REPORT 428

ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT
64 RUE DE VARENNE, PARIS VII

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HORIZONTAL LANDING TECHNIQUES FOR HYPERSONIC VEHICLES

by

ROBERT G. HOEY

JANUARY 1963

NORTH ATLANTIC TREATY ORGANIZATION

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~~This Report was~~ presented at the Aircraft Take-Off and Landing Specialists' Meeting, ~~sponsored by the AGARD Flight Mechanics Panel, held in Paris~~, 15-18 ~~January 1963~~

SUMMARY

The terminal approach and landing techniques presently being used for the X-15 hypersonic research vehicle are described. The development of these techniques and some flight test results are also discussed. The effects of wing loading, lift-drag ratio, visibility, handling qualities, speed brakes, and trim changes are analyzed as they pertain to low L/D landings of the X-15 and other hypersonic configurations.

The use of an in-flight landing simulator to provide pilot training and maintain pilot proficiency is emphasized.

SOMMAIRE

Les techniques d'approche terminale et d'atterrissage couramment employées pour le véhicule de recherche hypersonique X-15 sont décrites. Sont également étudiés l'évolution de ces techniques et certains des résultats d'essais en vol obtenus. L'influence des charges alaires du rapport portance traînée, de la visibilité, des qualités de maniabilité, des freins, et des variations de l'équilibrage est analysée dans la mesure où ceux-ci concernent les atterrissages L/D faible du X-15 et d'autres configurations hypersoniques.

L'emploi d'un simulateur d'atterrissage en cours de vol en vue de l'entraînement des pilotes et pour leur permettre d'atteindre un niveau éléve d'aptitude est souligné.

533.6.015.2:629.136.2

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NOTATION

L	lift
D	drag
L/D	lift-to-drag ratio
$(L/D)_{max}$	maximum value of lift-to-drag ratio
C_L	lift coefficient
x	longitudinal distance
y	lateral distance
h	altitude
S	wing area
W	aircraft weight

HORIZONTAL LANDING TECHNIQUES FOR HYPERSONIC VEHICLES

Robert G. Hoey*

In this Report I will discuss some of the results of the X-15 Program pertaining to the terminal phase of flight and show how these results can be useful in developing horizontal landing techniques for future gliding re-entry vehicles. For those who are not familiar with the X-15 Program, the X-15 is a stubby-winged rocket-powered aircraft of fairly conventional configuration which is air-launched from a B-52 mother ship (Fig. 1). It is capable of attaining a Mach number of 6.0 and altitudes in excess of 300,000 feet. After rocket burn-out at approximately 80 seconds, the airplane becomes a glider and performs a lifting re-entry followed by a deceleration and normal landing on Rogers Dry Lake at Edwards AFB, California. The techniques for recovery of the X-15 are similar to those of other proposed hypersonic lifting re-entry vehicles.

Figure 2 shows a typical lift/drag ratio (L/D) curve as a function of lift coefficient (C_L) for a lifting re-entry vehicle. Notice that the same L/D can be obtained at two different lift coefficients. Typically, a hypersonic entry is performed using the back side of the L/D curve to take advantage of the higher lift coefficient and resulting higher altitudes and reduced heating. Conventional supersonic and subsonic aircraft are normally flown only on the front side of the L/D curve where stability and control are generally much better and where more precise energy control is possible. The recovery operation for a hypersonic glider begins, then, with a transition maneuver from the back side of the L/D curve.

Figure 3 is a velocity versus altitude plot showing the terminal phase transition characteristics of the X-15. Maximum L/D and maximum trim lift coefficient curves are shown. The areas between these two lines correspond to the back side of the L/D curves shown in Figure 2. The area between $(L/D)_{max}$ and the dynamic pressure limit lines at the lower altitudes is the front side of the L/D curve. A 300 knot airspeed line is also shown for reference.

The entire recovery operation after hypersonic entry and glide can be divided into 3 phases: the transition maneuver, the terminal energy management and positioning, and the approach and landing. The envelope of actual gliding flight trajectories for X-15 speed missions is shown with cross hatching (burn-out is at the extreme right). At approximately 4000 feet per second the pilots have shown a *natural tendency* to perform a transition to the front side of the L/D curve. No specific instructions have been provided to the pilot with regard to this transition. It occurs as a natural result of the pilot's efforts to manage his energy and effect a safe landing.

X-15 pilot comments indicate that the lakebed, which is approximately 11 miles long and 5 miles wide, is easily discernible from as far out as 160 nautical miles at 100,000 feet and Mach 6.0 (engine burn-out). The pilot is, therefore, in easy visual contact with the lakebed at the start of transition and employs his speed

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* *Aerospace Engineer, Manned Spacecraft Engineering Office, Air Force Flight Test Center, Edwards Air Force Base, California, U.S.A.*

brakes during and after the transition as he seeks to establish a 300 knot airspeed and maneuver to a high key point for his landing approach. In general, the pilots have had little difficulty in managing their energy after performing the transition using only their cockpit instruments and visual references. In those instances where the energy management situation is approaching a critical point and maximum maneuvering or a maximum range glide is required to reach the lakebed, radioed assistance to the pilot is provided based on ground radar tracking.

When the X-15 is subsonic and in the vicinity of the landing site, the pilot attempts to establish a circular approach pattern over the runway, as shown in Figure 4. A plan view of the approach (x versus y) and a side elevation (x versus h) are shown. Notice that the nominal high key altitude for a 270 degree overhead approach is approximately 22,000 feet. Three patterns are shown for three different approach speeds, 285, 290, and 320 knots. These are indicative of the dispersions which have been experienced and from this spread it becomes apparent that this type of pattern is quite flexible. This approach technique is a fairly standard technique for performing flameout landings in jet fighters. The primary pattern modification for the X-15 has been the delayed extension of landing gear and flaps. A fairly long final approach is used wherein the pilot lines up with an aiming point on the ground approximately one mile short of the intended touchdown point. The flare is initiated between 300 and 1500 feet altitude, (nominally 700 feet) and the flaps are lowered during the flare. At completion of the flare, the skid type landing gear is extended and the landing performed in a normal manner. Vertical velocities at touchdown are between 0 and 6 feet per second.

The technique has become quite routine for the X-15 pilots. So much so, in fact, that we have asked them to attempt spot landings at the end of each flight. There are two reasons for the request. First, it provides the pilot with necessary practice to prepare him for possible emergency landings on the smaller, uprange lakebeds. Second, it provides statistical data on landing accuracy for future vehicles of this type. Figure 5 shows the dispersions which have resulted from these spot landing attempts. Touchdown dispersion in feet is plotted versus flight number. Notice that touchdown points are generally within 2000 feet of the intended spot. An interesting by-product of this study which has only recently come to light is the manner in which the speed brakes are used by the pilots to accomplish these spot landings.

Figure 6 shows the use of speed brakes by the X-15 pilots for energy management purposes. The percentage of flights where speed brakes are used is plotted versus the altitude at which they were used. For example, on 43 per cent of the flights the speed brakes were used between 5 and 10 thousand feet altitude. Speed brakes were used at some altitude to dissipate energy on 74 per cent of the flights. Notice the interesting distribution of brake usage per 5000 foot altitude increment. Significant speed brake usage is indicated in the altitude region above 40,000 feet as the pilot maneuvers to hit a window corresponding to high key. Even more brake usage is indicated during the landing pattern. The pilot has passed through the high key window and his attention is now concentrated on hitting the designated spot on the runway. It appears then that effective speed brakes are required to accurately hit a landing point with a low L/D glide vehicle.

The history of the development of the X-15 landing technique is of interest since the same general procedure would be required for any similar glide vehicle. Prior to the first flight of the X-15 a general low L/D landing study was performed using an F-104A. Various configurations were flown using combinations of speed brake, landing gear, flap, and power settings to provide variations in L/D. The results of these studies showed that landings in the X-15 L/D range were possible but special techniques were required to keep the L/D as high as possible during the flare and to maximize the amount of time from flare completion to touchdown. An F-104 configuration was then selected which matched the L/D values for the X-15, as shown in Figure 7. The approach technique was then developed using the F-104 as an in-flight simulator. The value of this in-flight L/D simulation as a training device cannot be over-emphasized. Each pilot devotes one entire F-104 flight to landing practise the day before he flies the X-15. This allows him to practice nominal and off-nominal approaches at Rogers Dry Lake and at the emergency lakebeds between the launch point and Edwards AFB.

The terminal approach and landing techniques used for the X-15 have been highly successful. Although the landings are relatively routine, they do require exacting pilot performance and a high degree of proficiency. Before applying the information to future low L/D re-entry configurations, several qualifying factors must be completely understood: (1) The cockpit window configuration and general external visibility are considered quite important in the performance of low L/D landings. The visibility from the X-15 cockpit is considered excellent. In one instance a cockpit glass failure occurred which caused one of the window panels to become completely opaque. Although the landing was successfully accomplished, the pilot was aware of a serious loss in depth perception during and after the flare using only one window panel. (2) The handling qualities of the X-15 in this speed and angle-of-attack range are also considered excellent. The all-movable horizontal tail for both pitch and roll control produces high airplane response with very little cross-coupling. All stability derivatives are stable and of fairly high magnitude in this flight regime. The predicted subsonic stability levels of many proposed lifting re-entry configurations are considerably lower than the X-15 and the landing characteristics would probably suffer as a result. (3) An effective method of speed control is necessary to perform accurate landings. The X-15 speed brakes have proven to be quite valuable during the approach and landing phase. These speed brakes, located on the trailing edge of the vertical tail, are very effective and have fairly rapid response. Less effective speed brakes could compromise the ability to perform accurate landings. (4) Any extreme trim change due to a configuration change would cause a serious compromise in the landing capability. Trim changes due to flaps, landing gear, and speed brake extension are minor and easily controlled on the X-15. (5) The standard F-104 external configuration is so similar to that of the X-15 that an in-flight L/D simulation was easily accomplished. This simulation has proven quite accurate and valuable in maintaining pilot proficiency in low L/D landings. If such an in-flight simulation for a future configuration cannot be accomplished, the experience level of the pilots will undoubtedly remain at a lower level than has existed on the X-15 Program. Recognizing that these features do exist on the X-15 and assuming comparable features on a future vehicle, we can use the X-15 results to predict the landing characteristics of other low L/D configurations.

In Figure 8 L/D is plotted versus lift coefficient divided by wing loading (which is also equivalent to load factor divided by dynamic pressure). The X-15 approach speed is nominally 300 knots; however, approach patterns have been flown successfully as high as 320 knots and as low as 250 knots. Notice that this places the approach conditions well down on the front side of the L/D curve. During the flare maneuver the C_L increases and the flare is accomplished at very close to maximum L/D . When the flare is completed the C_L again drops down the front side of the curve and the vehicle decelerates while gliding parallel to the ground. The pilot lowers the gear and flaps and prepares to land during the deceleration, and the lift coefficient gradually increases. The touchdown occurs when the lift coefficient has again reached the point of maximum L/D .

We can assume, therefore, that the pilot will prefer to fly any other hypothetical vehicle on approximately the same portion of the L/D curve as described for the X-15. NASA studies using F-102 and F5D aircraft with wing loadings considerably less than the X-15 confirm this assumption. We can then ratio the lift coefficient during the X-15 approach to the lift coefficient for maximum L/D and attempt to predict the best approach speeds for other glide vehicles. This is shown in Figure 9. Approach velocity in knots is plotted versus wing loading divided by the lift coefficient for maximum L/D . The flame-out approach speeds for several fighter type aircraft as suggested in the aircraft handbook are shown by the circles. The approach speeds predicted for these airplanes, as shown by the solid line, are seen to be in close agreement. Also shown, at the extreme lower left side, are two configurations of the NASA Flight Research Center Rogallo wing para-glider. Flight tests of this very low wing loading vehicle indicate that approach speeds of 50 to 60 knots are the most desirable. The two vertical lines indicate the approximate position on the curve of a typical delta-wing re-entry glider vehicle and a typical modified lifting-body configuration. This curve would indicate that either of these configurations could be landed using nominal approach speeds. Notice that this curve only attempts to predict approach speeds and is independent of the actual value of L/D . This is not to say the L/D has no effect on the landing characteristics. It is, of course, extremely important.

Since many papers have been given on this subject, I have elected to touch on it only lightly. The L/D during flare, which is generally very close to maximum L/D for a particular configuration, is plotted versus wing loading in Figure 10. Points representing several research vehicles are shown. The F-104 low L/D landing study mentioned earlier is represented by the two points labeled F-104 (MOD). Results of this study indicated that the practical lower limit for maximum L/D (or flare L/D) was approximately 2.5. One landing was performed in this configuration and the pilot felt that the timing of the flare initiation point and the extremely short time between flare completion and touchdown were extremely critical and chose not to repeat the landing a second time.

In conclusion, I have used the X-15 flight test results to show that successful and accurate landings can be accomplished on low L/D hypersonic re-entry configurations in the L/D range of 3.5 to 5.0 provided that certain factors in the configuration design are favorable. These factors are: good visibility, good handling qualities, effective speed brakes, and minor trim changes. A powered airplane which can accurately simulate the landing characteristics is also extremely valuable for pilot training and proficiency.

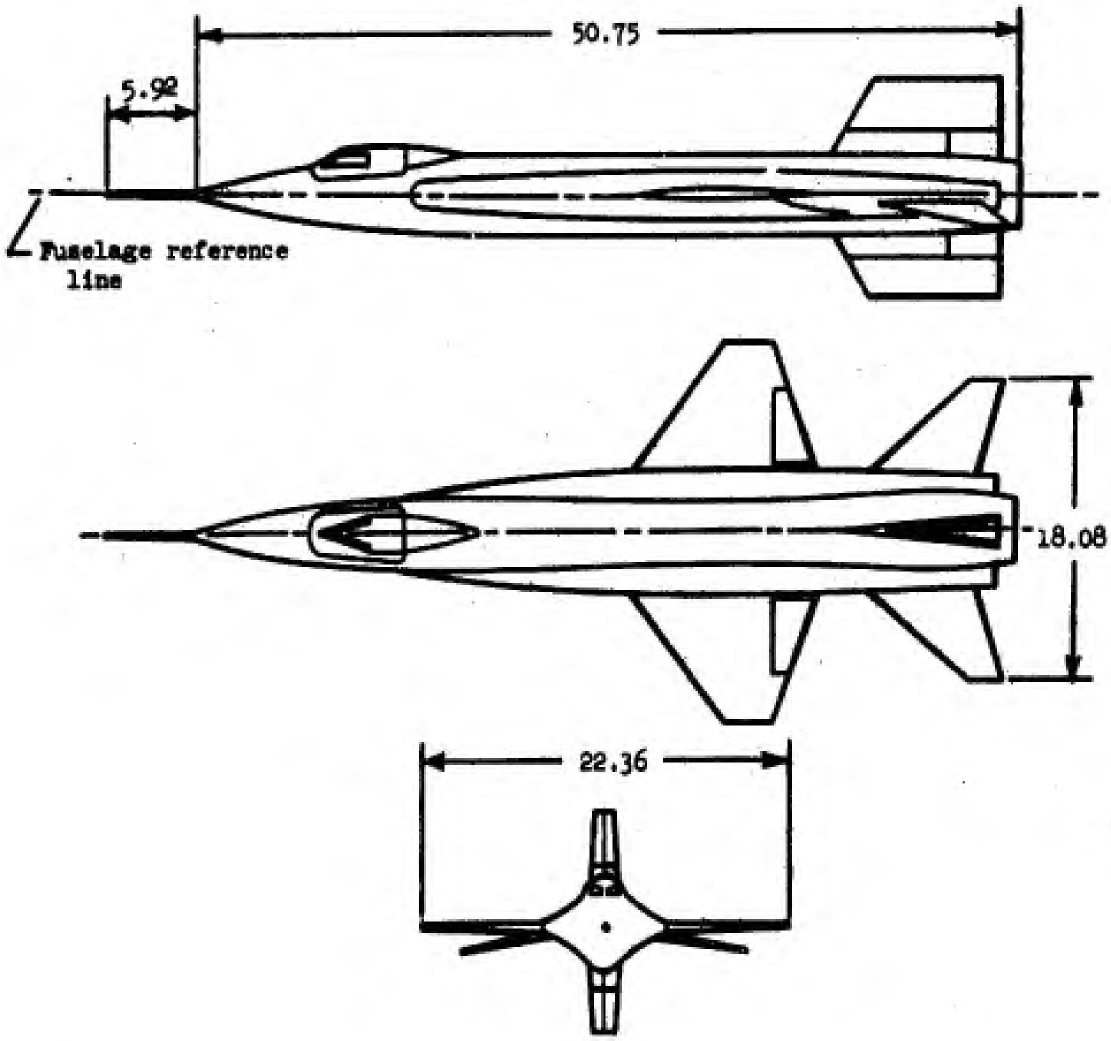

Fig. 1 Three-view drawing of the X-15 airplane (all dimensions in feet)

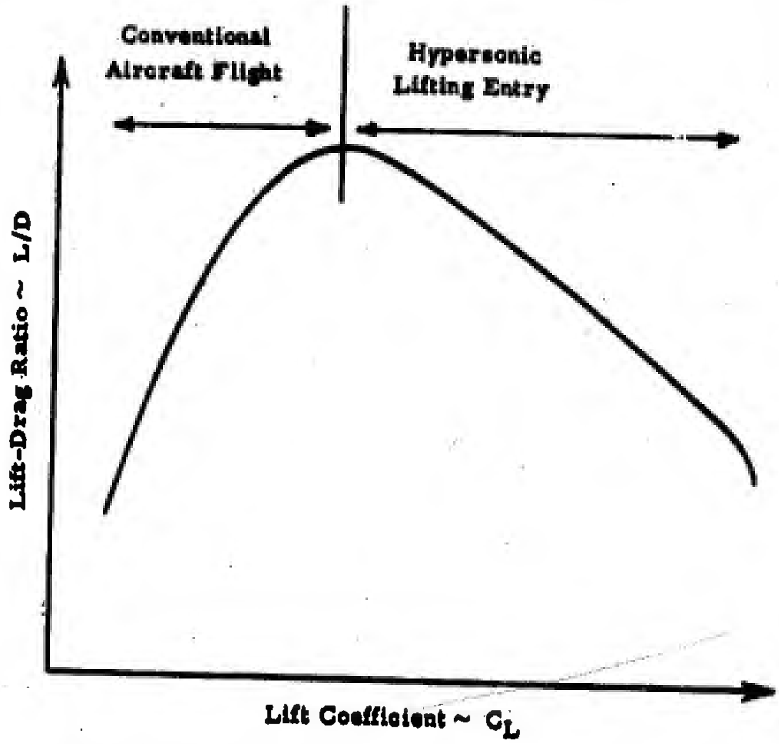

Fig. 2 Typical lift-drag ratio curve

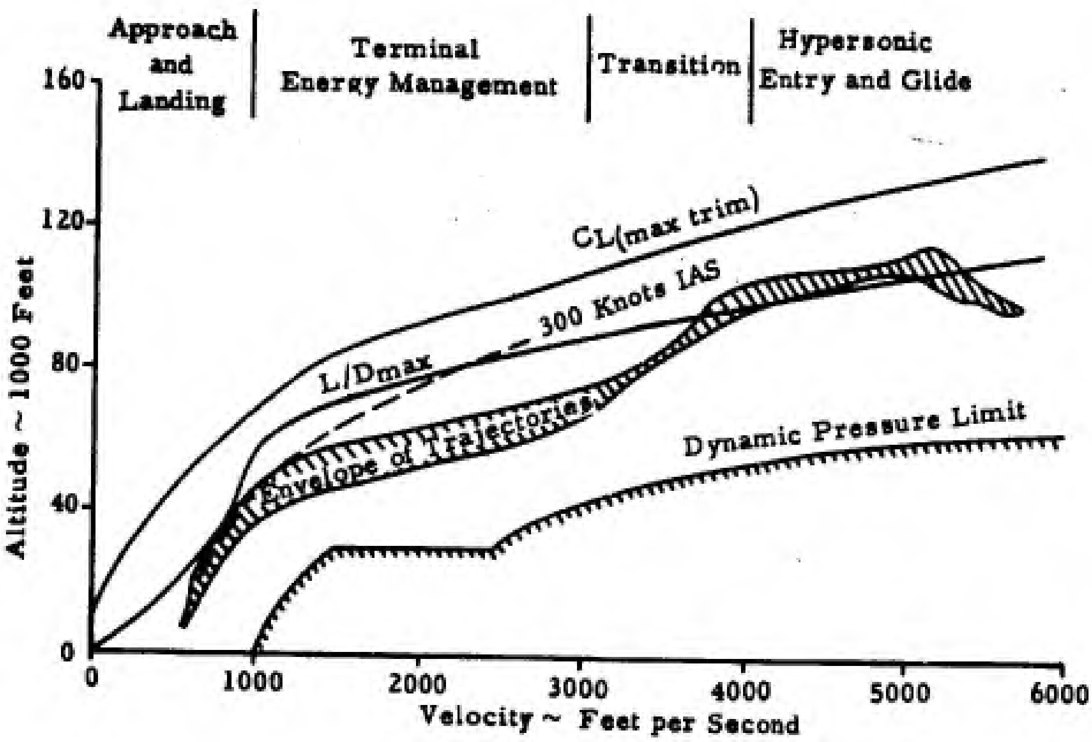

Fig. 3 X-15 terminal phase transition

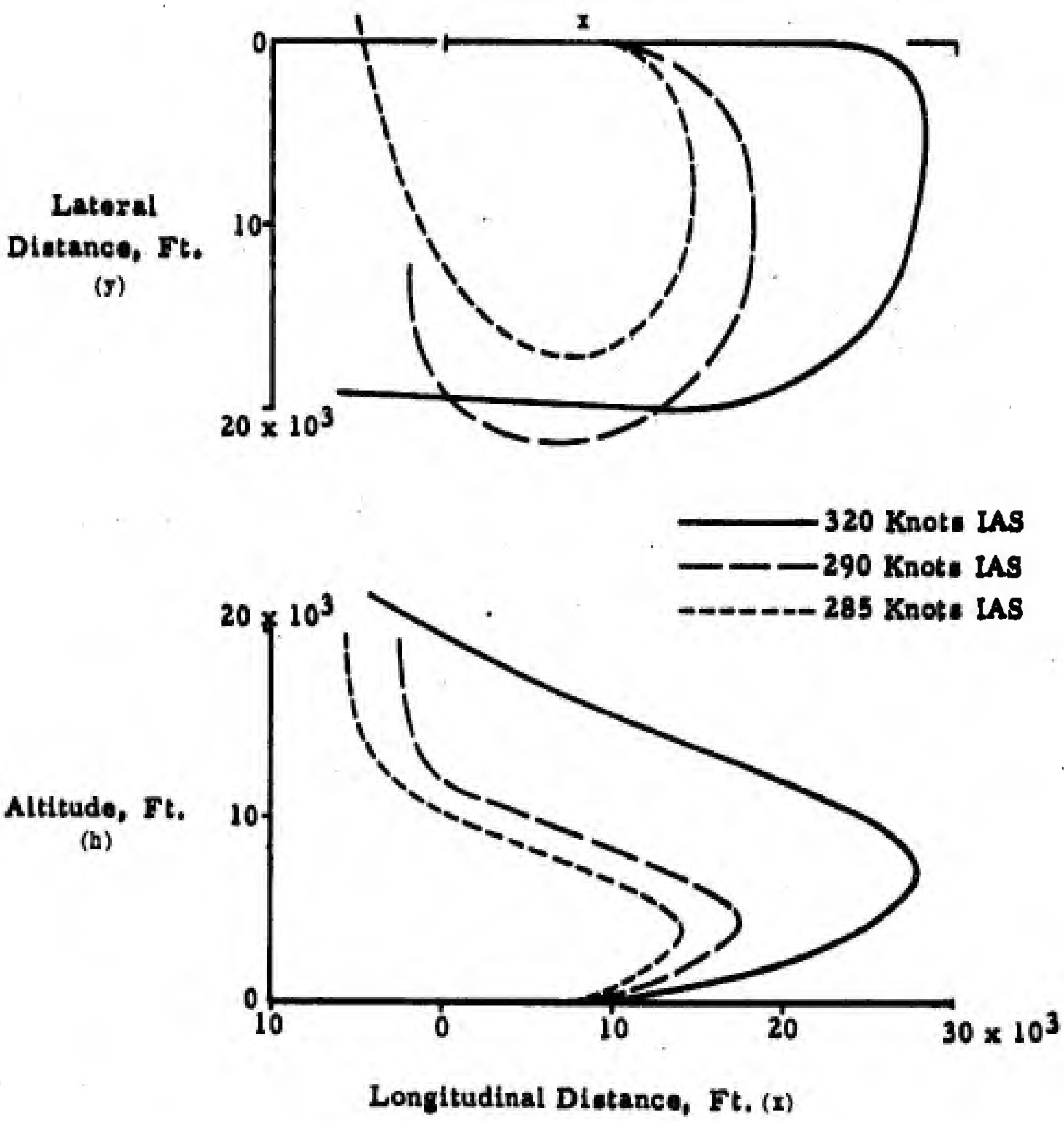

Fig. 4 X-15 approach patterns

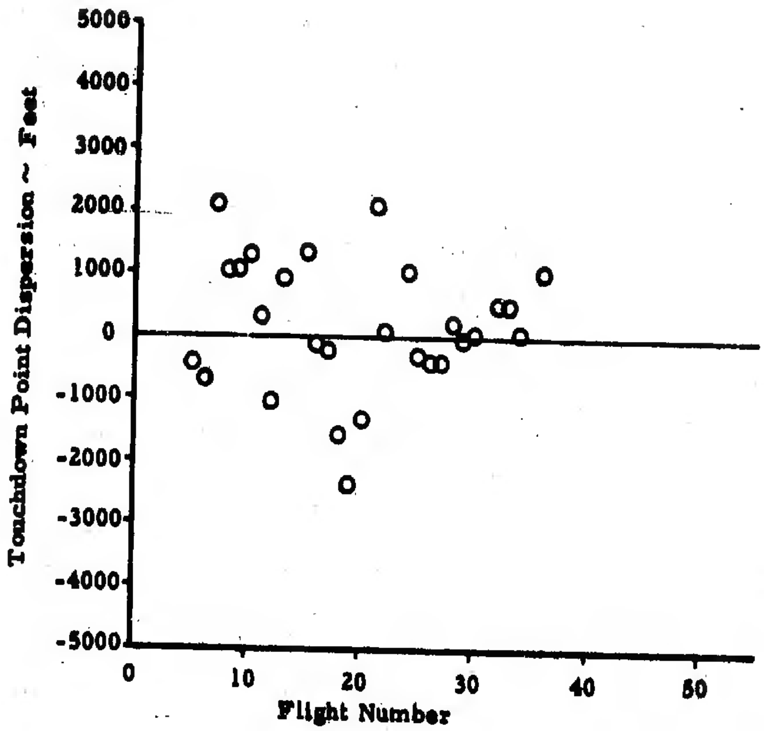

Fig. 5 X-15 landing accuracy

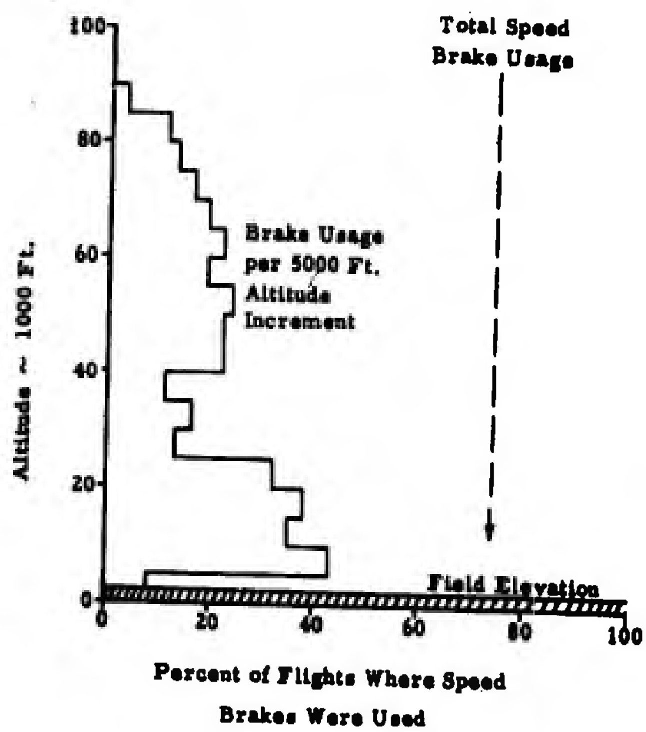

Fig. 6 X-15 use of speed brakes

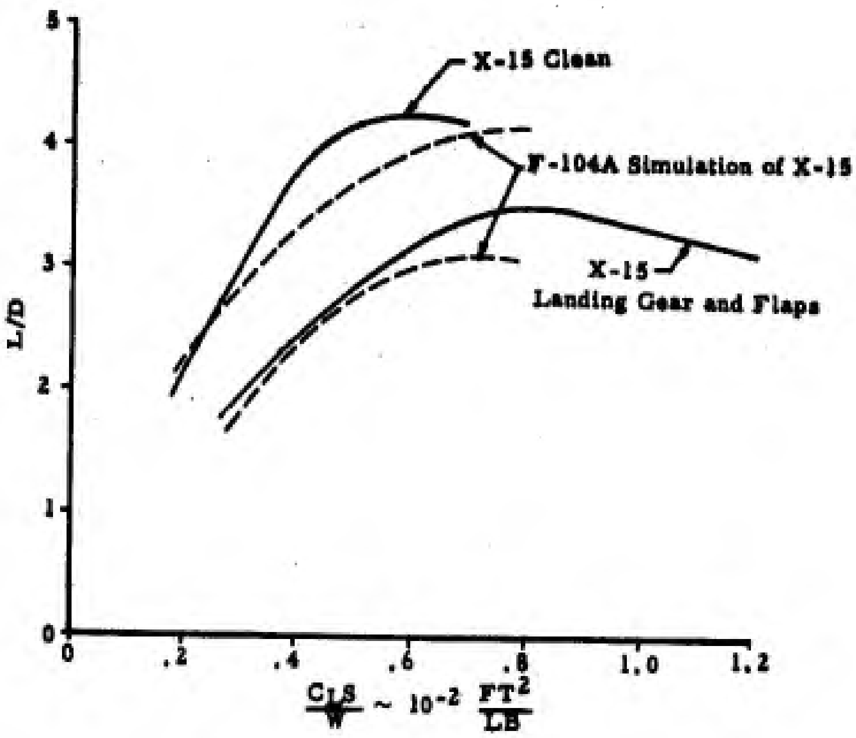

Fig. 7 F-104 simulation of X-15 landings

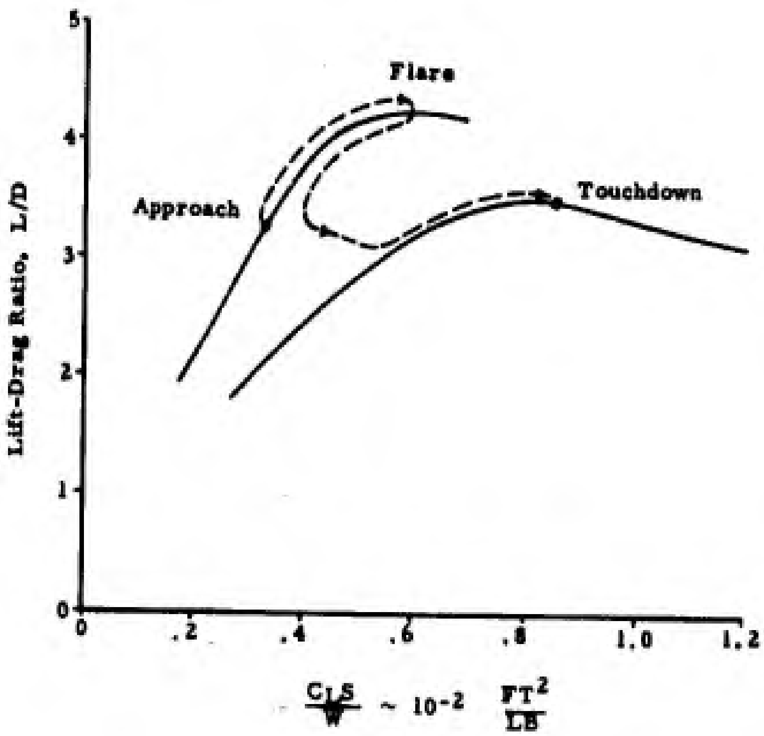

Fig. 8 Typical X-15 landing

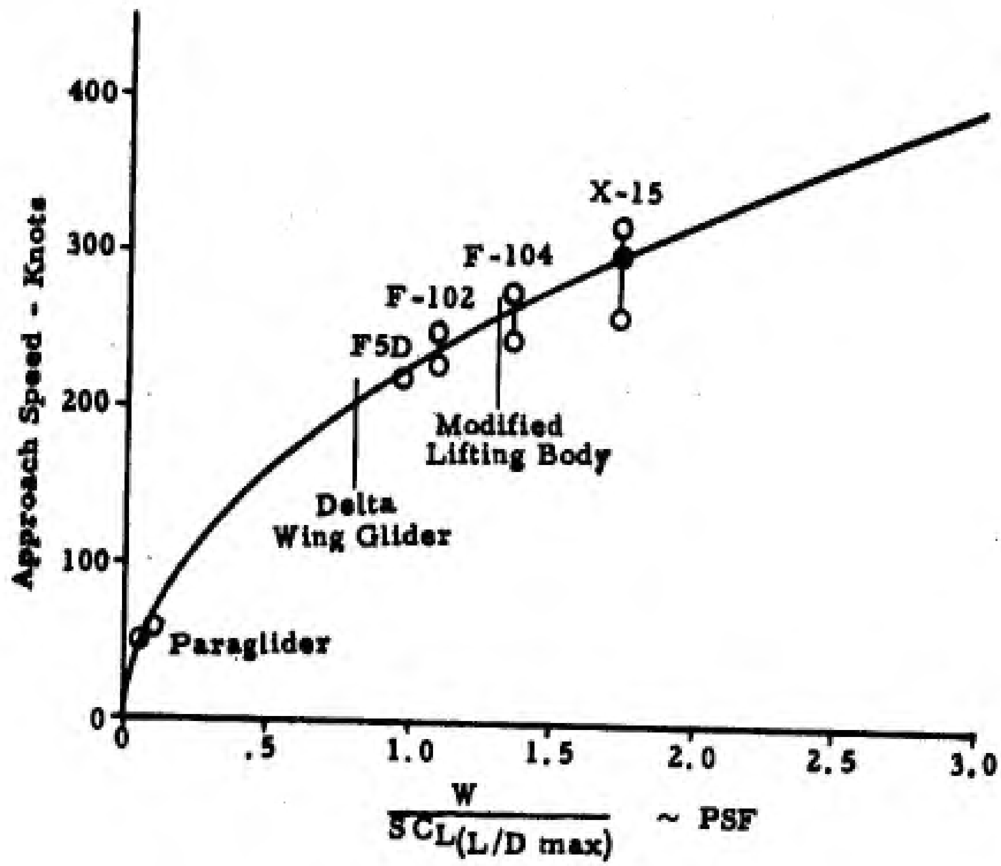

Fig.9 Predicted approach speeds for low L/D glide vehicles ($(L/D)_{max}$ range 3 to 5)

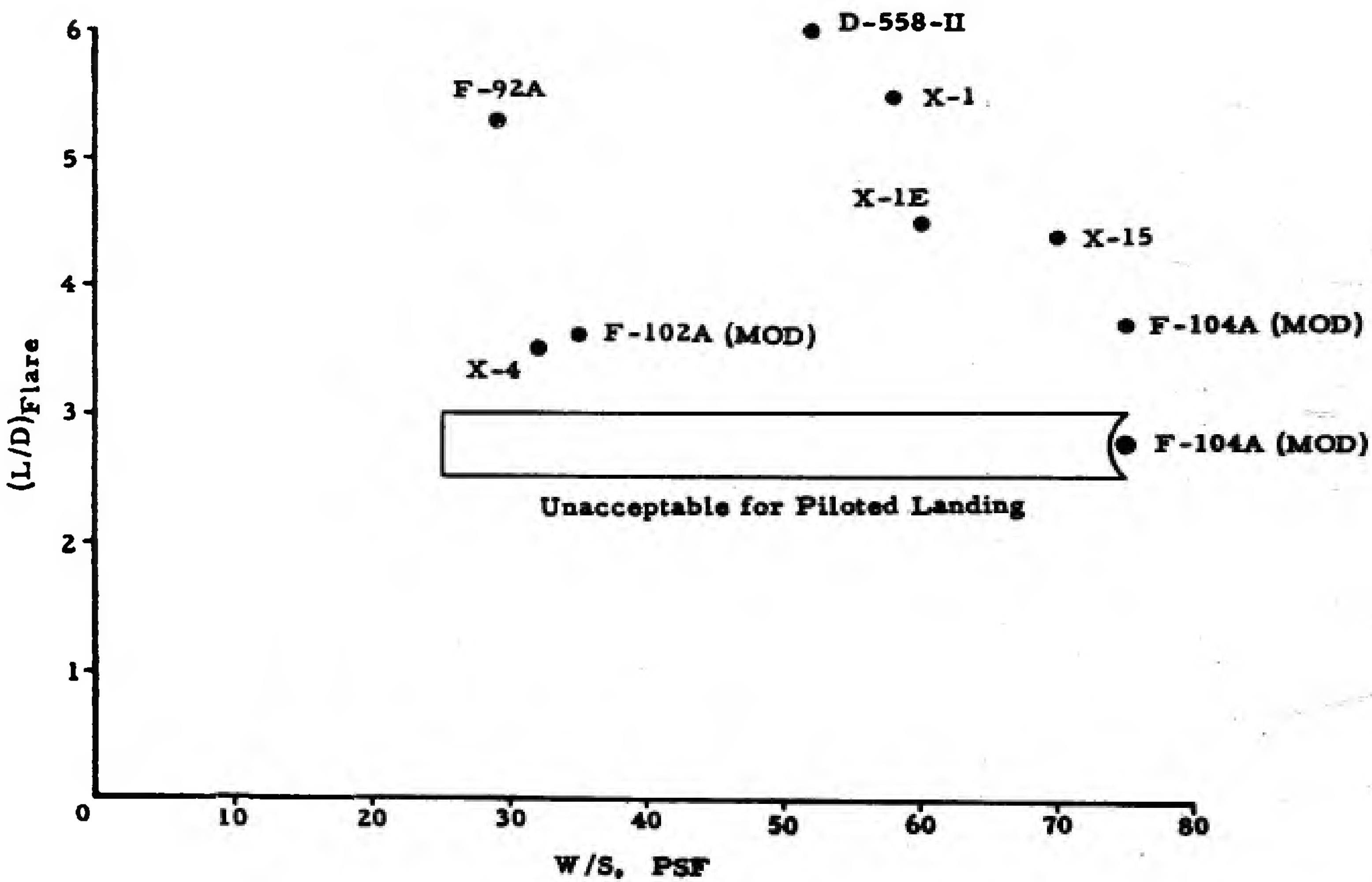

Fig. 10 Suggested criteria for piloted flared landing

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Printed by Technical Editing and Reproduction Ltd
Harford House, 7-9 Charlotte St. London. W.1.

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