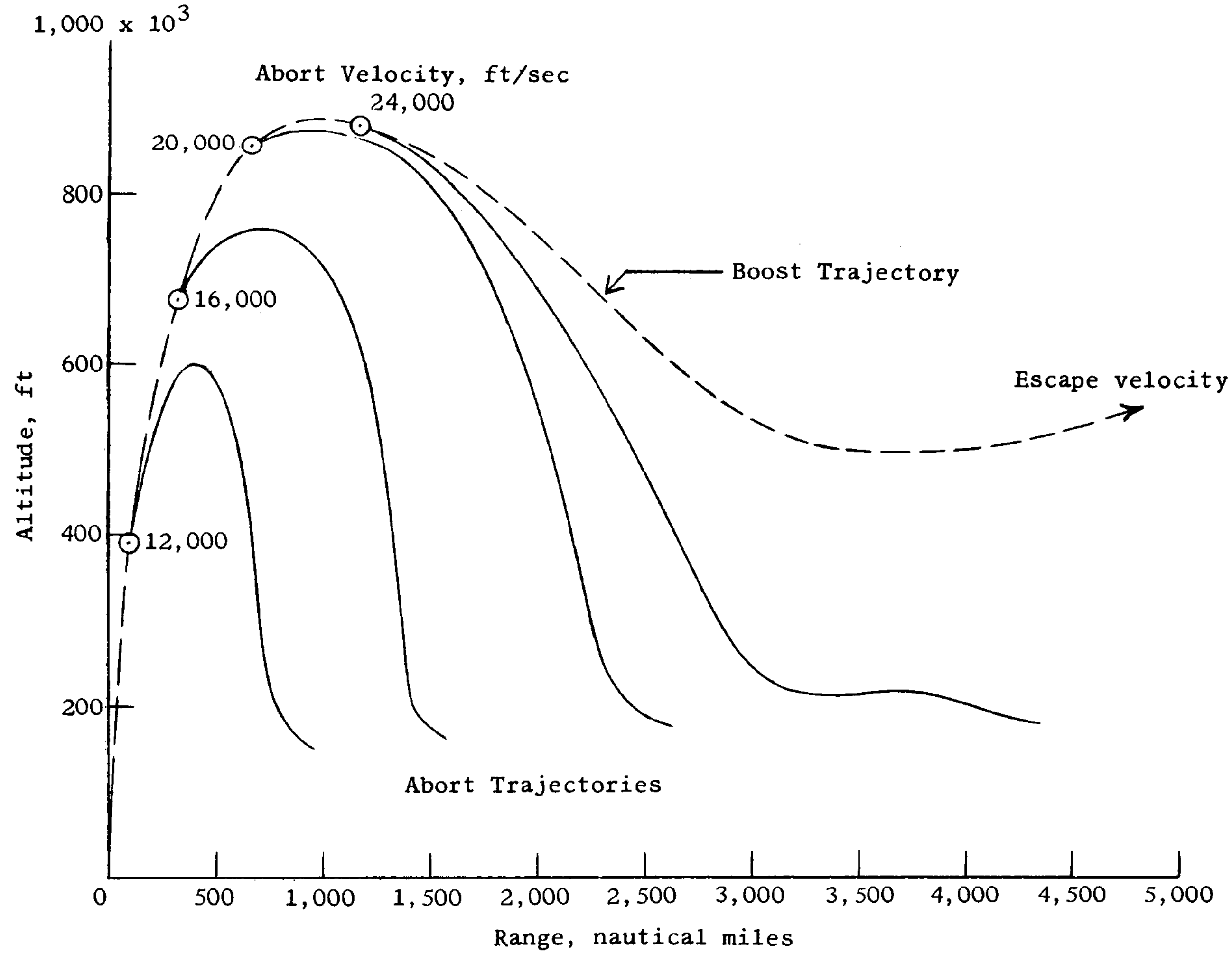

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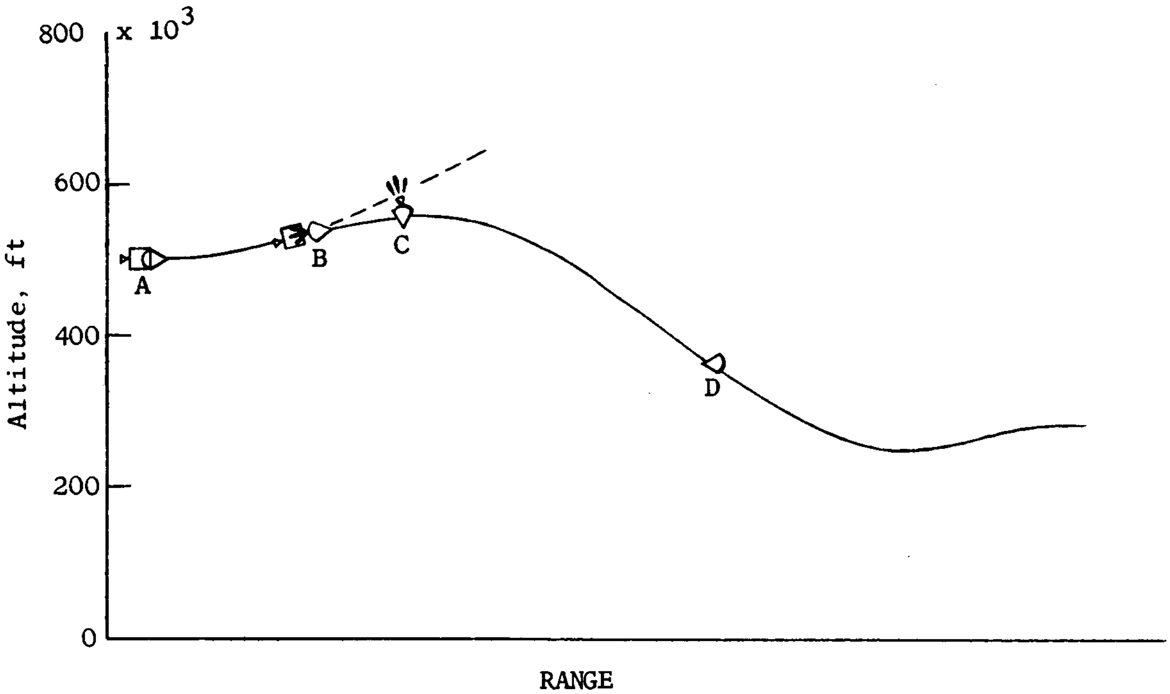
Figure 4.- The assumed boost trajectory including trajectories following aborts at different velocities.



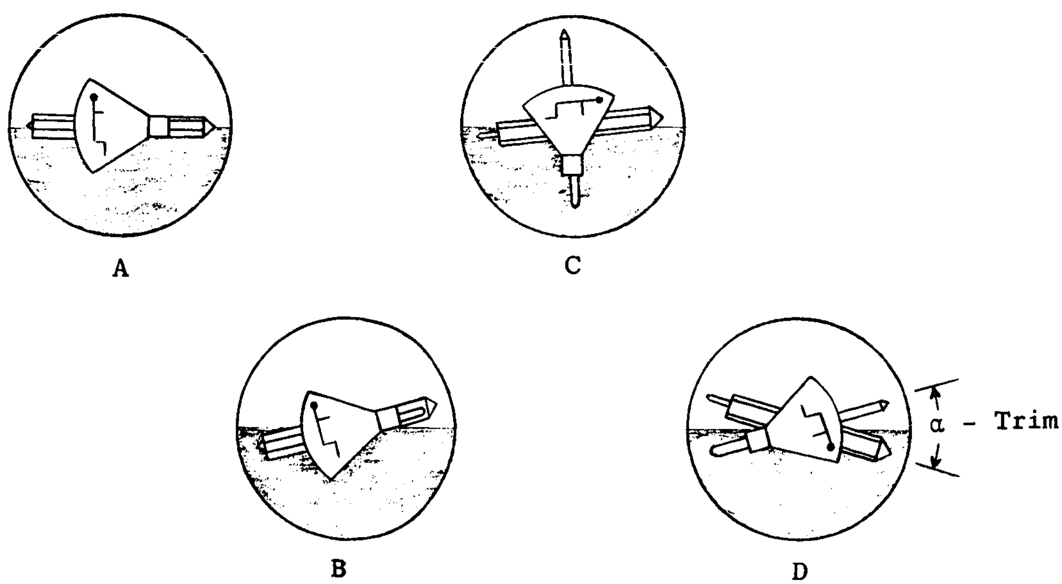


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Figure 5.- A typical superorbital abort illustrating piloting procedures and showing the abort instrument at positions along the trajectory.

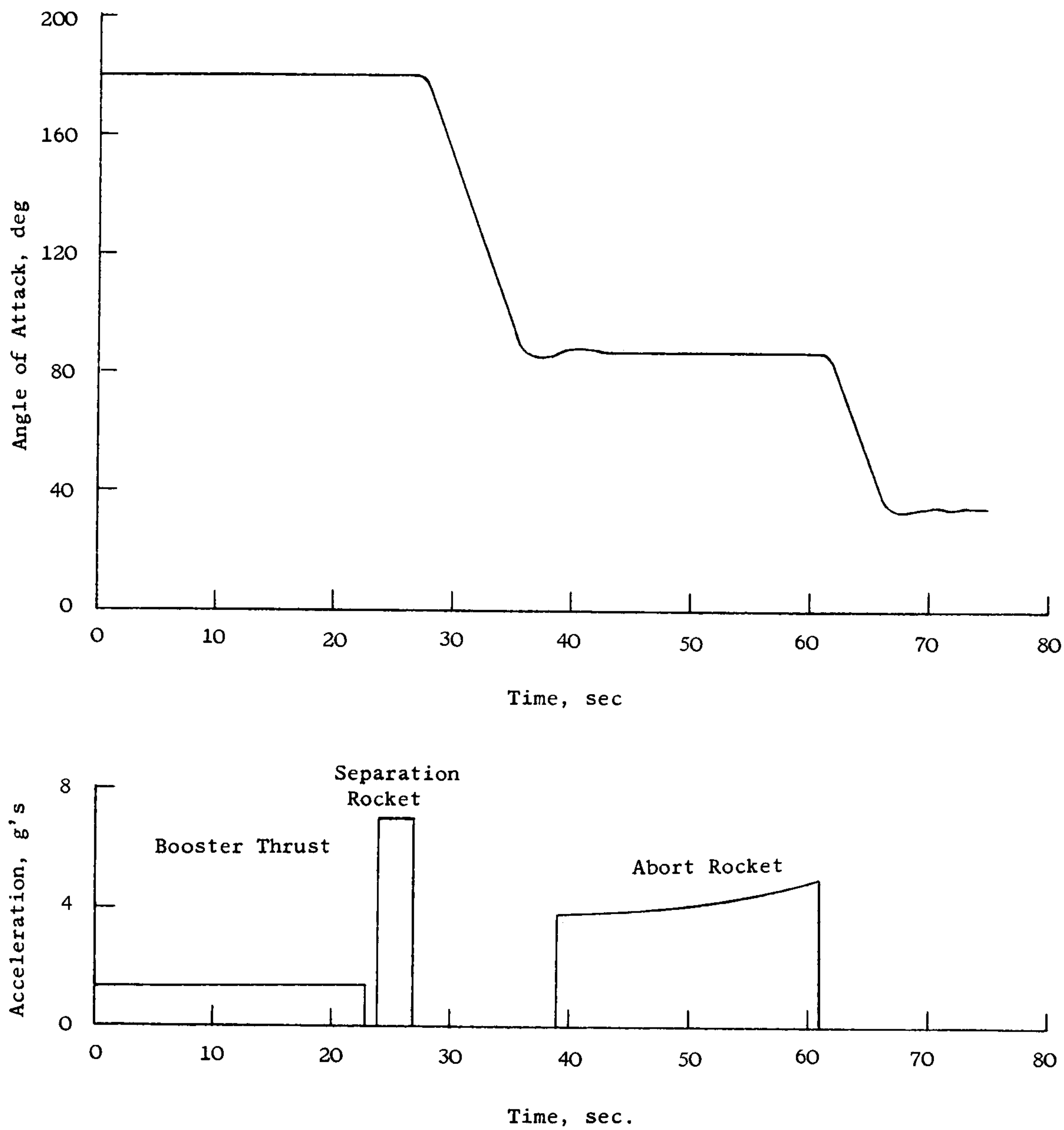

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Figure 6.- A typical pitching maneuver following superorbital abort.

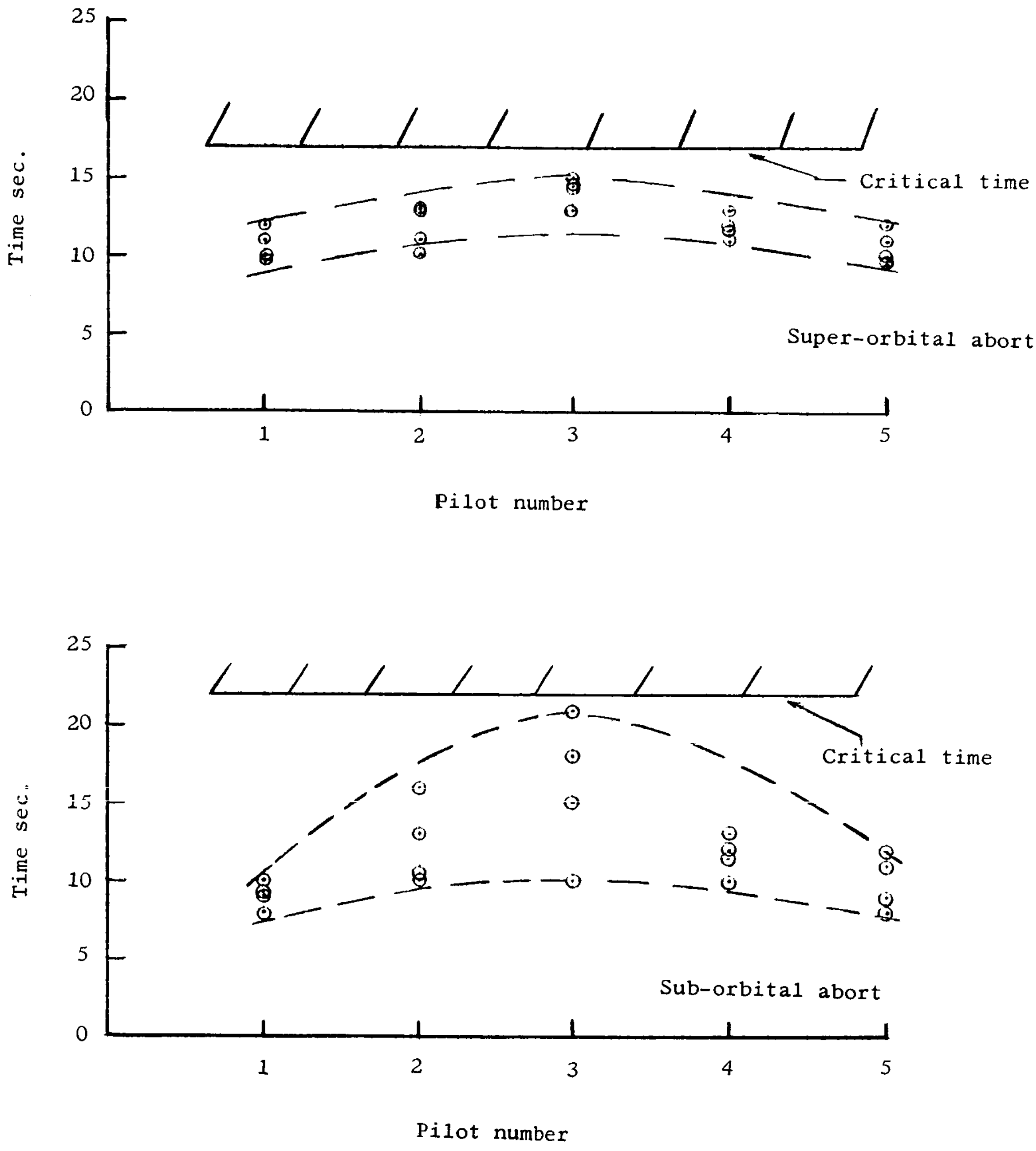

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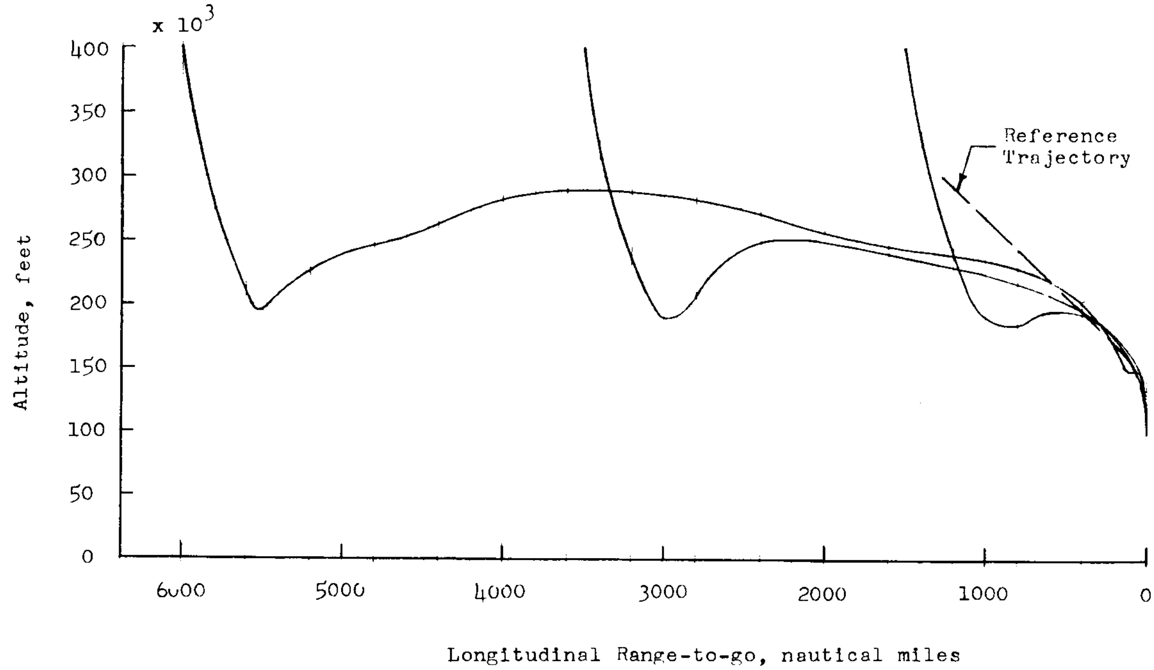
Figure 7.- A comparison of several pilots' ability to perform pitching maneuvers within a specified time following aborts at subcircular and supercircular velocities.



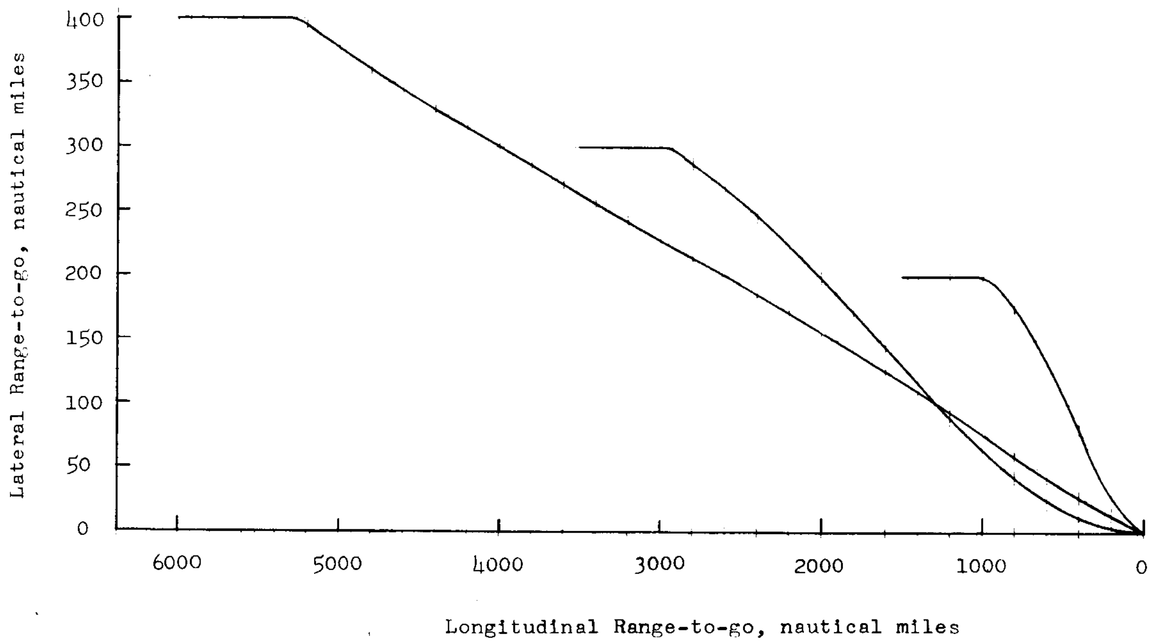


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Figure 8.- Typical trajectories illustrating piloting procedures for entries at parabolic velocity. h_o = 400,000 ft, v_o = 36,000 ft/sec, $\gamma_o = 6.5^{\circ}$.

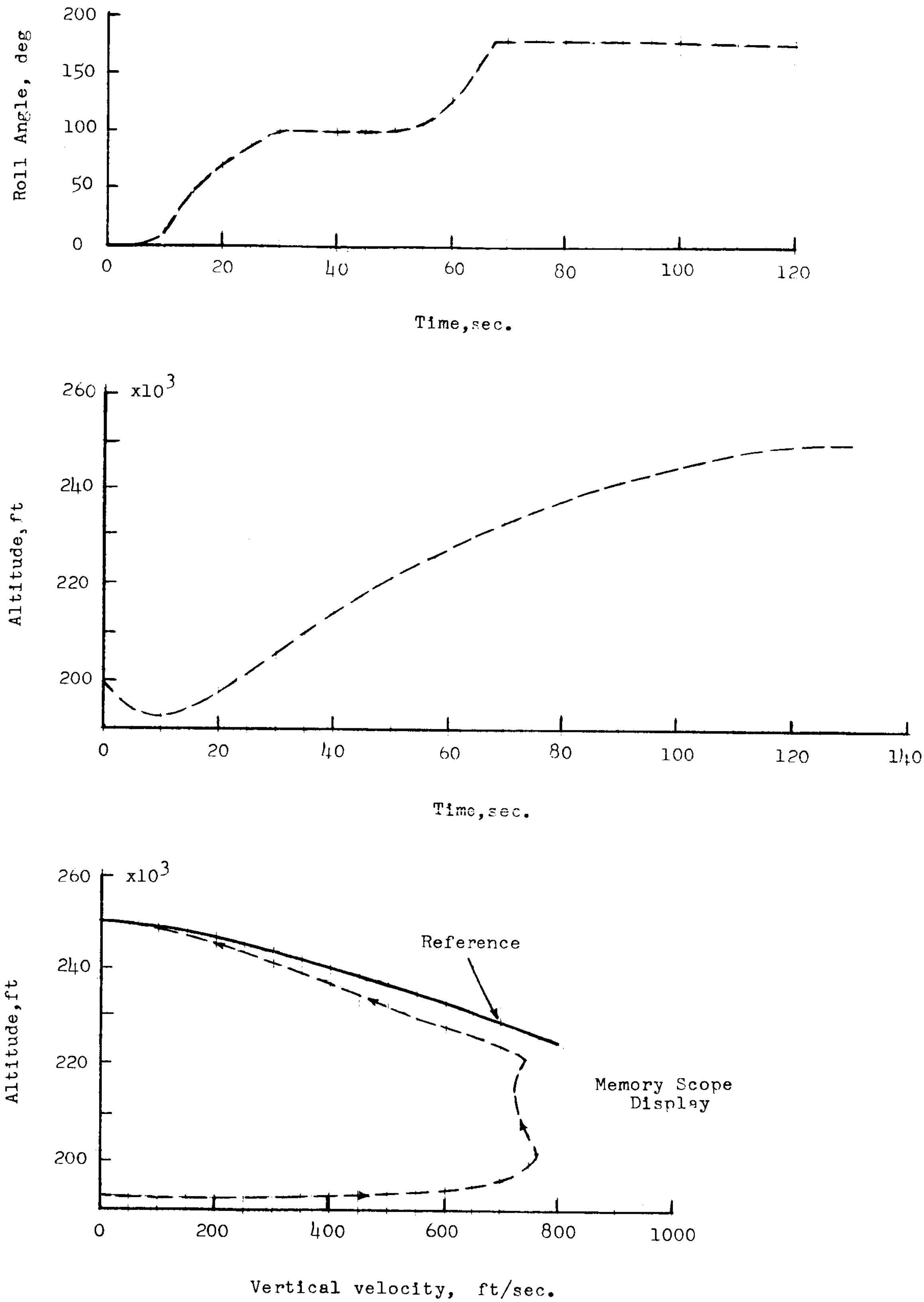

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Figure 9.- Memory-scope display illustrating the pull-up maneuver including time histories of altitude and roll angle.

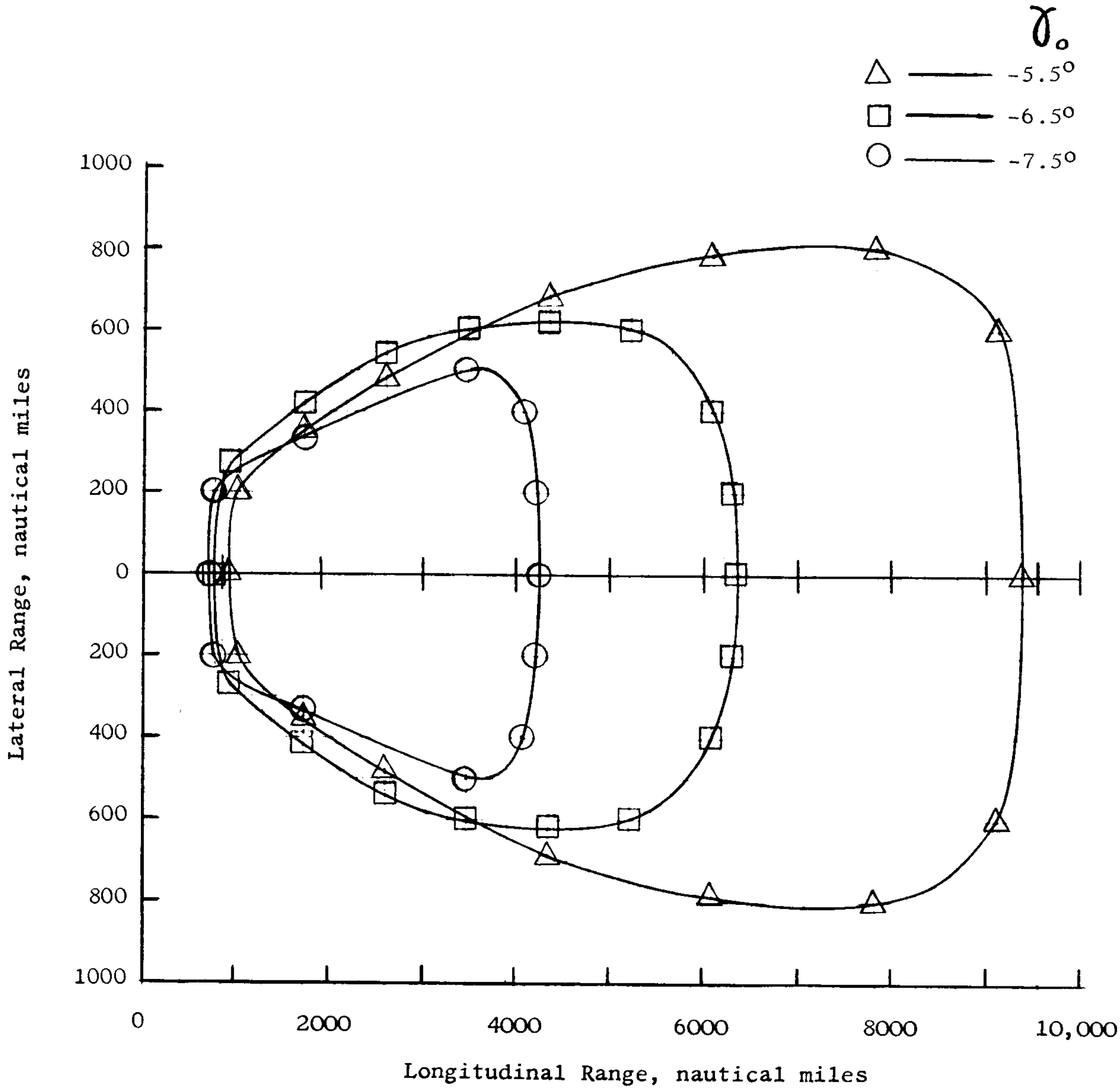

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Figure 10.- Locus of end points of trajectories showing the longitudinal and lateral range attainable for piloted entries at parabolic velocity. v_o = 36,000 ft/sec, h_o = 400,000 ft.

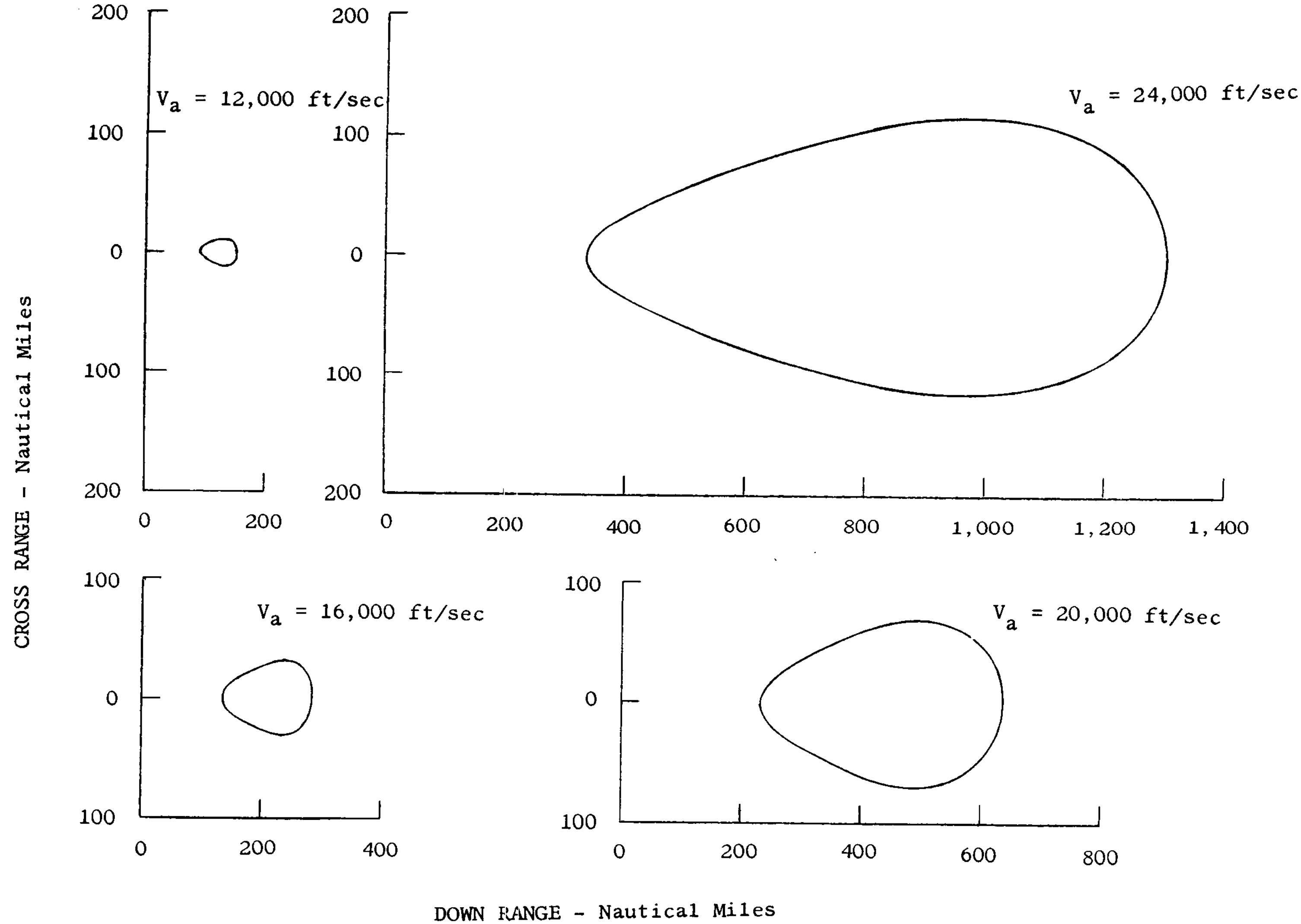

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Figure 11.- Locus of end points of trajectories showing the longitudinal and lateral range attainable for entries following abort at subcircular velocities.