EARTH ORBITAL LOGISTICS SPACECRAFT:

PERFORMANCE ASPECTS AND VEHICLE CONCEPTS

Eugene S. Love

NASA Langley Research Center
Langley Station, Hampton, Va.

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ABSTRACT

The paper is composed of two parts. The first reviews some implications of hypersonic performance with special emphasis on return of logistics spacecraft from orbit to the continental U.S. Among the factors considered are quick return, delayed return with varying and fixed wait time, relation of wait time to return opportunities, relation of maneuverability to clear-weather recovery and night landing, propulsive orbit phasing, propulsive plane change, and recovery costs. Some observations of the whole are made in relation to current spacecraft capability and future needs.

The second part of the paper surveys representative vehicle concepts ranging from low to high hypersonic lift-drag ratios. Particular attention is centered on landing modes and their implications. Among the concepts discussed are fixed and variable geometry for runway landers, and decoupled modes, such as parawing and sailwing devices, deployable rotors, and propulsive lift. Some observations are made of potential benefits and current deficiencies.

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THE CHARACTERISTICS OF LOGISTICS SYSTEMS required to support future Earth-orbital space stations continue to be extensively studied and debated. From this activity has evolved general agreement that a mix of manned and unmanned logistics spacecraft has a greater mission effectiveness than manned logistics spacecraft only, the mix generally resulting in some 25 percent fewer launches, e.g., (1).* Thus, a comprehensive treatment of logistics spacecraft should cover both manned and unmanned vehicles. However, such broad scope falls beyond the intent of this paper,** and while both vehicle categories are recognized in Fig. 1 as interacting and sharing equal importance with other dominant factors configuring logistics spacecraft - the general subject of concern herein - this discussion will be restricted to manned vehicles, hypersonic L/D, and landing mode. It will be recognized, nevertheless, that some of the content is equally applicable to unmanned systems. The first part of the paper will review some implications of hypersonic performance with special emphasis on return from orbit; the second part will be a survey of vehicle concepts with particular attention to landing modes.

PART I: HYPERSONIC PERFORMANCE ASPECTS***

The type of manned logistics system considered herein is illustrated in the lower

*Numbers in parentheses designate References at end of paper.

**This paper is in some respects a fragmentary updating of a synoptic lecture series presented at a 1961 conference under a similar title (2). While better understanding of problems and significant refinements to concepts have been contributed in the interim, apparently no new basic concepts have emerged that were not aired at that conference.

***Special acknowledgement is made to P. F. Holloway for his contributions.

part of Fig. 1; it consists of a launch vehicle, a combination cargo module and adapter, and the manned logistics spacecraft which is also the entry vehicle. The cargo module might also double as (or be replaced by) a space propulsion module. The cargo module and logistics spacecraft fly outbound as a unit until docked with, or in close proximity to, the space station. The cargo module does not accompany the logistics vehicle in return to Earth.

Fig. 2 illustrates the type of interplay that can occur between cargo requirements and logistics vehicle performance. Dependent upon launch vehicle capability, minimum cargo requirements, and desired cargo margin, the hypersonic performance that can be considered for the logistics vehicle could be constrained by the characteristic increase in the weight of logistics vehicles with L/D (solid curve). The trends shown here are representative of conditions exposed in past logistics studies, and point up one reason for continuing interest in low L/D logistics vehicles, namely, the sizable cargo margins that can be interpreted as growth potential for supporting increased space station activity.

The question of how long space station occupants should be forced to wait in orbit once they have decided to return, or for that matter, the permissible duration of time-consuming return maneuvers such as low-impulse orbit phasing, remains unresolved except in the sense that one accepts what existing vehicles will provide. Numerous studies, e.g., (3)-(7), have assessed the effect of hypersonic L/D in combination with varying orbit inclination, number of land sites, site location, etc., on frequency of return, maximum wait time in orbit, and other factors. At the risk of adding more drag than lift to a subject already well exercised, a brief review will be made of the interplay of L/D with some of the parameters in the return problems. It will be assumed that land landing is desired, and that in routine operations this should occur in CONUS (i.e., the continental U.S., Alaska excluded; where the term "southern CONUS" is employed, reference is to the region below about 35° latitude).

<u>Quick Return from Orbit</u> - As a point of departure consider first the case of quick return from orbit, i.e., the return in which the time from decision to return to initiation of return is no more than one orbit period. An overview of this case is given in

Fig. 3. With regard to orbit inclination, several past studies of space station utilization have suggested that programs of space systems research, development, and applications of most significance to national interest can be best served in orbit inclinations ranging from 30° to 90°, with special emphasis on the 50° to 70° range. For either of these ranges, and with a restriction to return to CONUS sites in both routine and emergency conditions, curves at the left in Fig. 3 show that the L/D required would be near 3 for quick return to some point in CONUS, and near 3.6 for quick return to every point in CONUS. As indicated, these values of L/D would be adequate for any orbit inclination. While quick return to CONUS, and therefore high L/D, remains a dubious requirement for a logistics vehicle in routine or most emergency returns from a space station (crew stay time at station > 30 days), high performance might be exploited to advantage in some conceivable emergencies. On a tangential note, some hypothesized military missions have developed substantial interest in quick return of manned spacecraft to CONUS; whether or not high L/D in manned military spacecraft gives practical advantage through offset maneuvers during ascent to orbit and/or glide and powered synergetic maneuvers for large plane change, e.g., (8)-(14), depends strongly upon the mission objective, particularly when the mission involves both manned and unmanned vehicles.

If the restriction to CONUS sites for quick return is removed so as to permit a choice of worldwide networks of sites, the trend shown on the right of Fig. 3 results (rigorously, composed of step functions). This picture embodies realistic geographical and geopolitical land mass and site constraints, with at least the primary site located in CONUS. This operational approach provides quick return for emergencies that demand it, and accepts the possibility that emergency quick return may mean recovery at one of the foreign sites. The major benefits of L/D in decreasing the minimum number of sites in the network are realized at moderate L/D - near one for any one orbit between 30° and 90°, and near two for all orbits in this range. In normal operation the procedure would be to accept whatever wait time in orbit is required to return to the primary CONUS site. This raises the question of the relation between wait time and L/D involved in delayed return to CONUS, some aspects of which will be treated next.

Delayed Return from Orbit, Varying Wait Time - Consider first the picture of L/D requirements for single-site return as a function of landing-site latitude for various orbit inclinations as shown in Fig. 4. These results are generated as follows: for landing-site latitudes less than the orbit inclination, the L/D is that required to reach a point midway between two successive orbit tracks; for landing-site latitudes greater than the orbit inclination, the L/D is that required to reach the site from the two successive tracks nearest the site. Although the attractiveness of this approach may lie partially in the fact that it permits an analytic solution, there is practical significance in that the values of L/D thus determined guarantee a minimum of two returns per day, but with a varying maximum wait time no less than 12 hours and as high as 24 hours. Thus, while one valid conclusion is that a vehicle with L/D near one would be capable of returning to almost any site in CONUS for orbit inclinations greater than 30°, it is important to recognize the varying wait-time qualification. Also, at other than equatorial or polar orbits, the minimum values of L/D guarantee return to a site along a specific latitude only; the longitudinal position of the site varies with launch time and orbit period for point return.

Delayed Return from Orbit, Fixed Wait Time - For fixed maximum wait times, the picture for single-site return is markedly different, as shown in Fig. 5. Increasing the maximum wait time from a nominal 7 hours to 24 hours substantially reduces the L/D required to cover all orbits between 30° and 90°. These results also illustrate that for maximum wait times of several hours or more, a CONUS site capable of serving all orbits between 30° and 90° lowers the L/D requirement if it is located in southern CONUS. The results for a maximum wait time of 24 hours are of special significance in that they define the minimum L/D required to guarantee daily return to a single site in CONUS by aerodynamic maneuvering only; to cover orbits from 30° to 90°, with a site in southern CONUS, requires an L/D of about 0.85. The minimum values of L/D indicated here guarantee return to a site at a specific latitude and at any desired longitudinal location.

Wait Time and Return Opportunities - The effect of maneuverability on the relation between maximum wait time and number of return opportunities per day is also of interest. An example is shown in Figs. 6(a) to 6(c), including an illustration of the benefits of going from single to multiple CONUS sites. It is emphasized that the sites selected for this example, Edwards AFB, Langley AFB, and Hickam AFB (Hawaii), are not optima in any sense, but simply existing sites with reasonably good weather history and dispersed so as to make them candidates for the range of orbits considered, i.e., 30° to 90°. Edwards is assumed to be the primary site, and solutions for return to it were obtained in detail as indicated by the step-function curves. Solutions for the addition of Langley, and the addition of Langley and Hickam, were obtained at the selected values of L/D indicated by the symbols.

The general picture is one of decreasing maximum wait time and increasing return opportunities with increasing L/D or increasing number of sites. However, these examples bring out several features departing from the general trends that are common to most any CONUS and/or global site, or network of sites, chosen to serve a wide range of orbit inclinations, such as:

(a) An increase in L/D may increase return opportunities without reducing maximum wait time (e.g., note arrowheads on Edwards curve for 60° and 90° orbits).

(b) The addition of a site that is generally beneficial may increase return opportunities without decreasing maximum wait time (note overlapping symbols near L/D of one for 60° orbit).

(c) For orbits inclined from about 50° to 90°, there is usually a major discontinuous reduction in maximum wait time as L/D exceeds about one; however, there is no associated prominent increase in return opportunities, this being usually no greater than that for moderately inclined orbits.

One final observation from this example is that a network of a few CONUS sites can assure once daily return of vehicles with L/D near 1/2 for orbits from 30° to 90°; however, this precludes arbitrary selection of a specific landing site within this network at the time of return.

Maneuverability and Clear-Weather Recovery - An example of the effect of maneuverability upon the probability of clear-weather land recovery is shown in Fig. 7 for a 60° orbit and for the beginning months of each quarter of a year. Clear weather is defined as less than 3/10 cloud cover, and the probability of this is shown as a function of orbit number (repeatable daily). Two vehicles were considered with lateral range capabilities of 210 n.m. (L/D ≈ 1/2) and 780 n.m. (L/D ≈ 1). Networks of ten existing sites were selected for each vehicle on the basis of location and statistical weather history so as to permit quick return in emergency situations with high probability of good weather conditions. For either of these networks normal scheduled returns would be to the prime recovery site (one of the CONUS sites). The sites in this example are given below:

210 n.m. vehicle

Edwards AFB, California
Langley AFB, Virginia
Brownsville, Texas
Hickam AFB, Hawaii
Churchill, Canada
Chitose, Japan
Kimpo, South Korea
Stockholm, Sweden
Gertzog, South Africa
Tehran, Iran

780 n.m. vehicle

Edwards AFB, California
Langley AFB, Virginia
Spokane, Washington
Moron, Argentina
Pearce, Australia
Alice Springs, Australia
Kimpo, South Africa
Dhahran, Saudi Arabia
Gertzog, South Africa
Ambala, India

The results in Fig. 7 illustrate that increased maneuverability can markedly improve the probability of clear-weather land recovery, not only because the higher performance vehicle can reach more of the sites for almost any orbit number, but also because sites with a higher probability of clear weather can be included in the network. The average yearly probability of clear-weather recovery for the L/D ≈ 1/2 vehicle returning to its network is 44 percent, while that for the L/D ≈ 1 vehicle and its network is 79 percent. Significantly higher L/D would give higher probability of clear-weather recovery with fewer sites in the network. It is important to temper these conclusions, nevertheless, by noting that clear-weather recovery may not be as crucial to some landing modes as to others. Moreover, in normal operations, it is not inconceivable that return from a space station could, in otherwise normal operations, be postponed to "wait out" some weather conditions.

Maneuverability and Night Landing - Periodically, the orbit-plane-sun-line geometry is such that logistics vehicles may be unable to return to CONUS sites in daylight for several days, e.g., (4) and (15). Fig. 8 presents an example of the effect of increasing maneuverability in reducing the fraction of the period of the day-night landing cycle which is restricted to night-only landings. In this example, the orbit altitude is 300 n.m.; the landing latitude is 30°, and two orbit inclinations are considered, 30° and 50°. The average period of the day-night landing cycle (orbit-plane-sun-line precession cycle) is about 48 days for the 30° orbit and about 62 days for the 50° orbit. Thus, these results illustrate the typical conclusion that the number of days as well as the fractional period for night-only landings are reduced by increasing orbit inclination. The indication that an L/D near 2 would permit at least one daylight landing at CONUS sites during each day of the cycle is typical for orbits from 30° to 90°, regardless of the season. Note that quick return is not an objective here. As would be expected, summer is more favorable than winter because of the greater coverage of sunlight on the northern hemisphere.

Whether or not night landings are a genuine concern in logistics operation again depends strongly on the landing mode of the logistics vehicle. Moreover, if other operational factors permit, night landings can be avoided in normal operations by tailoring the crew rotation/resupply cycle to the orbit-plane-sun-line precession cycle. Finally, daylight return can generally be accomplished with low L/D vehicles if appreciable wait time in orbit is combined with propulsive orbit phasing, some aspects of which will be discussed next.

Propulsive Orbit Phasing - The propulsive orbit phasing maneuver considered here consists of either raising the apogee or lowering the perigee of the logistics vehicle after cast-off from the station. Either approach changes the orbit period. After waiting in this new phasing orbit for a certain period of time the landing site intersects the orbit plane; the logistics vehicle is then in the proper position to perform its retromaneuver and descend to the landing site.

To illustrate the application of orbit phasing, consider a space station in which the crew activity for a given rotational cycle has been completed. The logistics vehicle is standing by ready to perform its return; it is a low L/D type (less than 1/2) and is equipped with a propulsion system capable of providing a velocity change of a few hundred ft/sec beyond that required for the usual retromaneuver. The crew must make a choice within two limits; they can leave the station immediately and use less than the full propulsive phasing velocity available to perform a phasing maneuver that could approach two days in duration for highly adverse phase angles - or they can wait at the station for a period of time that is the difference between the return time if they departed immediately, and the time required for the phasing maneuver if all the propulsive phasing velocity was used. Or - they can use any combination between these two limits. The point to note is that the time consumed in the phasing maneuver is the total time in the return activity only when the wait time is zero.

An example of the relation between phasing velocity and time consumed in the phasing maneuver only is given in Fig. 9 for a case of highly adverse phase angle, and a phasing maneuver that lowers the perigee from 200 n.m. to 100 n.m. Landing sites are assumed to be located in the southern CONUS. As shown, a ballistic vehicle could return to a single landing site if both large phasing times and the weight associated with the required phasing velocity are acceptable. If landing at any site in a 4-site network is permitted, marked reductions in phasing time and phasing velocity are possible. Combining aerodynamic maneuvering with propulsive orbit phasing gives further benefit, as illustrated by the L/D = 0.4 curves. For large phasing velocities (several thousand ft/sec) it is possible to create a highly elliptic orbit that would permit return within a quick-recall time span for L/D near 0.2; in this case the hazard of passage through the radiation belts must be assessed.

Propulsive Plane Change - In-orbit propulsion can also provide lateral range through plane-change maneuvers. In Fig. 10, a comparison is presented of the weight increase for ballistic vehicles using this maneuver with that for lifting vehicles using only aerodynamic maneuver. A number of such comparisons in the past, e.g., (3) and (14), have used a compilation (16) for the relative weight ratio of aerodynamically maneuvering vehicles shown by the hatched band in the left-hand graph. However, this 1962 compilation embraced a variety of configuration types (a major factor contributing to the band width) and covered

1- to 3-man vehicles only; conclusions involving its use have been dependent upon arbitrary averages drawn through the band and, to a lesser degree, upon the assumed specific impulse of the propulsion system for the ballistic vehicle (see dashed curves; the abscissa for these is the equivalent L/D that corresponds to the range provided by propulsion). Studies of logistics for space stations designed for long-term operation (as contrasted to early minimum concepts) show a preference for logistics vehicles capable of transporting between 9 to 12 men with greater emphasis on 9. The graph at the right presents results derived from recent studies of the weight of logistics vehicles (lower weight concepts were selected if there was comparable in-depth design); a marked decrease in relative weight ratio occurs as the vehicle capacity is increased from 3 to 9 men, which in turn significantly affects the comparison with propulsive plane change. For 9-man vehicles, the weight advantage appears to lie with lifting vehicles if their $L/D \gtrsim 1$; at lower L/D a 9-man ballistic vehicle with propulsive plane change appears competitive with lifting vehicles if the specific impulse is sufficiently high.

Plane Change Versus Increased Entry Velocity - If propulsion is available to lifting vehicles in orbit to extend lateral range capability, a plane-change maneuver is not necessarily the best approach. Several studies have shown, e.g., (17), that vehicles with at least moderate hypersonic performance can, for fuel weights of about 10 percent of vehicle weight, get some 15 to 20 percent better extension in lateral range if the space propulsion is used to increase entry velocity than if the same amount of fuel is expended in a plane-change maneuver. This assumes that the vehicle enters at optimum entry angle and bank angle. The increase in entry velocity associated with this range gain is only some 300 to 400 ft/sec; accordingly, the increase in vehicle weight required to handle the minor increase in the severity of entry environment is negligible.

Recovery Costs - Figure 11 summarizes the effect of recovery costs relative to that for a vehicle having L/D of 1/4, operating in 90° orbit, and with a worldwide land-site network affording quick return for emergencies. At least the primary site is located in CONUS, and for the quick-return results, return to it could involve some wait time. For typical inputs, see (4). Both normal recovery and launch abort recovery costs are included, and the trends shown are representative of launch rates from about 10 to 30 per year. For both quick return and a maximum wait time of 24 hours, increasing the orbit inclination from intermediate to polar markedly increases the recovery costs for low L/D vehicles; also at low L/D, the 24-hour maximum wait time reduces the cost significantly below that for quick return. These results are typical in indicating that most of the reduction in recovery cost occurs as L/D increases to about one.

The dashed curve entered on the graph for 24-hour maximum wait time indicates the recovery costs for this wait time plus unrestricted time for whatever orbit phasing is required to reach CONUS sites only (a maximum of 400 ft/sec phasing velocity was assumed). As shown, the recovery costs at low L/D are greatly reduced by this approach, the remaining gradual decrease in cost with L/D reflecting primarily the cost trend of the boost abort fleet operations, which is the same as that for no-orbit phasing. Thus, if long total return times are acceptable (i.e., wait time plus orbit phasing time) low L/D vehicles can, in normal return, be recovered with relatively small increase in cost over that for higher performance vehicles.

Concluding Remarks - An overview of the foregoing limited discussion of the role of performance in manned logistics spacecraft operations prompts some observations in excess of the usual summation. These are offered here for continuity. In the formulation of these remarks no consideration has been given to possible military requirements.

A requirement for quick return to CONUS appears difficult to justify at this time for routine logistics operations. In some emergencies it would be attractive, but again difficult to regard as essential if quick return can be made to predesignated emergency sites outside CONUS. On the other hand, total time in the return activity approaching two days (as can occur under certain situations for low L/D, single-site CONUS return, involving modest orbit phasing velocities) seems an undesirable opposite extreme. The privilege to return to a primary site in CONUS at least once a day is suggested as a minimum objective for normal operations. This can be assured without resort to propulsive maneuvers in orbit, and for a range of orbit inclinations of most interest to space station activities, with a vehicle having a hypersonic L/D near one. For vehicles with crew capacity of most interest - about 9 men - equivalent ranging capability can apparently also be achieved for comparable total weight with a ballistic vehicle employing propulsive maneuvers in orbit. There is a tendency to interpret the latter conclusion as eliminating any requirement for lifting logistics vehicles whose L/D is less than about one. Aside from the fact that the weight picture may change in the future as it has in the past, weight is not necessarily the overriding criterion for vehicle selection, as pointed out early in the discussion. Other factors such as the alleviation of deceleration forces during entry, point versus zone return, and the ability to compensate for unavoidable operational errors and variations in the atmosphere - so as to insure arrival at the prescribed landing area - point up the need for at least a small amount of lift. Operational studies plus experience in the Gemini program suggest that an L/D capability similar to that of the Apollo spacecraft can essentially fulfill these needs. Thus, if the maximum wait time and minimum return opportunity suggested above are acceptable for space station support, the use of existing semiballistic spacecraft adapted for land landing and with enlarged space propulsion capability seems to be a better solution than building a new lifting entry vehicle.

However, the crew capacity of existing vehicles - even if modified internally to maximize crew capacity - does not approach 9 men; if this or greater capacity is needed for support of long-term space stations, a new logistics vehicle will be required. In this event, the choice of vehicle deserves a critical and fresh examination.

Figure 12 has been prepared as an aid in summarizing a few aspects of the relation between space propulsion and hypersonic performance that would deserve consideration in the choice of a new logistics vehicle. First, there is the minimum ΔV, defined as the total velocity change required for the essential space maneuvers associated with rendezvous, docking, and retro. This minimum ΔV is, by definition, insensitive to L/D since none of it can be counted upon for augmenting return lateral ranging by maneuvers in orbit. Second, there is the minimum L/D defined as that required for g-alleviation and for refining the entry trajectory so as to compensate for unavoidable operational errors, etc., as mentioned above.

This minimum L/D is, by definition, insensitive to ΔV; a value near 1/2 was suggested earlier for this minimum. The minima thus established determine the point A and the horizontal and vertical boundaries stemming therefrom. Trade-off studies would focus on the area above and to the right of these boundaries, respectively, in assessing the merits of providing additional operational versatility through increased L/D and/or ΔV. The vertical bars B-B, C-C, etc., indicate the L/D regimes previously identified as providing special increased capabilities in return operations. These capabilities are noted briefly below and cover orbit inclinations from 30° to 90° unless otherwise noted.

A - Wait times in orbit greater than 24 hours permitted; CONUS recovery; multiple CONUS sites permitted.

B-B - Assures maximum wait time in orbit of 24 hours in return to a single site anywhere in southern CONUS; provides major discontinuous reductions in maximum wait time in orbit for highly inclined orbits; regime of diminishing return in reducing number of worldwide landing sites for emergency quick return to a site network tailored for <u>any one</u> orbit inclination; regime of diminishing return in reducing recovery costs; below this regime, lateral ranging by propulsive plane change appears weight competitive with that by aerodynamic maneuver only, if specific impulse is sufficiently high and crew capacity is about 9 men.

C-C - Assures daylight landing at least once each day; maximum wait time in orbit of 12 hours in return to a single site anywhere in southern CONUS; regime of diminishing return in reducing number of worldwide landing sites for emergency quick return to a site network suitable for <u>all</u> orbit inclinations. (Also assures 12-hour maximum wait time in return to southern CONUS from orbits inclined less than 30°, and quick return to southern CONUS from an equatorial orbit; these cases were not treated in the text.)

D-D - Assures quick return to <u>some</u> point in CONUS from any orbit inclination from 0° to 90°.

E-E - Assures quick return to <u>every</u> point in CONUS from any orbit inclination from 0° to 90°.

There is also the consideration that any of the foregoing benefits can be achieved by increasing the space propulsion capability above the minimum ΔV (launch vehicle payload-limits permitting). In Fig. 12, each line $B-B_1$, $C-C_1$, etc., qualitatively represents combinations of L/D and ΔV for which the lateral range and return versatility are constant. Since space propulsion can be used to increase return versatility, and is essential for rendezvous, docking, etc., an overage in ΔV capability to provide for contingencies is particularly attractive. However, if routine return depends upon a combination of L/D and ΔV, the fuel required for this ΔV should not be regarded as available for other use except in dire emergencies. The possibility of failure to conserve this ΔV gives rise to the obvious, i.e., built-in L/D cannot be inadvertently expended in orbit.

In choosing between additional L/D or ΔV, the answer to the weight question is not always obvious. To illustrate, a representative 9-man Apollo-type vehicle would have an L/D near 1/2 and dimensions of about 16 feet in maximum diameter and 12 feet along its axis of symmetry; a 9-man axisymmetric blunt-base vehicle with about 3 times this L/D (see Fig. 19 in the second part of this paper) would be about 10 feet in maximum diameter and 20 feet along its axis. Both vehicles could employ gliding-parawing-type devices for terminal descent, maneuvering, and land landing; both could employ the Gemini- and Apollo-developed roll modulation techniques for maneuver during entry. The latter vehicle, combining its L/D with sufficient ΔV to eliminate the days of night-only landing for moderate to highly inclined orbits and arbitrary orbit schedules, would weigh significantly less than the Apollo-type vehicle with sufficient ΔV to do the same job. A countering argument could be that the Apollo-type vehicle would better capitalize on developed technology.

The thought here is not an attempt to expose or resolve the many arguments affecting the choice of a new logistics vehicle, but a belief that the choice should reflect, among other considerations, objective evaluation of performance requirements - aerodynamic and propulsive - that will best support long-term space station activity.

Eugene S. Love

PART II: VEHICLE AND LANDING MODE CONCEPTS

This portion of the paper will survey some representative vehicle concepts with particular attention to landing mode. The upper part of Fig. 13 lists some desirable goals* in terminal descent and landing of manned logistics spacecraft. It may be helpful to refer to these in assessing the concepts covered herein; as will be observed, some landing systems now under study and/or development hold promise of meeting most if not all of these objectives.

In the lower part of the figure the landing system concepts that will be considered are shown grouped in two categories. The first, runway landing, denotes aircraft-type approach and landing, and a requirement that the landing area have smoothness, dimensions, and close-by obstacle restrictions comparable to those of ordinary airfields. Under the subheading, propulsion, instant L/D refers to the use of small rockets for a brief period during the final flare maneuver to improve performance; go-around refers to air-breathing propulsion providing landing decision reversal in a go-around flight not exceeding a few minutes; subsonic cruise refers to air-breathing propulsion providing an increase of several hundred miles in range capability, as well as go-around capability.

The second system concept is decoupled modes, discussed in some detail in (18). This category includes landing systems that essentially decouple terminal descent and landing from further dependence on the parent vehicle's continued aerodynamic flight, thereby circumventing the hypersonic-subsonic compatibility problem in configuration design. Several types are indicated.

Low L/D Vehicles - Examples of vehicles in the low hypersonic L/D class are given in Fig. 14. The concept at the left is representative of a number of compact shapes that have been conceived with the objective of runway landing. Both fixed- and variable-geometry types have been proposed. For the vehicle shown, the fixed-geometry version would conform to the solid lines; the variable-geometry version would enter with the form shown ahead of the dashed line, and at low speeds would deploy an inflated afterbody and fins to form the aft shape. A subsonic L/D potential of about 3 is

*See also (2).

common to such vehicles. While research programs have seemingly proved the feasibility of these concepts, the subsonic performance leaves something to be desired. The success of the Gemini program, the development of the Apollo vehicle having competitive hypersonic L/D, and the on-going effort to provide land-landing capability for Apollo types weigh heavily against further development of runway-landing types in this hypersonic performance class. Since Apollo-type vehicles (at the right of Fig. 14) will be strong contenders for early logistics missions, a few aspects of landing systems for these types deserve special mention.

Landing Systems for Apollo-Type Vehicles - An evolutionary survey of this subject is given elsewhere (19). The current Apollo landing system consists of three 83.5-foot-diameter ringsail parachutes. Landing is on water. As illustrated on the right of Fig. 15, the deceleration experienced at impact is strongly affected by the hang angle as defined by the sketch. A nominal hang angle of 28° has been selected as a compromise between excessive deceleration at low hang angles and structural constraints at high hang angles. Still, the impact forces in water landing are sufficiently high to require impact attenuation struts on the crew couches and an increase in structural strength for the heat shield. In adapting Apollo types for land landing, major improvements in the landing system will be required, as indicated by deceleration that would be experienced in landing on hard land. This leads to consideration of both active and passive impact attenuation systems.

As illustrated at the left of Fig. 15, below a certain touchdown velocity (dependent on several factors) the weight of an optimally sized rocket-plus-parachute combination becomes less than that of a parachute only. This has led to investigations of the use of rockets to reduce the terminal descent velocity of Apollo-type vehicles. An example of a rocket installation employed in one such test program (20) is shown in Fig. 16. A reduction from 30 to approximately 5g was accomplished in land landings with this system; even so, the impact is severe enough to make further reduction desirable. In this regard, below a descent velocity of about 15 ft/sec, mechanical impact attenuation systems become more weight efficient than rocket systems. Accordingly, a number of studies and test programs have been evaluating mechanical systems to soften the impact of Apollo types at vertical impact velocities of 15 ft/sec or less, on the assumption that these initial conditions would be produced by the rocket-plus-parachute combination, or by glide-chute devices. Fig. 17 shows representative mechanical system concepts for land-landing that have been examined (21). Ground slopes and the horizontal velocities that might be produced by wind drift or glide chutes are among the factors of concern in evaluating the ability of these systems to prevent overturn while absorbing impact. While feasibility has been established, there is room for innovation. On-going programs call for full-scale testing of the more promising systems under all expected landing conditions.

With the goal of spacecraft reuse, land-landing, and sufficient maneuverability to compensate for moderate winds, avoid local obstacles, and overcome minor but ever-present operational and control errors, gliding parachute-like devices hold special promise. Fig. 18 shows three such devices along with the general range of performance and nominal values of vertical and horizontal velocity for equivalent wing loadings of about one. Recent attention has centered on the parawing and sailwing because of their higher performance potential, the success they have had in personnel-size versions, and the fact that both have weight and volume requirements considerably lower than comparable nongliding canopies; both are being further developed and evaluated in NASA programs with the objective of perfecting the most promising for suspended weights approaching 15,000 pounds. If a device of this type can be developed with this load capability and an L/D of 3, it could provide good wind penetration velocity while keeping the vertical touchdown velocity low enough to allow the use of passive impact attenuation systems only; if the device can be flared in the landing maneuver, further reductions in touchdown velocity are possible. The low landing velocities and maneuverability of these devices would permit emergency landings at unprepared land sites or on water with low risk to the occupants. As with any landing system involving maneuver to a landing point in terminal descent, adequate visibility from the spacecraft will be essential. This presents unique but not insurmountable problems in applying this decoupled landing mode to Apollo-type spacecraft.

Moderate L/D Fixed-Geometry Vehicles - The potential application of the devices just discussed is not restricted to Apollo types but extends to vehicles in almost any hypersonic performance class. Vehicles of the type shown at the left in Fig. 19 are particularly suited to this application. The axisymmetric vehicle would use the reaction-control, roll-modulation technique perfected in the Gemini and Apollo programs for maneuver during entry. It is self-trimming through a small vertical offset of center of gravity in combination with a small bevel-cut at the bottom rear. Landing could be made pointed-nose-forward or blunt-base-forward on simple skids, as indicated at the middle left. For the former, special windows that are equipped with removable thermal covers would be required in the forward cone; suspension in the nose-down attitude shown would improve visibility in terminal descent and landing. The base-forward landing could use the docking windows in the base (see also Fig. 28) which require no thermal covers. This points up another advantage of the fully decoupled mode: the opportunity to employ orientations of the vehicle in landing that are greatly different from those in entry flight so as to exploit certain features to serve both space and landing activities.

The asymmetrical vehicle at the lower left is self-trimming through external contouring, envisions a combination of reaction and aerodynamic control during entry, and might eliminate a need for landing skids by landing on its belly with the "rocker-bottom" shape alleviating impact. The above remarks regarding windows and landing orientation might also apply to this concept.

At the right of Fig. 19, three runway landing types are shown, the NASA HL-10 and M-2/F2, and the USAF X-24. All three vehicles have been built in 1-man versions that are launched from beneath the wing of a B-52 and recovered at Edwards AFB. They can achieve moderate supersonic speeds through the use of rocket engines. The purpose of this flight program is to investigate flying qualities through a speed spectrum representative of the terminal portion of the entry flight that is in close proximity to the landing site, and in so doing, identify problem areas and practical solutions. Wing loading and location of center of gravity are among the variables being studied. As of the date of this writing, only the M-2/F-2 and HL-10 have been flown, and at the lower wing loadings only. Thus far, both vehicles have proven to be landable without the use of their "instant L/D" landing-assist rockets; however, the flights have exposed some undesirable characteristics in the area of control and stability, and remedial modifications have been necessary in some areas.

Inasmuch as the flight program is far from complete, assessment of the merits of this class of vehicles is in many respects premature. Moreover, subsonic performance is not in each case up to the vehicle's potential, nor have already-defined straightforward modifications that would improve performance and/or handling qualities been incorporated in the fin-elevon regions. Nevertheless, and with pragmatic recognition that better designs are possible (a view hardly peculiar to this vehicle class), an objective view cannot ignore the more complex features, the implications of the high descent rates at start of flare and the order-of-magnitude higher landing velocities of these vehicles as compared with the decoupled landing types on the left. Thus, if reliable large parawings or sailwings as described earlier are developed successfully, a better case than has yet developed from considerations of logistics missions only will be needed to regard unpowered runway landers of this type (and other types to be mentioned subsequently) as serious contenders for the role of manned logistics spacecraft. The inclusion of go-around propulsion, and thus close-in decision-reversal capability and control of descent rate and flare-initiation altitude, would place these runway landers in a more competitive position, for about 10-percent increase in total vehicle weight (9-man vehicle).

High L/D Fixed-Geometry Vehicles - Fig. 20 illustrates several concepts that have been proposed in this class, ranging from the older wing-body concept at the top to the newer lifting-body types at the bottom. As shown, the latter have low subsonic performance in unpowered flight; accordingly, propulsion assist in the form of "instant L/D" or a go-around engine would be a desirable if not an essential aid to landing. However, even with the higher effective L/D of propulsion assist, the low aspect ratio of the more recent concepts could be expected to generate special (but not necessarily insuperable) subsonic problems in handling and stability, and the landing velocities would remain high. It is not surprising, therefore, that increased attention has been given to variable geometry (i.e., deployable rigid wings from here on) with the hope of retaining the advantages of the lifting-body types at hypersonic speeds while easing the terminal descent and touchdown conditions for runway landing.

Variable-Geometry Vehicles - Several variable-geometry concepts are shown in Fig. 21, along with names generally used in referring to the type of wing and its deployment, and representative values of hypersonic and subsonic L/D. Most concepts envision deployment at high subsonic speeds, although some would employ partial deployment as a stability aid in negotiating the transonic regime; a few consider deployment at low hypersonic speeds. With the exception of the stubby drop-wing types, most blunt-based variable-geometry configurations yield a subsonic L/D between 5 and 9. The debates over the merits of blunt-base versus boattailed-base appear to hinge primarily on transonic aerodynamics, the ideas for best handling booster mating, crew transfer, and docking concepts at the space station, plus what is regarded as ample subsonic performance; there is no question that the highly boattailed types, as illustrated by the configuration at the bottom, are capable of higher subsonic performance. It is evident that variable geometry does not provide as much freedom from the hypersonic-subsonic aerodynamic compatibility problem as the fully decoupled landing modes, since the body shape and the stability and control surfaces continue to play a strong role in the subsonic flight characteristics. Nevertheless, if runway landing becomes a requirement, this feature can provide operational improvements, e.g., (22). To achieve these requires close attention to the improvement in lift as well as L/D; in general, variable-geometry concepts have landing velocities that, while reduced from those of their fixed-geometry competitors, remain sufficiently high to be subject to the same criticisms and to suggest propulsion as a desirable aid to landing. Weight, complexity, transient aerodynamics during the wing deployment phase, and incorporation of go-around propulsion are other areas requiring better definition in these concepts.

Variable-Geometry—Subsonic-Cruise Vehicles - One argument advanced in support of the high subsonic L/D attainable by variable-geometry types is the possibility of exploiting this performance by the addition of subsonic-cruise capability to create a vehicle with onboard-payload and lateral-range capability applicable to a broad mission spectrum. This is illustrated qualitatively in Fig. 22. Generally, hypothesized logistics missions develop considerably higher payload requirements than certain envisioned military missions, whereas the reverse is true for lateral-range requirements. These diverse requirements are indicated by the position of the shaded areas and the solid lines depicting the level of payload weight for moderate and high L/D vehicles. The gliding-vehicle boundary is the envelope of the right-hand termini of such lines and represents the trend of decreasing payload weight with increasing hypersonic performance. The dashed lines depict the increase in lateral range and reduction in payload caused by increasing the in-orbit propulsion capability beyond that reserved for rendezvous, docking, etc. The line whose dotted portion represents subsonic cruise illustrates two advantages claimed for this approach: first, by optimum combination of hypersonic L/D, subsonic L/D, and subsonic-cruise capability, a vehicle can be designed that covers the large lateral-range requirements of certain military missions while retaining enough payload capability to be of interest for many logistics missions; second, as lateral range is increased by propulsion (excluding modest increases beyond that provided by hypersonic L/D only) the optimum vehicle employing subsonic cruise exhibits increasing payload advantage over a vehicle of the same hypersonic performance but employing in-orbit propulsion for range extension. Convincing substantiation of these claims awaits detailed design and system studies. Examples of recent variable-geometry concepts embodying subsonic-cruise capability are shown in Figs. 23 and 24, the former having fixed engines and the latter* featuring retractable engines. Clearly, such vehicles present challenging problems in systems integration. These concepts, of course, provide runway landing with decision-reversal capability equivalent to that of current aircraft.

Deployable Rotor Vehicles - The deployable rotor is also receiving attention as a possible decoupled landing mode for ballistic and lifting entry vehicles, e.g., (23) to (25). A representative deployment sequence for a high L/D vehicle is illustrated in Fig. 25. For vehicles with at least moderate hypersonic performance, rotor deployment is generally conceived to occur at subsonic speeds. Following initial deployment in a trailing position, the rotor undergoes aerodynamic spin-up, and

*A Convair concept.

centrifugal force extends the blades in an opening cycle that is rapid, smooth, and devoid of opening shock loads. Stability and control during the transition and gliding flight are maintained manually through cyclic pitch of the rotor. By use of a coordinated cyclic and collective flare maneuver, low-velocity landings in small landing areas can be performed, much as have been performed for some time in power-off autorotative landings of helicopters. This final flare uses the stored kinetic energy of the rotor to reduce approach velocities from some 70 or so ft/sec to less than 10 ft/sec. The rotor is generally estimated to augment the vehicle's steady subsonic glide L/D by increments of 3 to 4. Weight estimates of deployable rotor systems vary between about 7 and 14 percent of the total vehicle weight. Simulator studies have shown that the rotor provides more than adequate control power to maneuver to desired landing points. Lightweight rockets on the tips of the rotor blades have been suggested as a means for providing partial power descent and/or limited hover capability with essentially zero velocity at touchdown.

For ballistic vehicles the rotor has been studied as a means for providing both low touchdown velocities and signficant hypersonic performance. This calls for rotor deployment under high heating conditions; rotors made of nickel superalloys operating at temperatures up to about 1700° F offer a possible solution. The hypersonic L/D claimed for a rotor applied to a ballistic vehicle varies with the type of installation, but values are usually near 1.

While there appear to be no insoluble problems in the deployable rotor concept, and many ingredients of such systems have been flight tested at low speeds, each configuration appears to generate special stowage, deployment, and/or operational difficulties. It is becoming increasingly evident that, with few exceptions, the better concepts are designed with this landing mode in mind from the outset, as against equipping existing configurations with deployable rotors. (This design philosophy applies equally well to some other landing modes, notably variable geometry.) In addition, current methods for estimating rotor aerodynamic characteristics in autorotation need better verification (even if new methods are developed), particularly for the higher disc loadings.

The promise of higher subsonic performance, better wind penetration, better maneuverability, and lower touchdown velocities than are presently foreseen for parawing-type devices, at a weight expense no greater (and possibly less) than that incurred by variable geometry, has prompted increased interest in the deployable rotor, and suggests the need for more detailed design and operational studies to determine if these advantages can be realized within practical constraints.

<u>Propulsive-Lift Vehicles</u> - Technology and operational experience developed for and by VTOL aircraft and NASA's Lunar Landing Research Vehicle, Fig. 26, and Lunar Excursion Module have given rise to the possibility of acquiring the landing versatility of propulsive lift for spacecraft landing on Earth. A recent feasibility study has been made of this decoupled landing concept (26). The terminal phase of entry might be accomplished as indicated in Fig. 27. At moderate supersonic speeds a single drogue is deployed, assuring stable deceleration through the transonic regime; a second drogue provides further subsonic braking until main parachute deployment. Lift engines are started at an altitude near 10,000 feet, allowing a 5-minute checkout and power-increase period prior to parachute jettison under conditions of low descent rate at an altitude near 100 feet. Powered flight on the lift engines is then made to the desired touchdown point.

An example of an axisymmetric 4-man vehicle in the moderate hypersonic L/D class designed for this decoupled landing mode is shown in Fig. 28. It features two lift engines, an "on-off" control concept through use of the same attitude control system employed in space and entry, and emergency landing rockets serving the dual purpose of reducing the sink rate at touchdown to zero if the lift engines failed to start, and safe landing in the event of engine failure while hovering or translating close to the ground; reliability studies of the lift engines indicate that either emergency condition is highly unlikely. This concept has a 5-minute hover time capability with low-level ranging capability of several miles. Good visibility in terminal flight is obtained by facing the "barber-chair" seats rearward, using the large docking windows in the base, and flying the vehicle base-forward. Simulator studies have demonstrated good handling and control characteristics, and that transition from parachute to lift engines can be accomplished with relative ease.

The propulsive-lift landing concept provides close-in decision reversal, relaxes the normal landing point restraints from runway-type dimensions and smoothness to point touchdown on land surfaces with moderate irregularities, and, in short, gains all the advantages of near-zero vertical and horizontal velocities during terminal approach, descent, and touchdown at normal and unprepared sites.

Of course, this landing versatility comes with added system complexity (the same can be said for some other modes, such as variable geometry) and the obvious question of weight expense. With regard to the latter, Fig. 29 presents the ratio of the total weight of the HL-10 fixed-geometry runway lander (Fig. 19) to that of the propulsive-lift configuration of Fig. 28, both being in the same hypersonic performance class and sized for the same crew and mission. Compared to the HL-10 without capability for emergency landing at unprepared sites, the propulsive-lift concept is significantly heavier; however, when the HL-10 is equipped with its emergency parachute and made more competitive in landing versatility by the addition of go-around propulsion, the two concepts weigh approximately the same. Even so, the powered runway lander clearly does not have the versatility of the propulsive-lift type in landing at normal and unprepared sites.

If the fuel, lift engines, main parachutes, and emergency landing rocket systems were removed from the propulsive-lift configuration in Fig. 28 and replaced with a large parawing (or sailwing) and an identical backup for emergency, the vehicle could accommodate 9 men with approximately the same total weight as the 4-man propulsive-lift version. Although the landing versatility of this parawing version could not match that of the propulsive-lift version (in such areas as close-in decision reversal, wind compensation, and freedom in choice of touchdown point), it would be sufficiently competitive to lend support to the case made earlier for the development of large parawings and for their application to simple vehicle shapes of appreciable hypersonic performance.

While landing of spacecraft on Earth by propulsive lift may lie in the distant future, the systems to accomplish it are developed and improvements can be expected. Landing by all-rocket systems with direct transition from entry flight to rocket-powered terminal descent (no parachute transition phase) may be the eventual mode, e.g., (27).

Concluding Remarks - In this limited survey of vehicle and landing mode concepts, many aspects have been omitted. Illustrative of these are considerations related to advanced two-stage, fully reusable, manned logistics concepts (28). These will be left for the reader to pursue, but it is noted here that such studies generally advocate 9- to 12-man capacity in the spacecraft, moderate aerodynamic maneuver capability, and conclude that the most logical first development step appears to be a reusable spacecraft.

There is little question that logistics spacecraft should be designed for land landing in routine operations, and provide high confidence for crew survival in the event of emergency landing at unprepared land sites or on water. As for landing mode, the following observations are offered.

First, the simplicity of parawing-type devices combined with their lightweight, low landing velocities, and apparent ease of application to simple lifting-body shapes covering a broad L/D spectrum, holds promise of both early and long-term application, provided they can be developed in large size without sacrifice in reliability.

Second, if runway landing emerges as a requirement for advanced logistics spacecraft, limited propulsion for landing assist and go-around will be desirable, if not essential. If both runway landing and moderate-to-high hypersonic performance become requirements, vehicles employing variable geometry (deployable rigid wings) will be strong candidates. This is not to say that no further interest exists in fixed-geometry concepts; there is a distinct lack of studies aimed at identifying trade-offs between fixed- and variable-geometry concepts that are designed from the outset to use go-around propulsion systems in normal operation.

Third, deployable rotors and propulsive lift deserve further study. The deployable rotor shows promise of better operational versatility and performance than presently foreseen for parawing-type devices, at a weight expense no greater than that for variable geometry. Propulsive lift may lie farthest in the future of all modes envisioned to date for landing spacecraft on Earth, but it also has the potential for greatest landing versatility and the eventual use of common systems for both space maneuvers and landing.

Eugene S. Love

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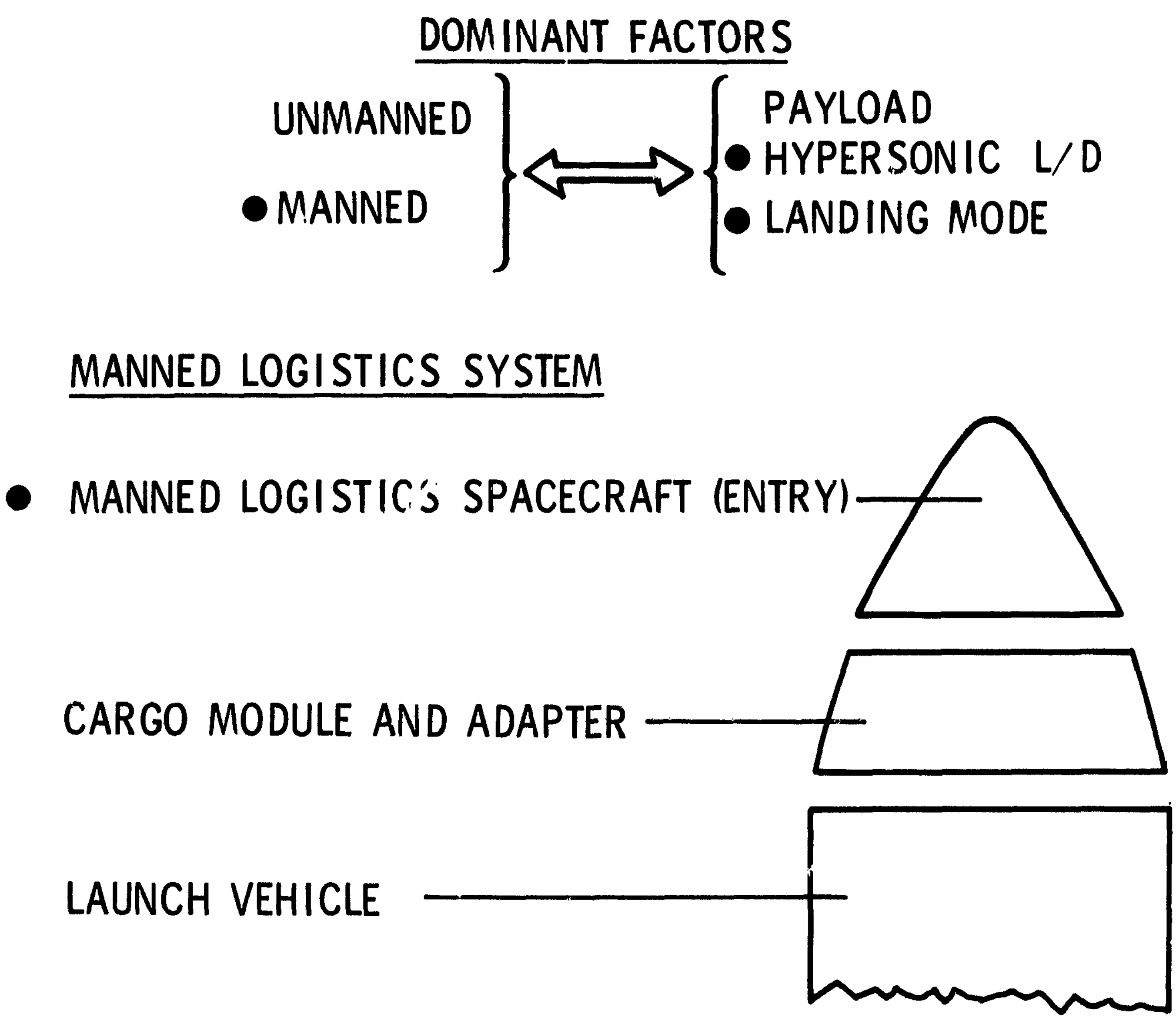


Figure 1.- Dominant factors configuring logistics spacecraft.

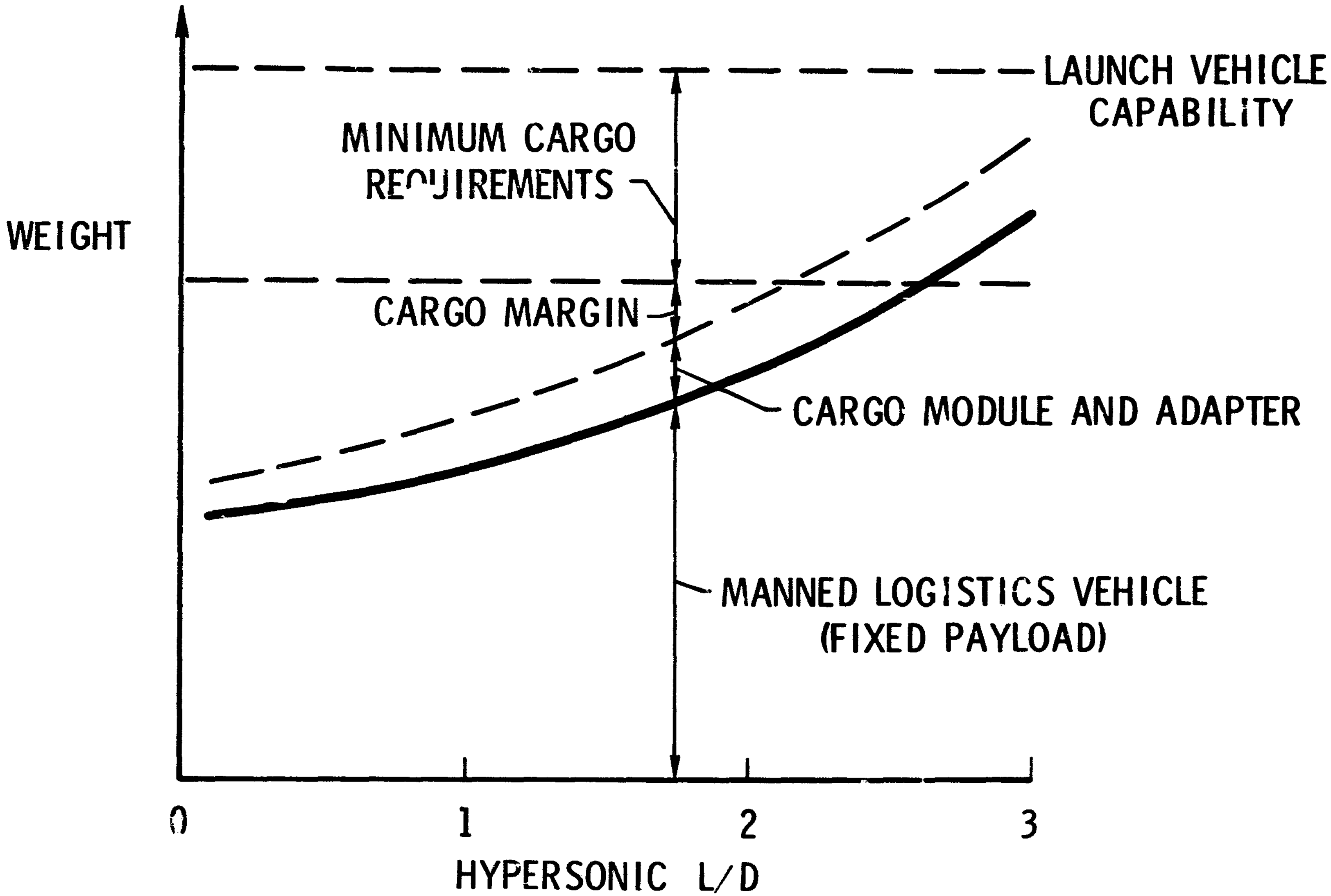


Figure 2.- Logistics vehicle performance and cargo requirements.

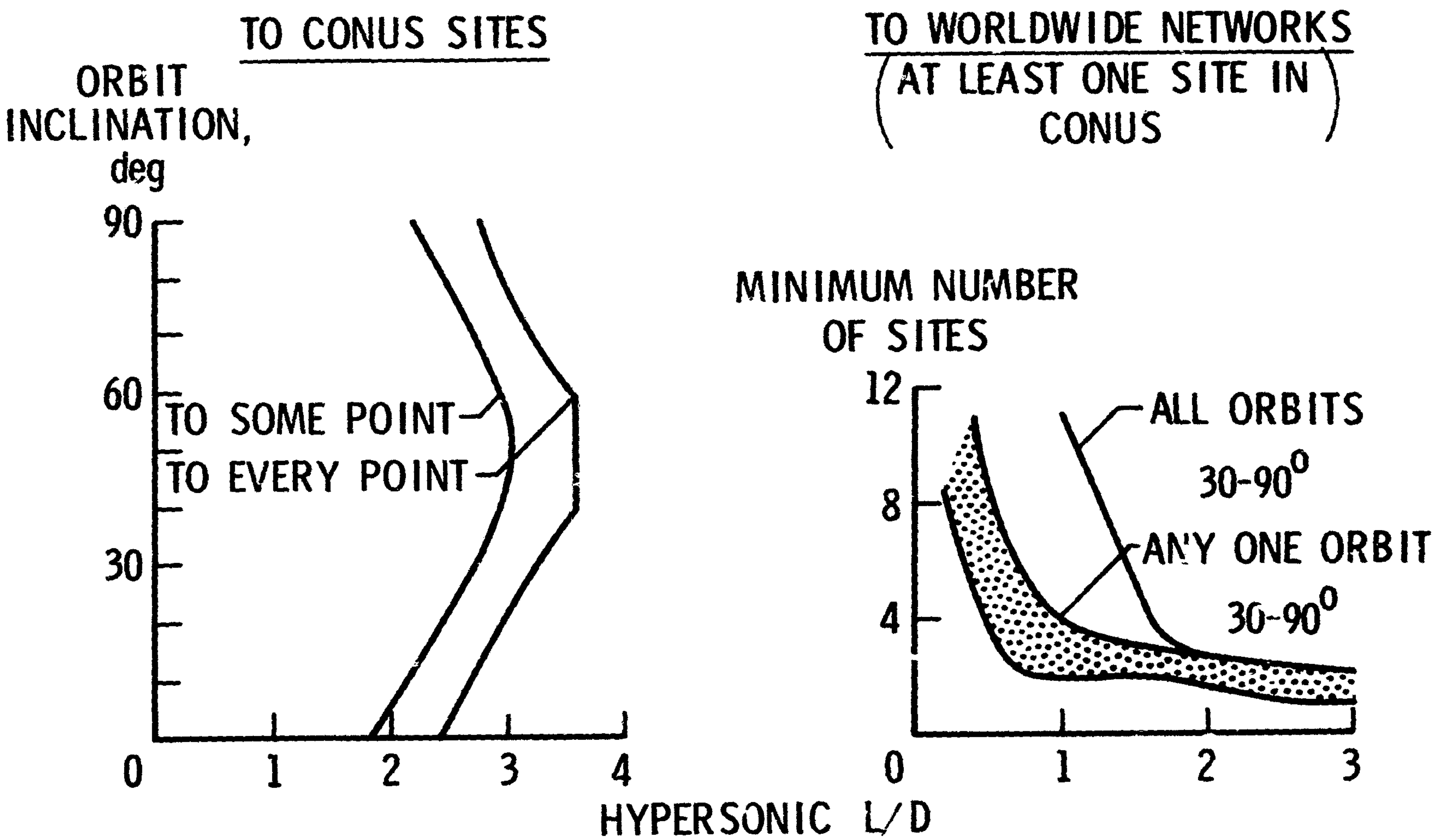


Figure 3.- Quick return from orbit.

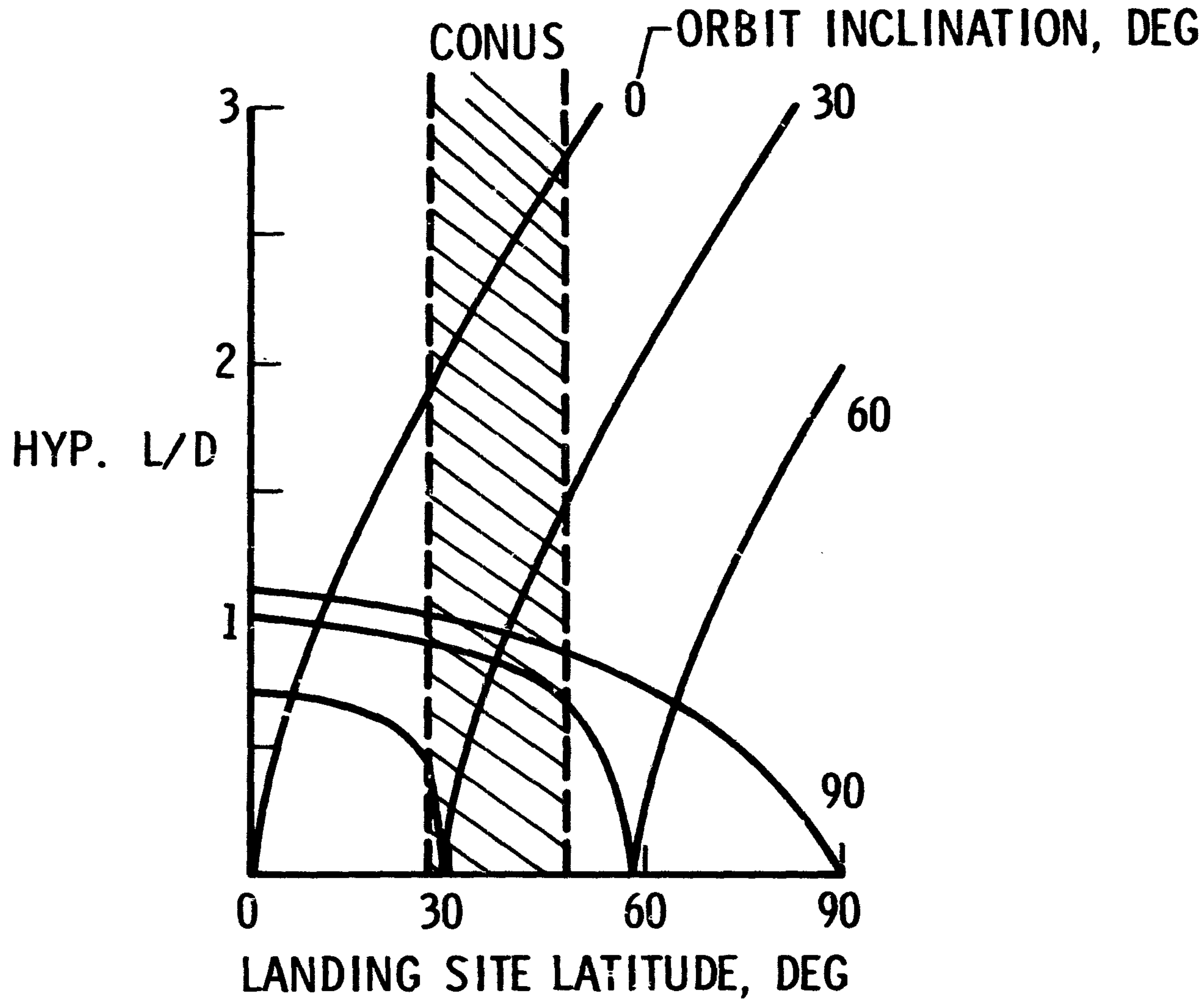


Figure 4.- Delayed return to single site, varying maximum wait time (12 to 24 hrs).

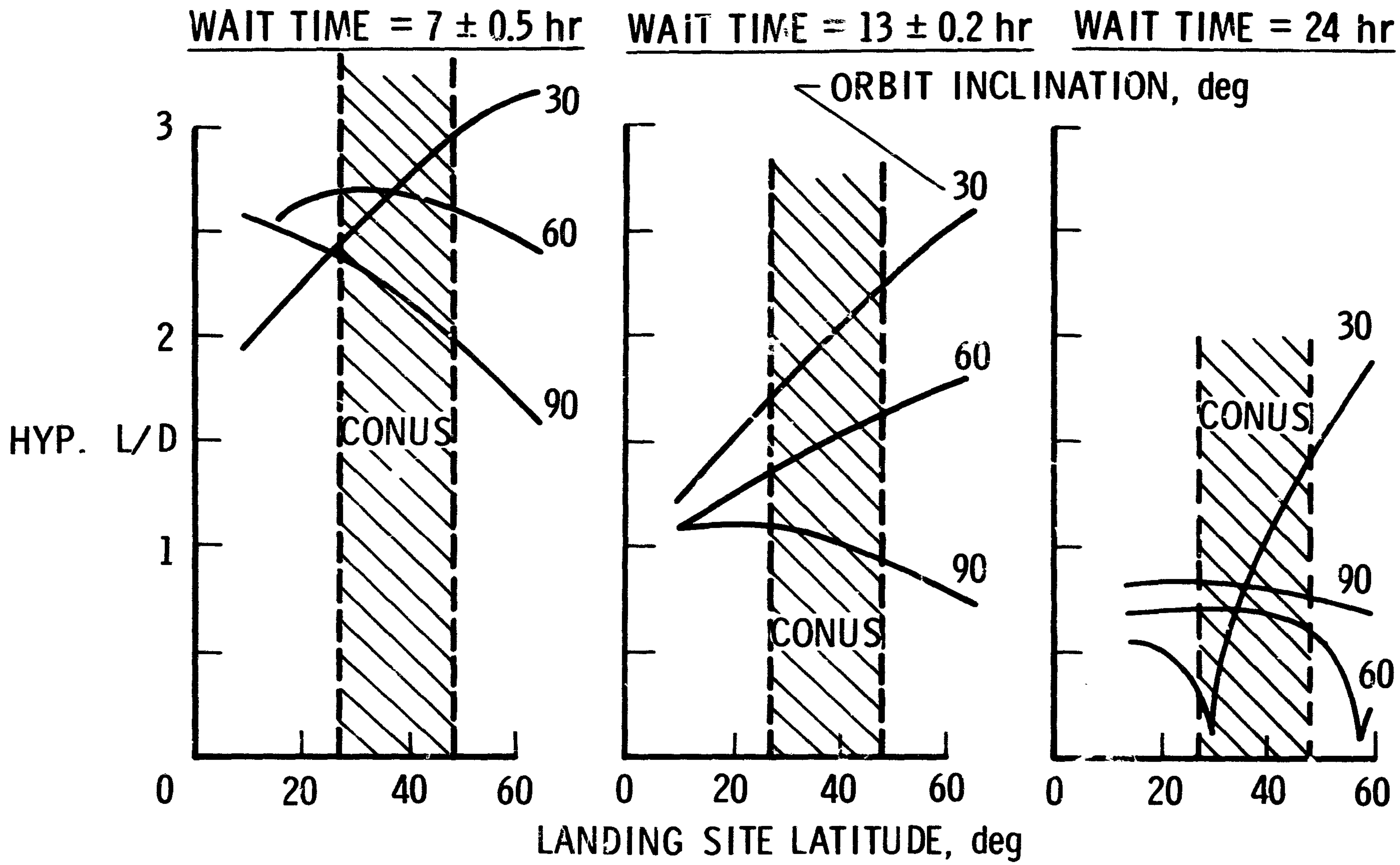


Figure 5.- Delayed return to single site, fixed maximum wait time.

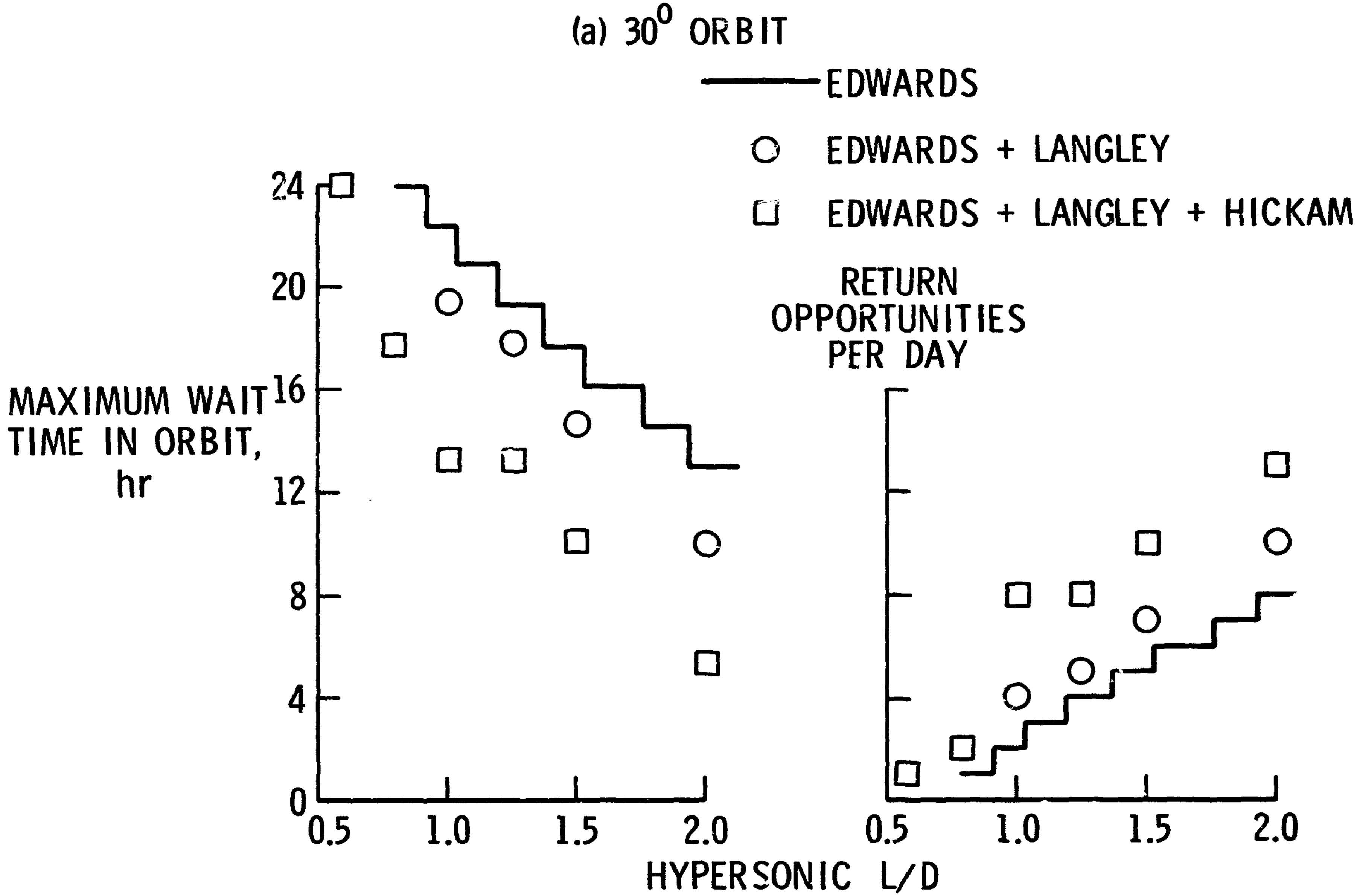


Figure 6.- Effect of maneuverability on maximum wait time and return opportunities to single and multiple CONUS sites.

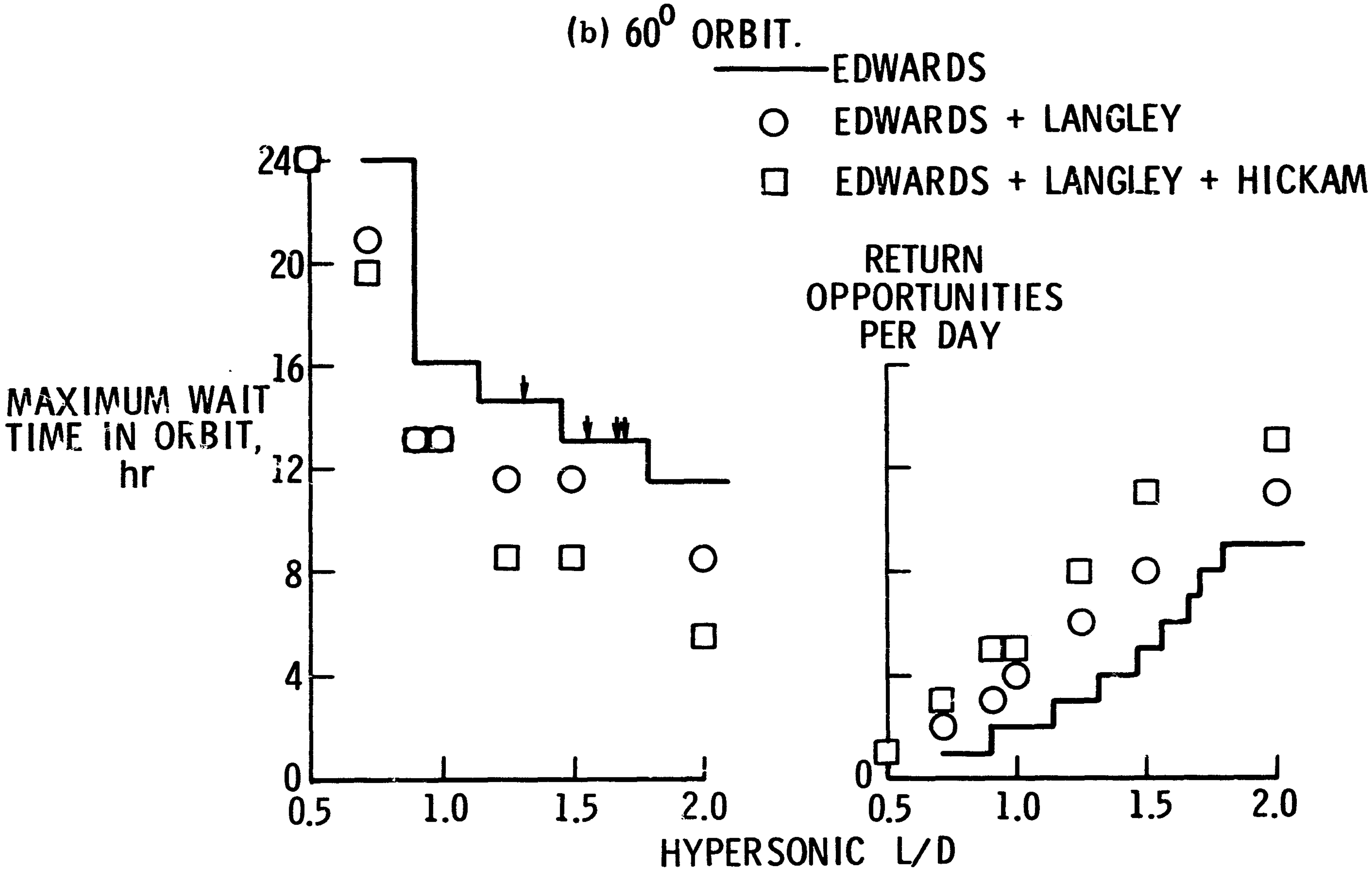


Figure 6.- Continued.

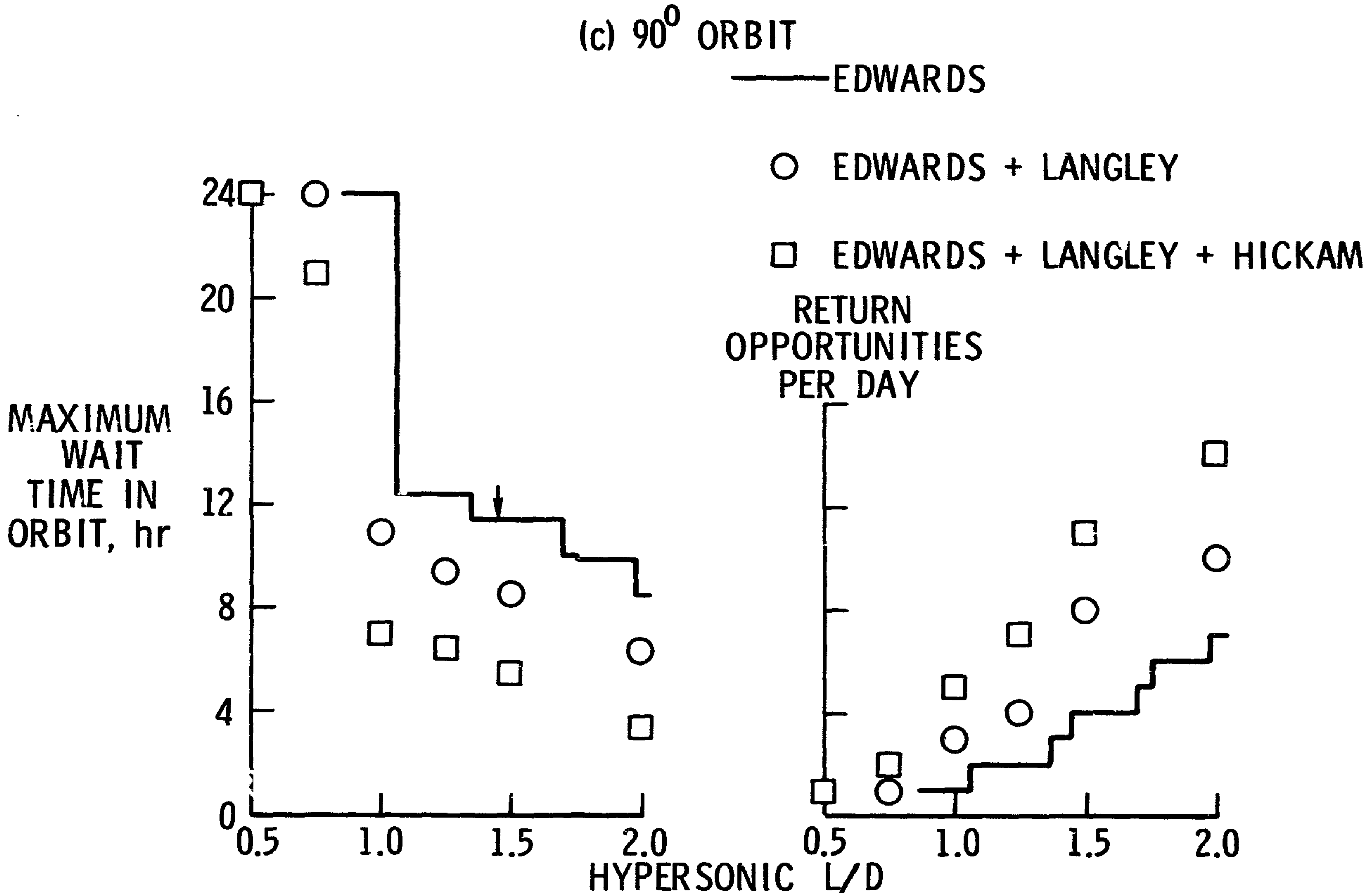


Figure 6.- Concluded.

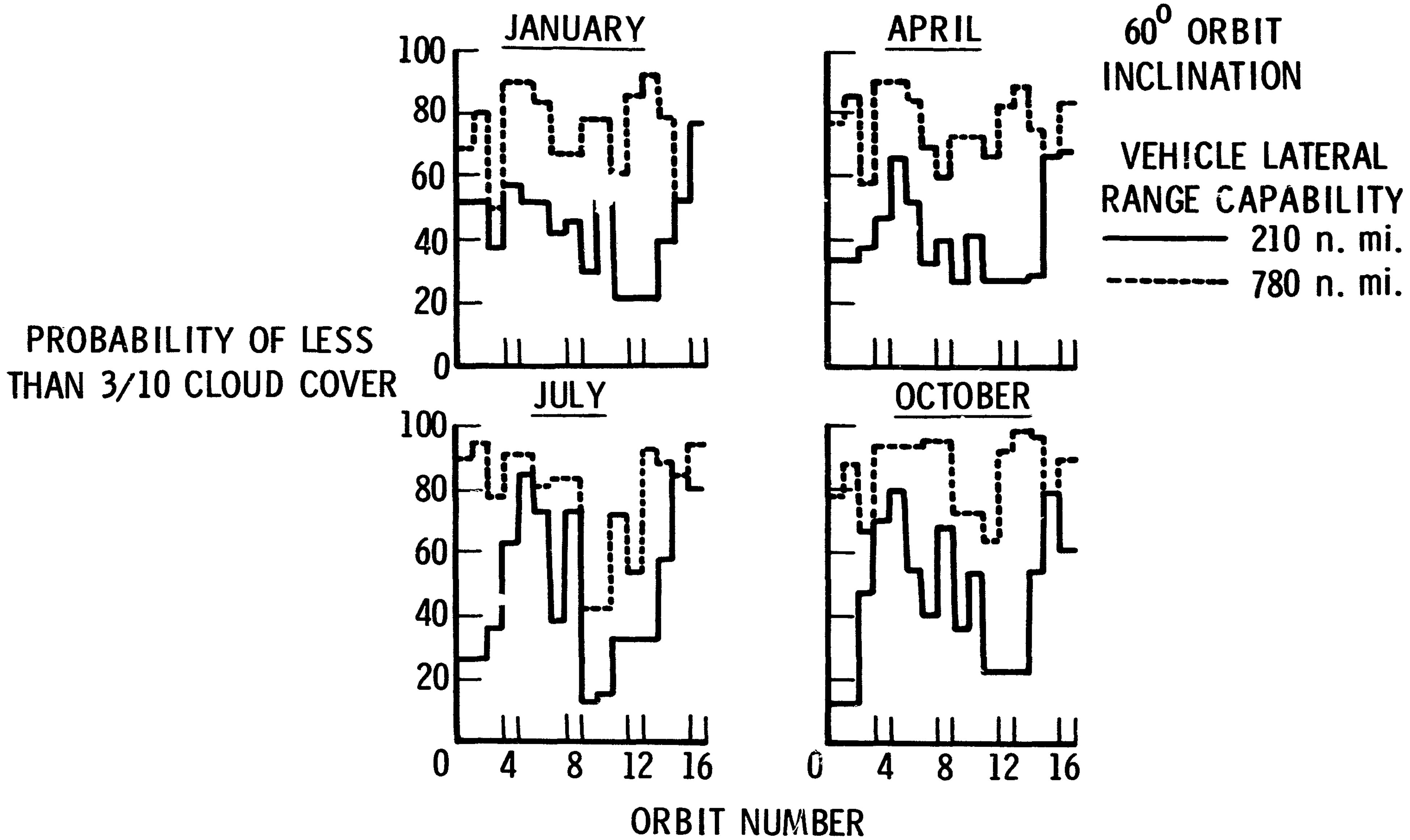


Figure 7.- Effect of maneuverability on probability of clear weather land recovery in return to 10-site network.

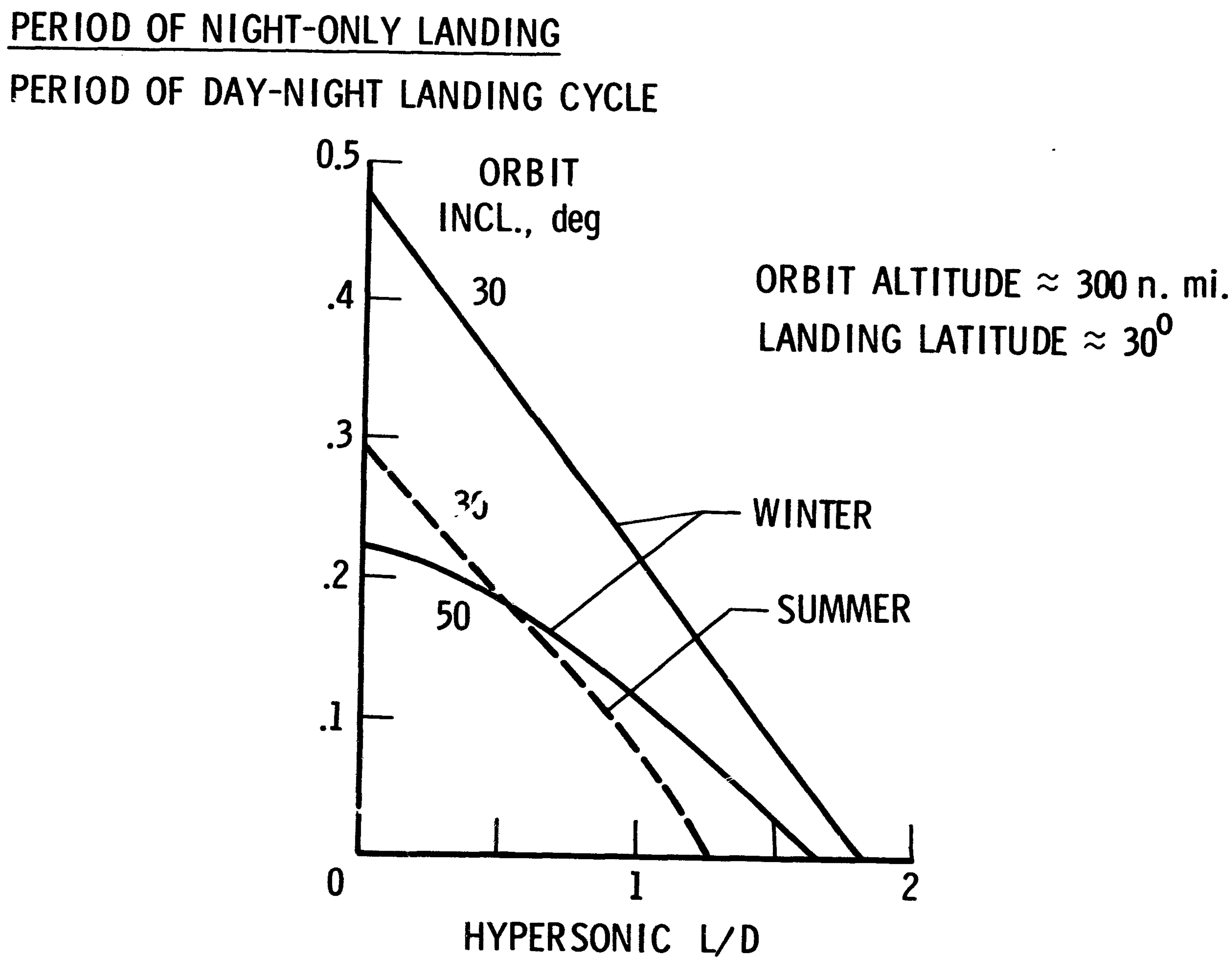


Figure 8.- Reduction in night-only landing periods by increased maneuverability.

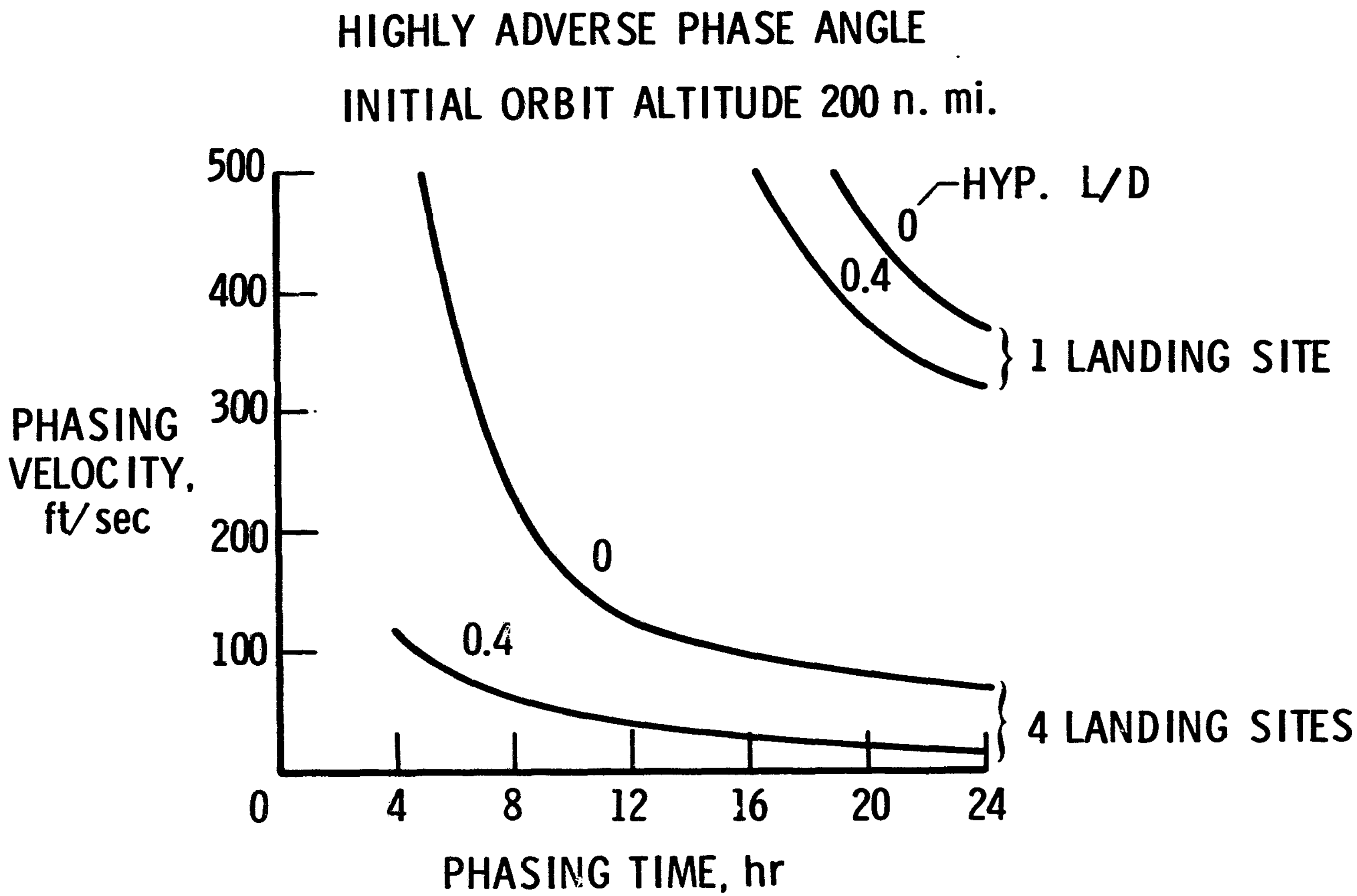


Figure 9.- Return to CONUS by use of orbit phasing.

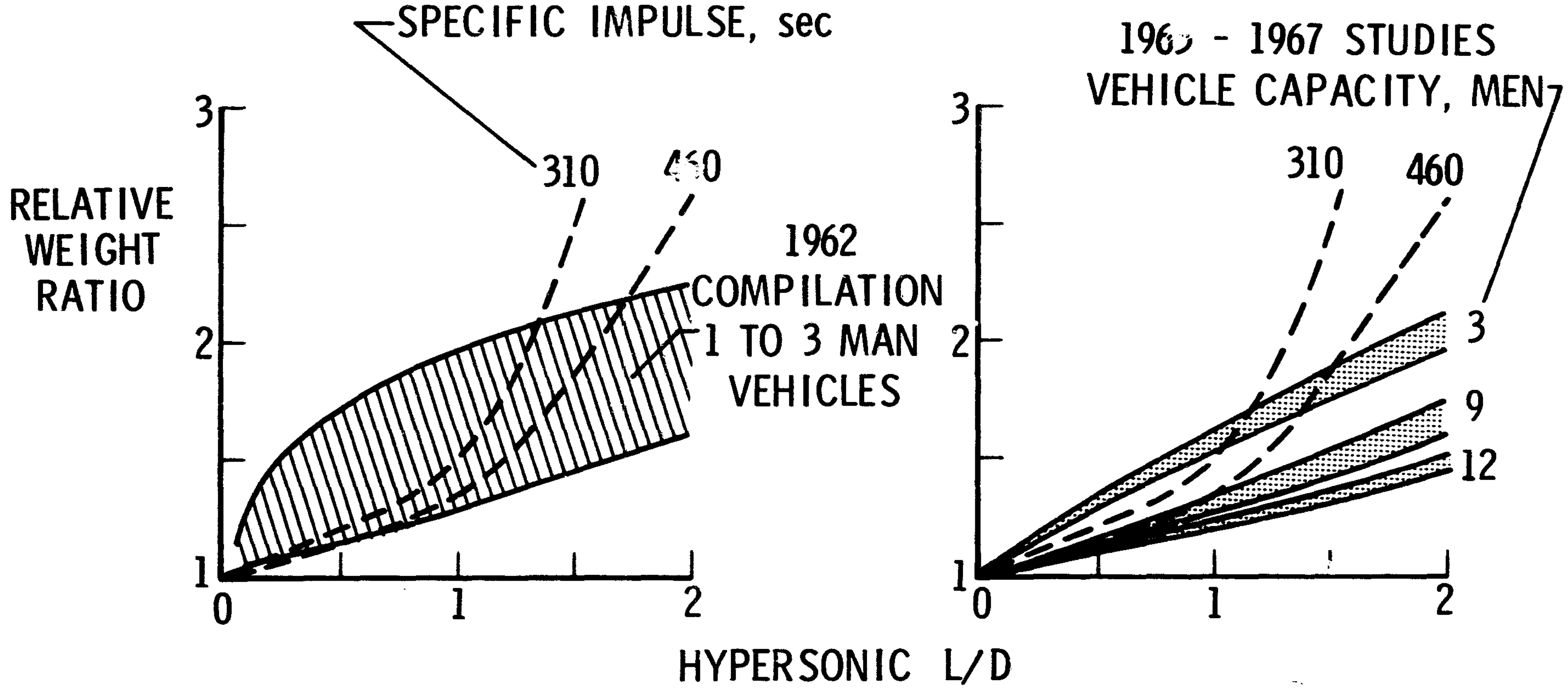


Figure 10.- Comparison of weight trends to obtain lateral range, propulsive plane change versus aerodynamic maneuver.

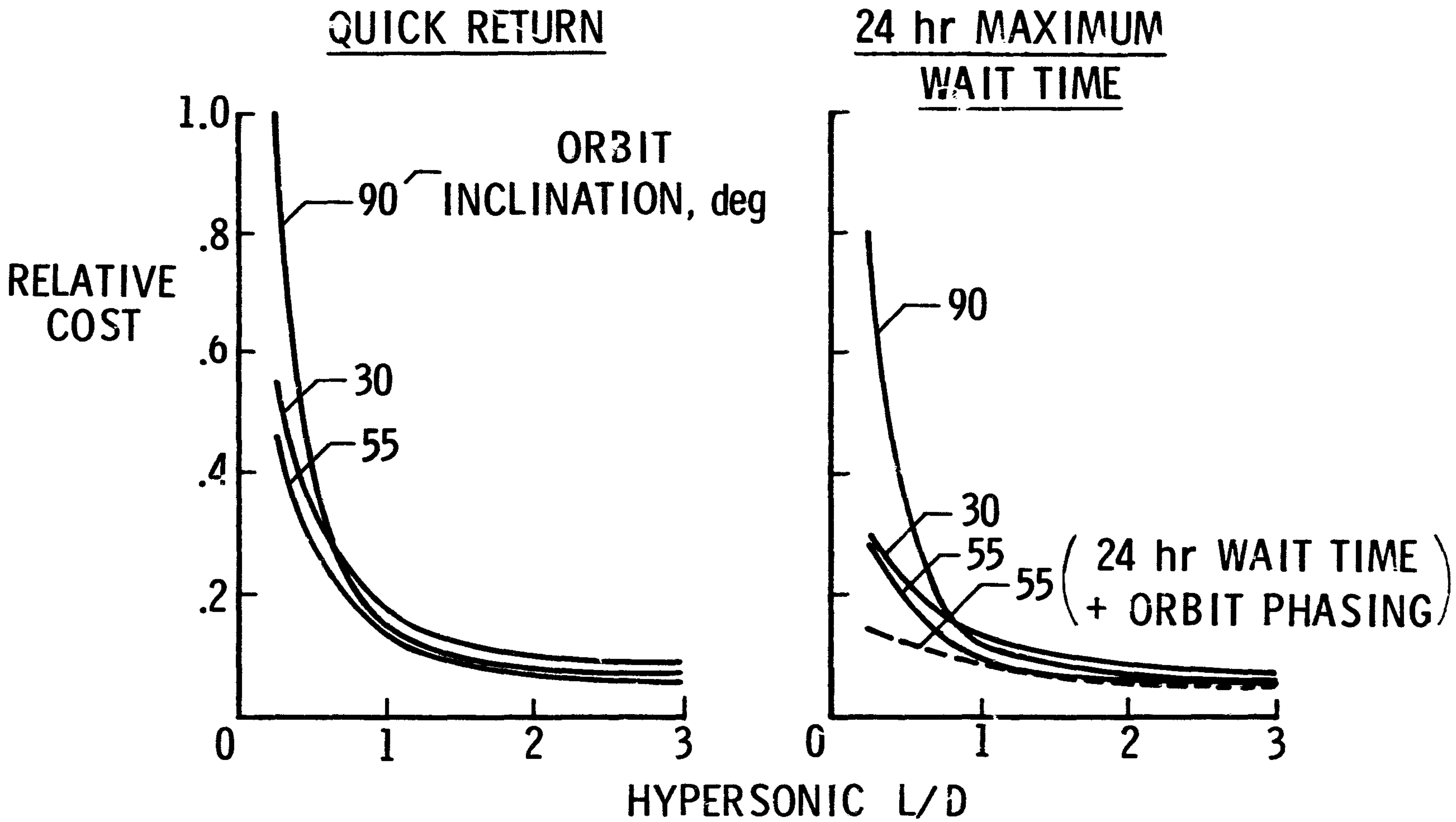


Figure 11.- Recovery costs.

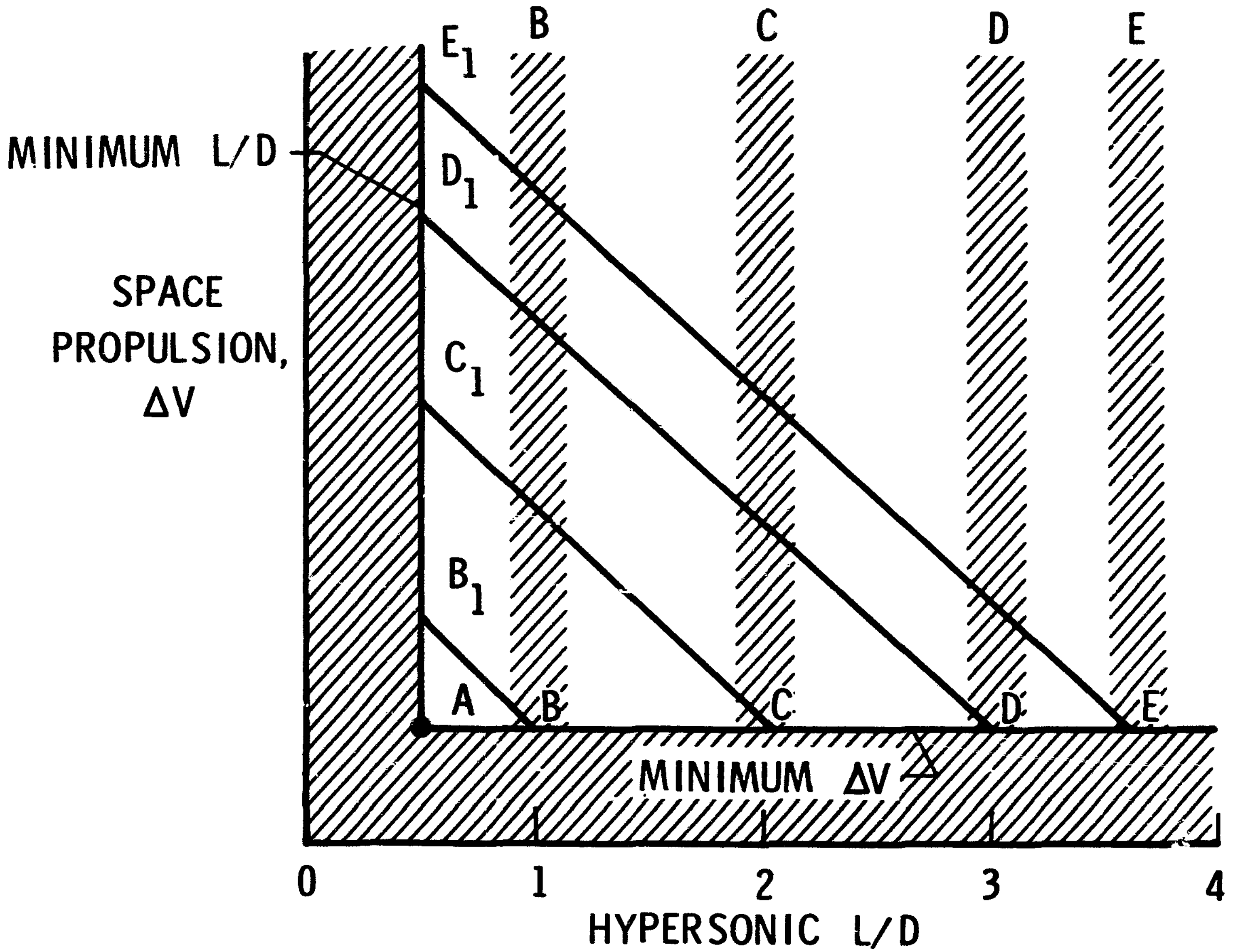


Figure 12.- Space propulsion and hypersonic L/D considerations in logistics missions.

DESIRABLE GOALS

- LAND LANDING (SMALL ZONES)
- LOW VERTICAL AND HORIZONTAL TOUCHDOWN VELOCITY
- SAME SYSTEM FOR LANDING AT NORMAL AND UNPREPARED SITES (LAND OR WATER)
- PRECISE MANEUVERING TO LANDING ZONE; COPE WITH WINDS, OBSTACLES
- LOW SENSITIVITY TO WEATHER AND NIGHT
- NEGLIGIBLE COMPROMISE OF HYPERSONIC CONFIGURATION
- CLOSE-IN DECISION REVERSAL
- SIMPLE, RELIABLE, LIGHTWEIGHT

SYSTEM CONCEPTS

- RUNWAY LANDING: UNPOWERED GLIDE (FIXED AND VARIABLE GEOMETRY)
  PROPULSION (INSTANT L/D, GO-AROUND, SUBSONIC CRUISE)
- DECOUPLED MODES: PARACHUTES, GLIDING CHUTE-LIKE DEVICES, ROTOR, PROPULSIVE LIFT

Figure 13.- Terminal descent and landing of spacecraft.

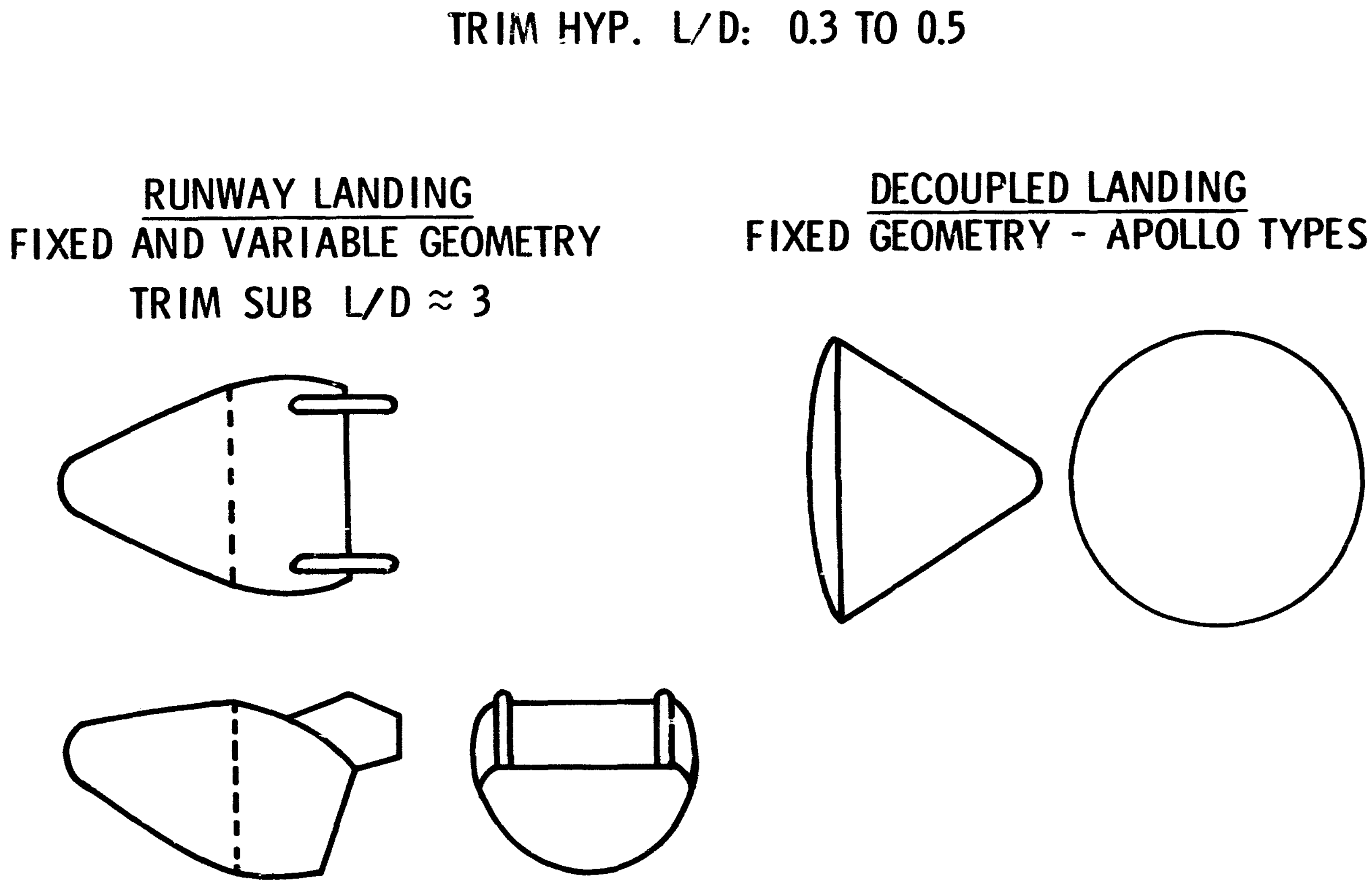
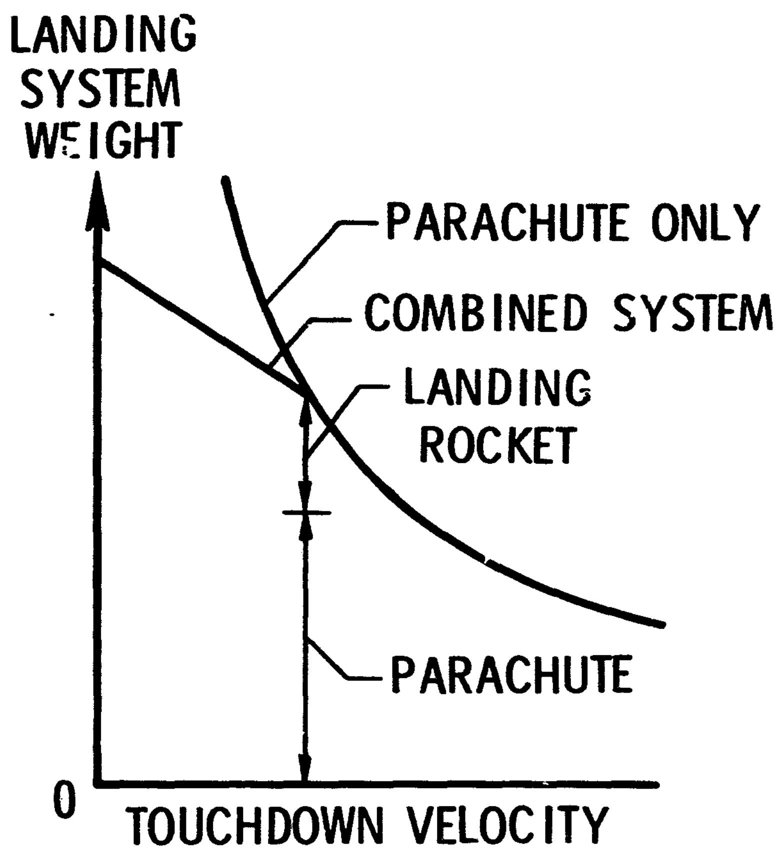
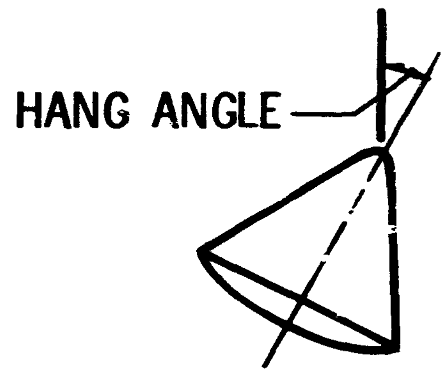


Figure 14.- Low hypersonic L/D vehicles.

WEIGHT OF PARACHUTE-ONLY AND PARACHUTE-LANDING ROCKET



PARACHUTE -ONLY DESCENT



HANG ANGLE, deg	SURFACE	G's
0	WATER	40
28	WATER	8
38	WATER	4
28	LAND (HARD)	30 TO 40

Figure 15.- Water versus land landing by parachute for Apollo types.

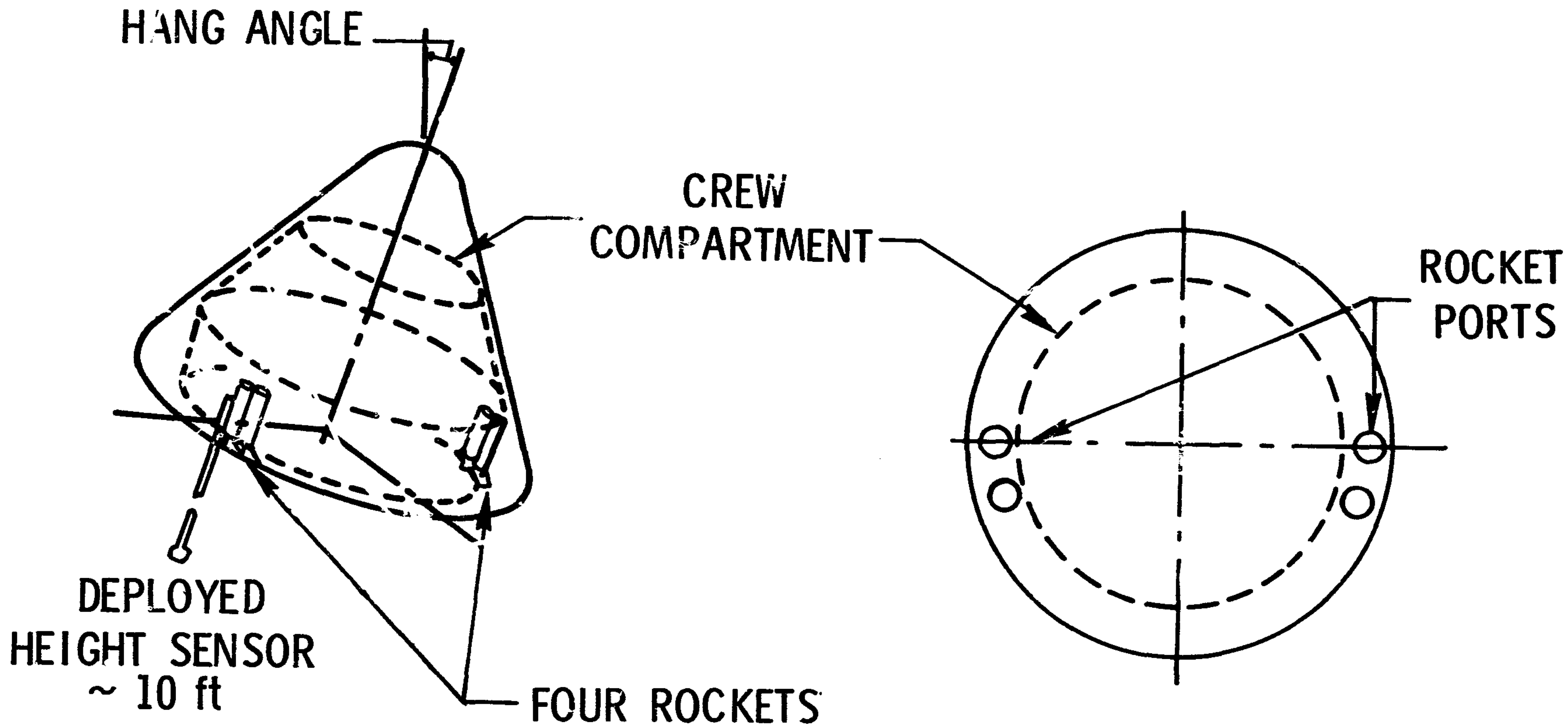


Figure 16.- Terminal landing rocket systems for Apollo types.

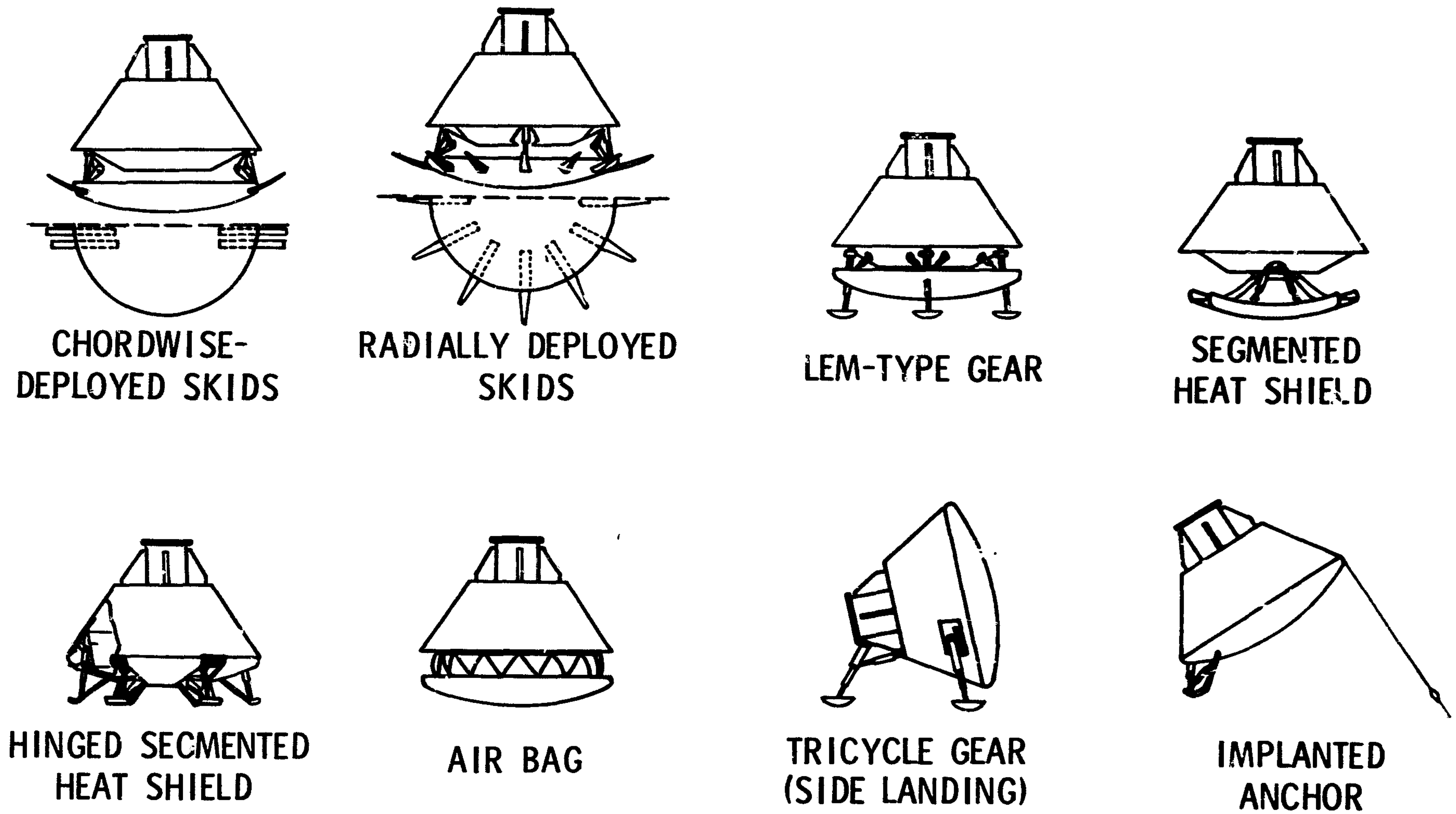
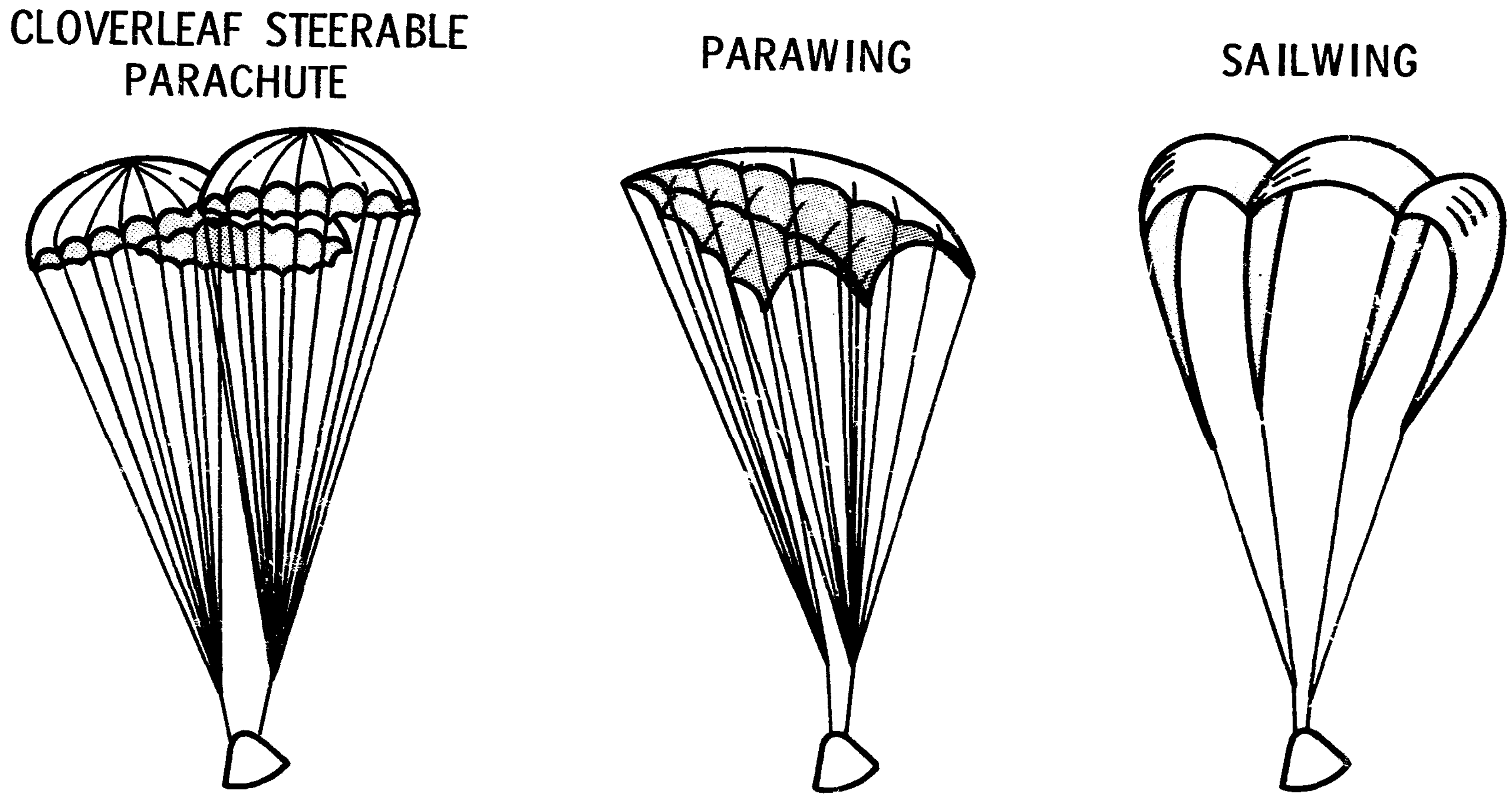


Figure 17.- Mechanical systems to reduce ground impact loads for Apollo types.



	Cloverleaf steerable parachute	Parawing	Sailwing
L/D	0.7 TO 1.6	2 TO 3	2 TO 3
V_V ft/sec	16	10	10
V_H ft/sec	25	25	25

Figure 18.- Decoupled landing: gliding parachute-like devices.

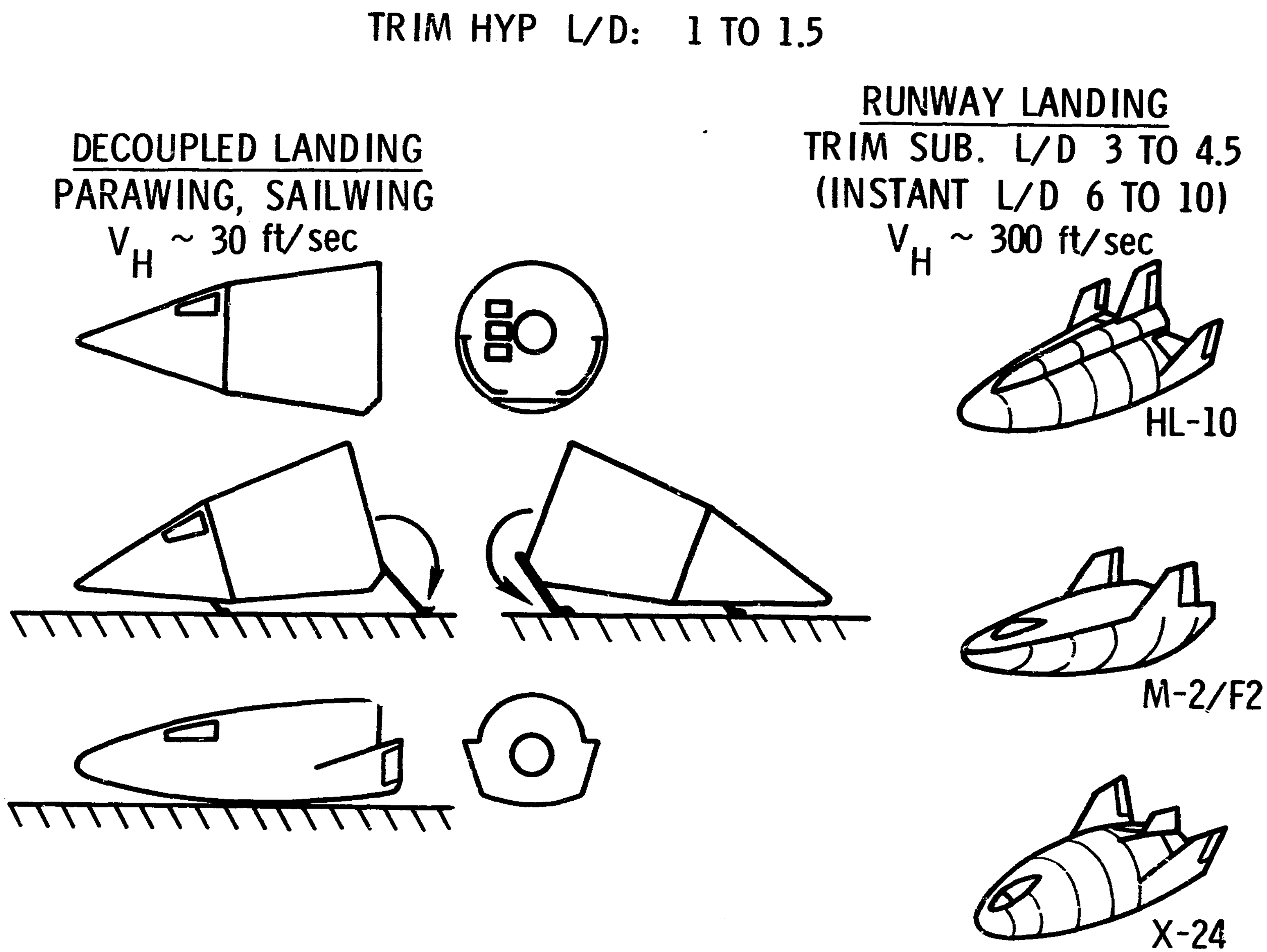
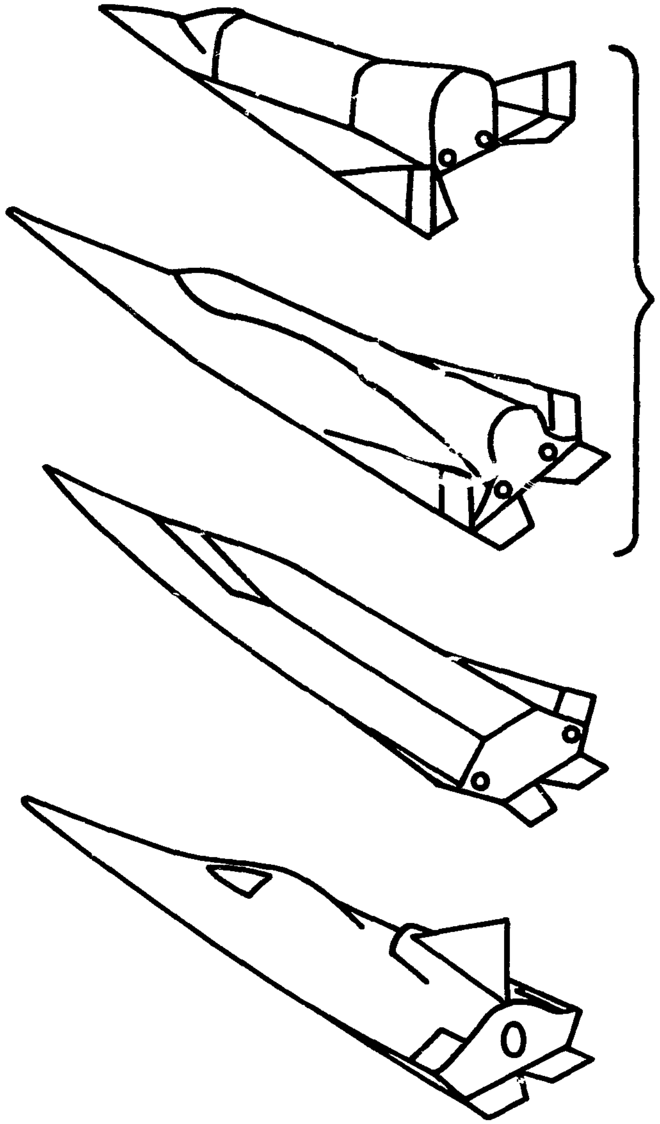


Figure 19.- Moderate hypersonic L/D fixed geometry vehicles.

RUNWAY LANDING, $V_H \sim 300$ ft/sec TRIM HYP L/D $\gtrsim 2$



	TRIM SUB L/D	
	UNPOWERED GLIDE	PROPULSION ASSIST
	3 TO 5	8 TO 10 (INSTANT L/D)
	2 TO 3	6 TO 8 (INSTANT L/D)
	2 TO 3	6 TO 8 (GO-AROUND)

Figure 20.- High hypersonic L/D fixed geometry vehicles.

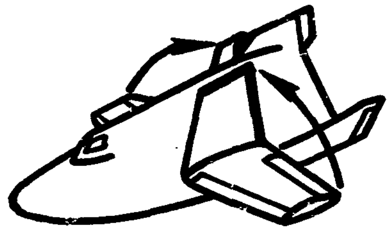
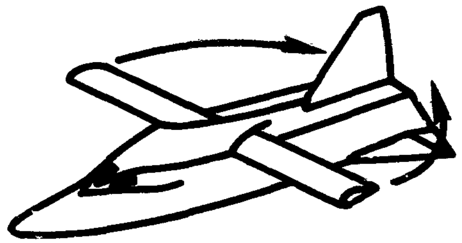
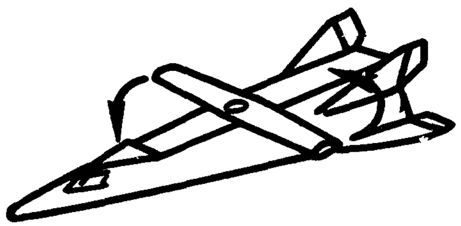
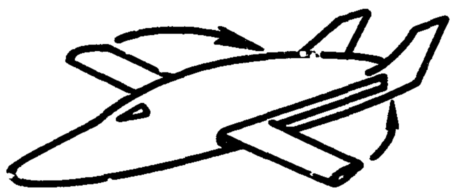
	WING TYPE	TRIM HYP L/D (WINGS STOWED)	TRIM SUB L/D (WINGS DEPLOYED)
	FOLD-DOWN DROP	1 TO 1.5	3 TO 5
	SWITCH-BLADE SCISSORS	1.5 TO 2.5	5 TO 9
	SWING PIVOT SKEWED	2.5 TO 3	5 TO 7
	SWITCH-BLADE SCISSORS	1.5 TO 2.5	10 TO 15

Figure 21.- Variable geometry lifting body vehicles.

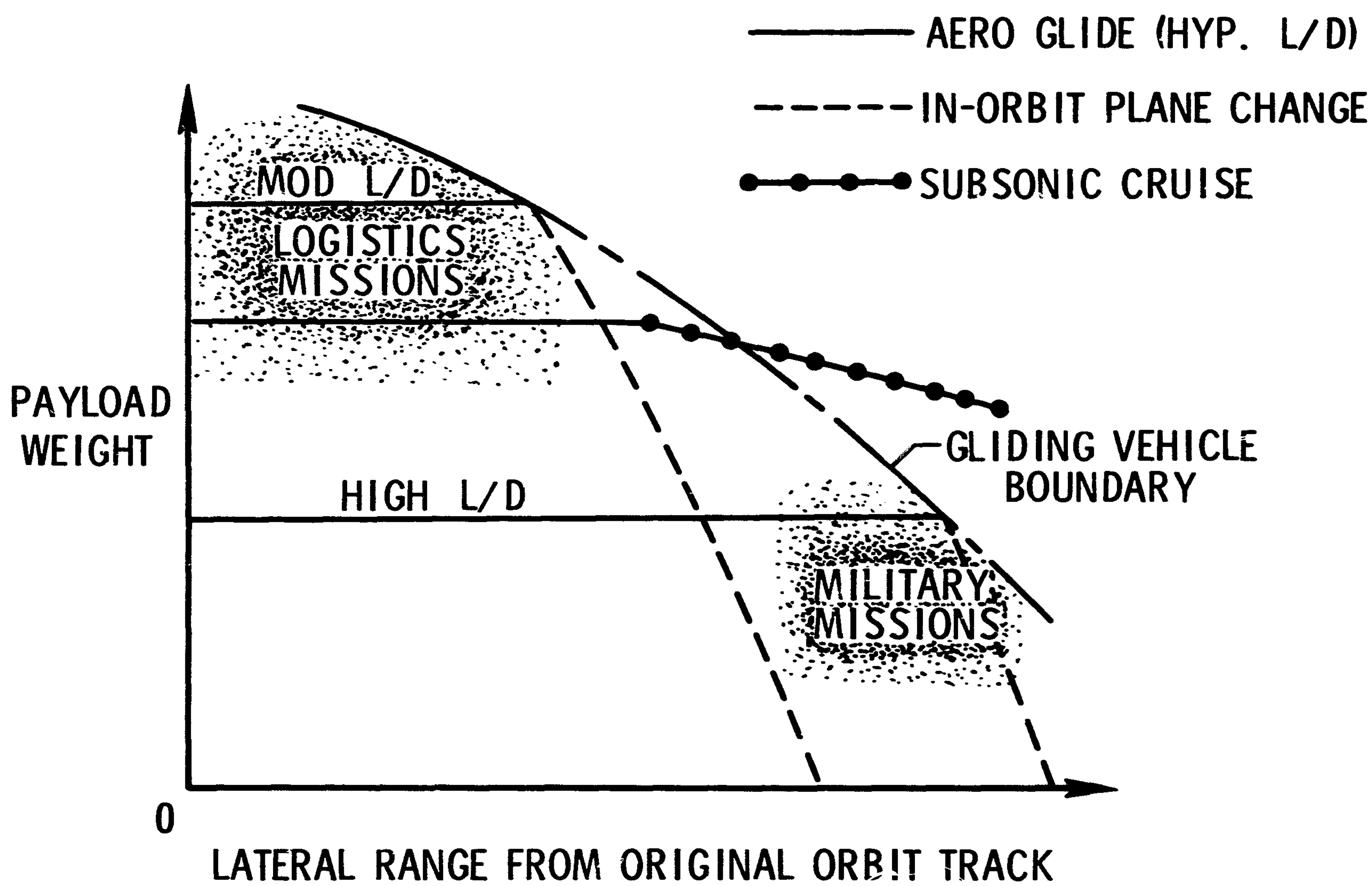


Figure 22.- Possible mission effects upon payload and lateral range requirements.

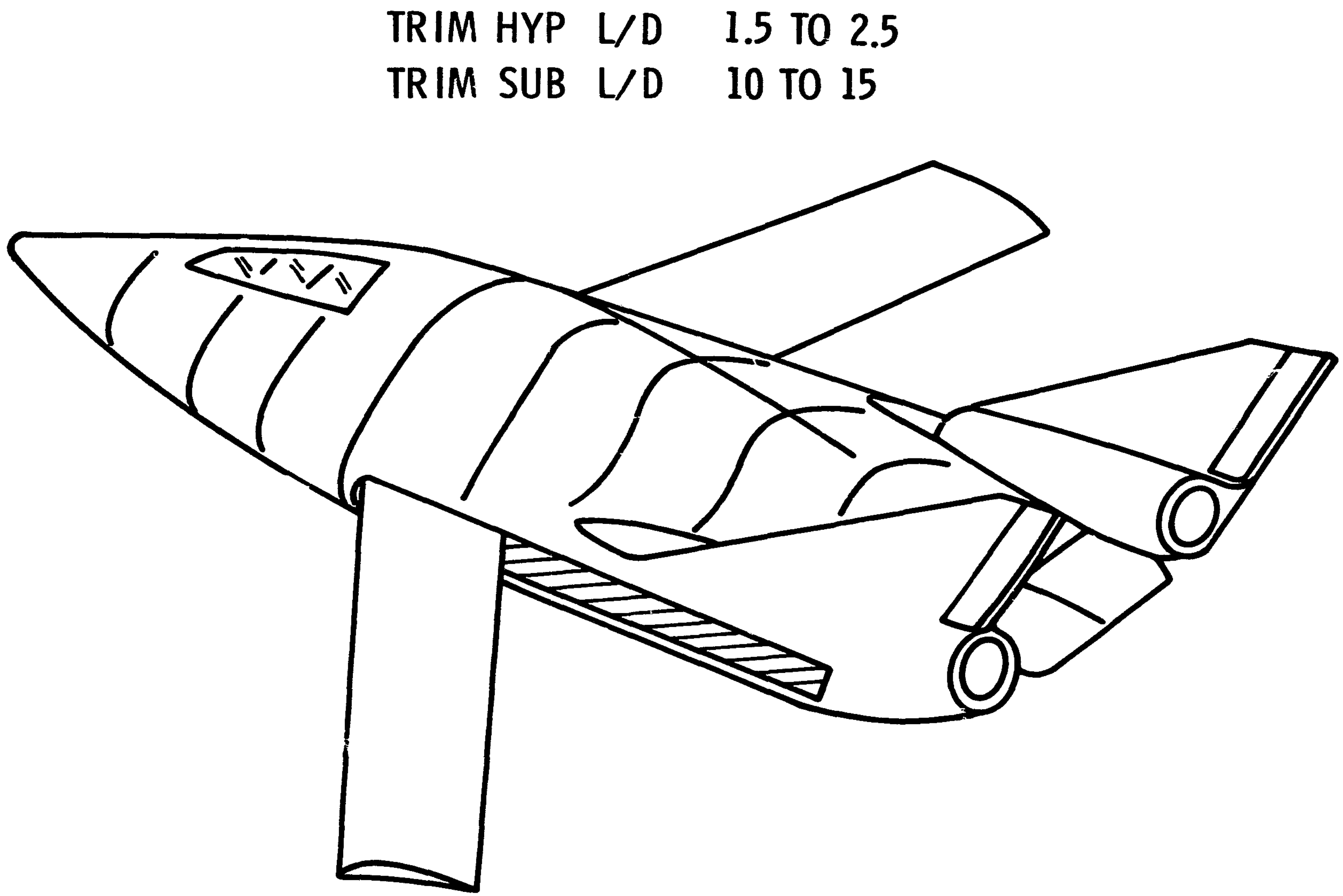


Figure 23.- Variable geometry, subsonic cruise vehicle, fixed engines.

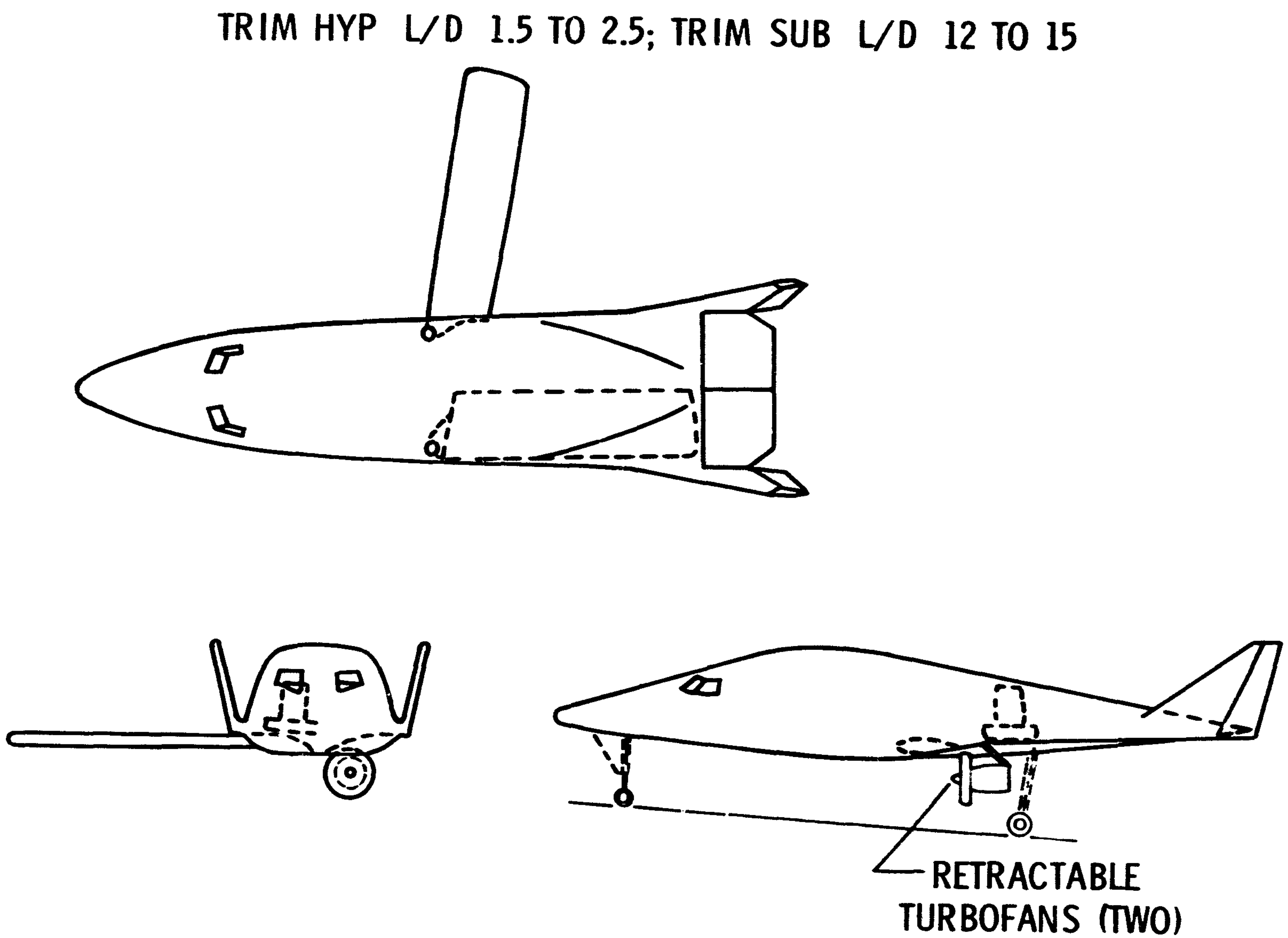


Figure 24.- Variable geometry, subsonic cruise vehicle, retractable engines.

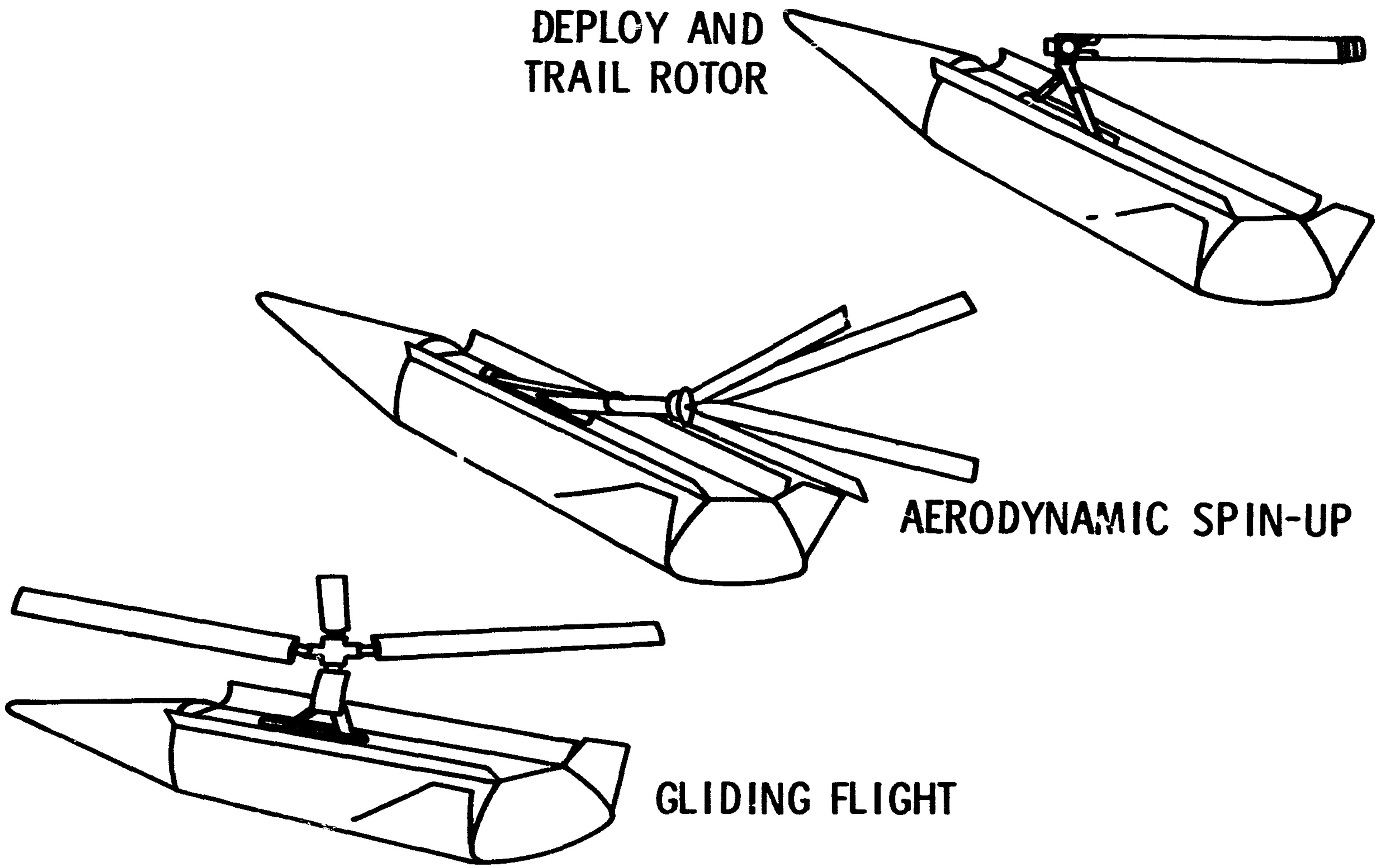


Figure 25.- Decoupled landing: deployable rotor vehicle.

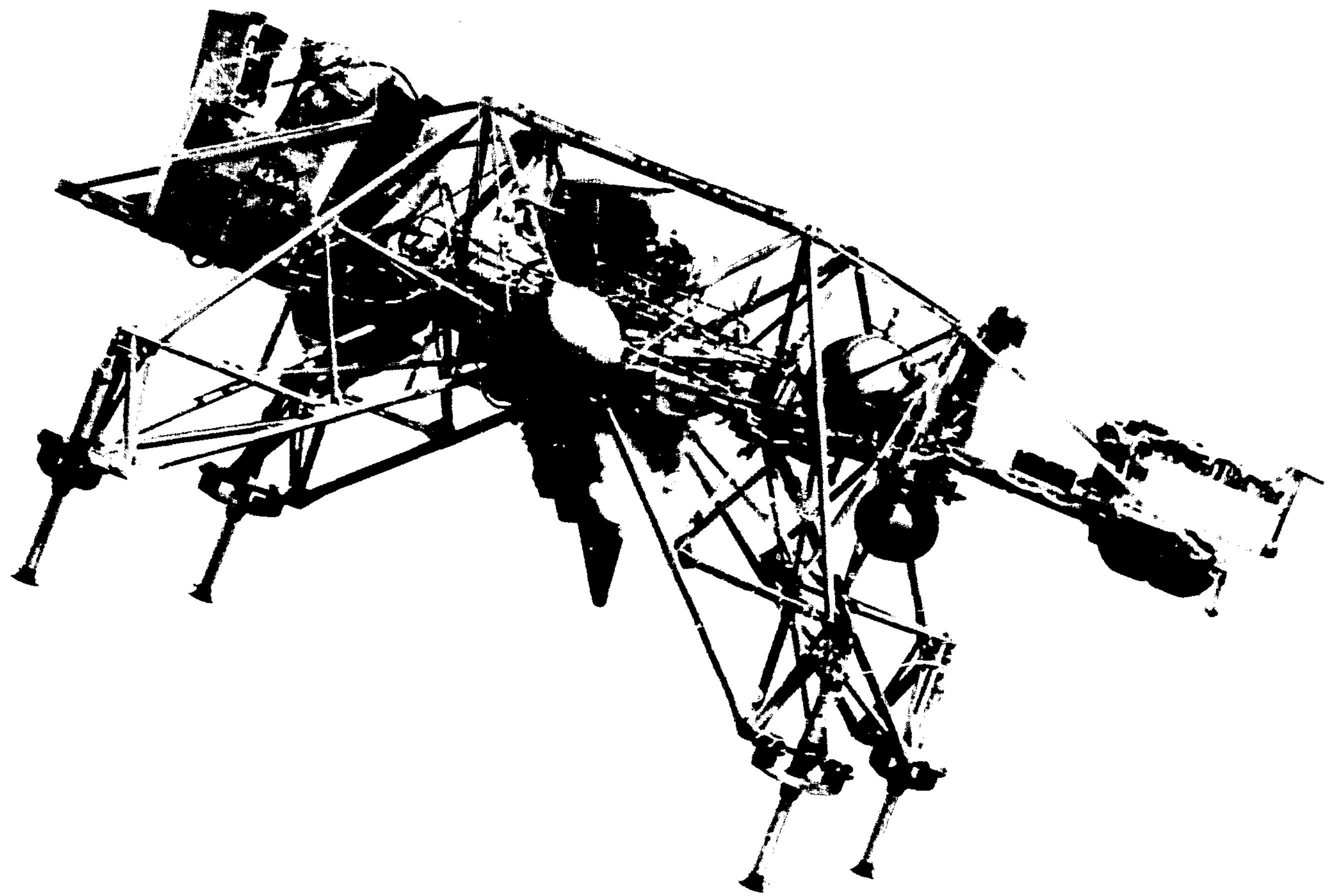


Figure 26.- Lunar Landing Research Vehicle in flight.

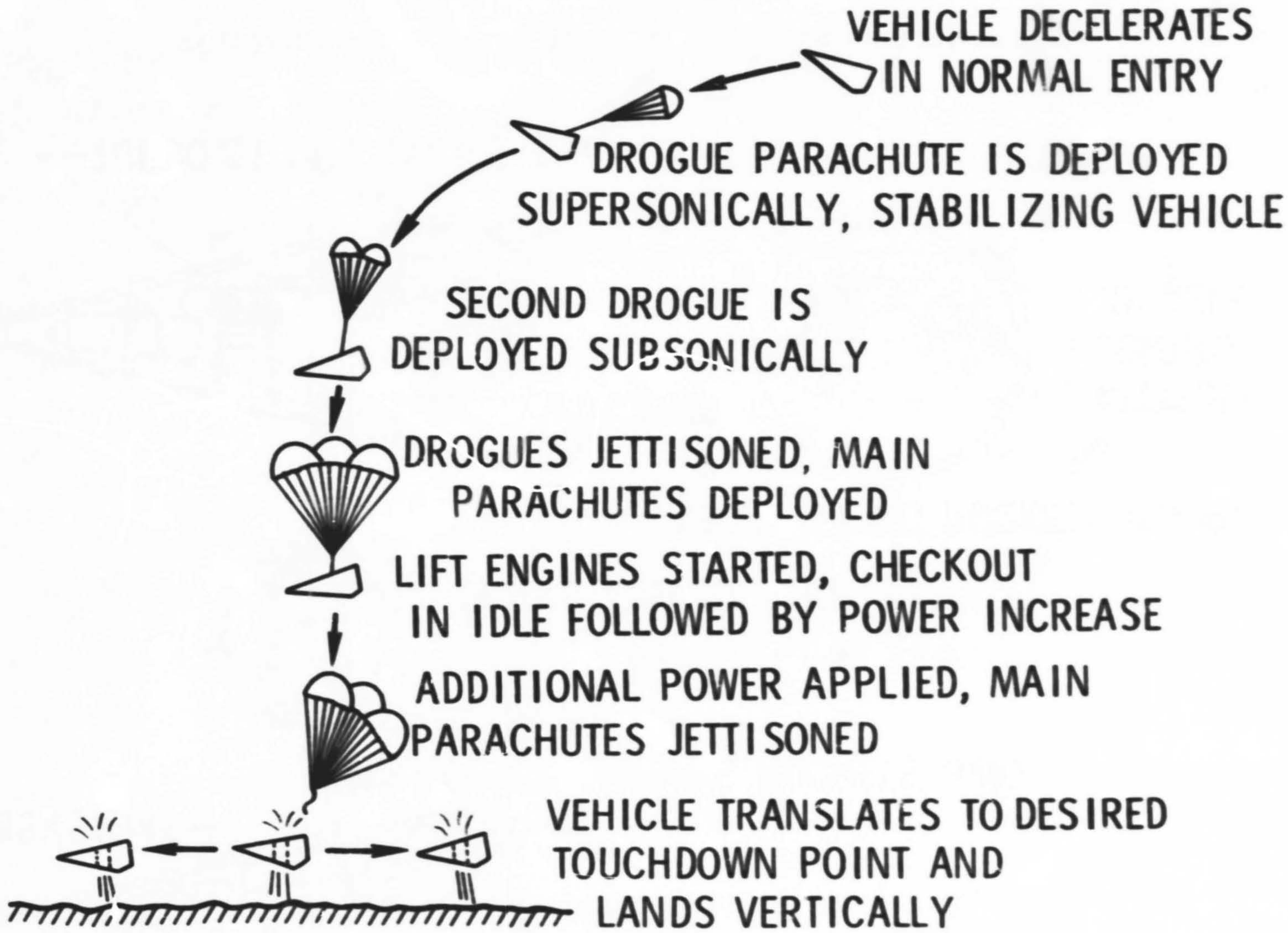


Figure 27.- Decoupled landing by propulsive lift, indirect transition by parachute.

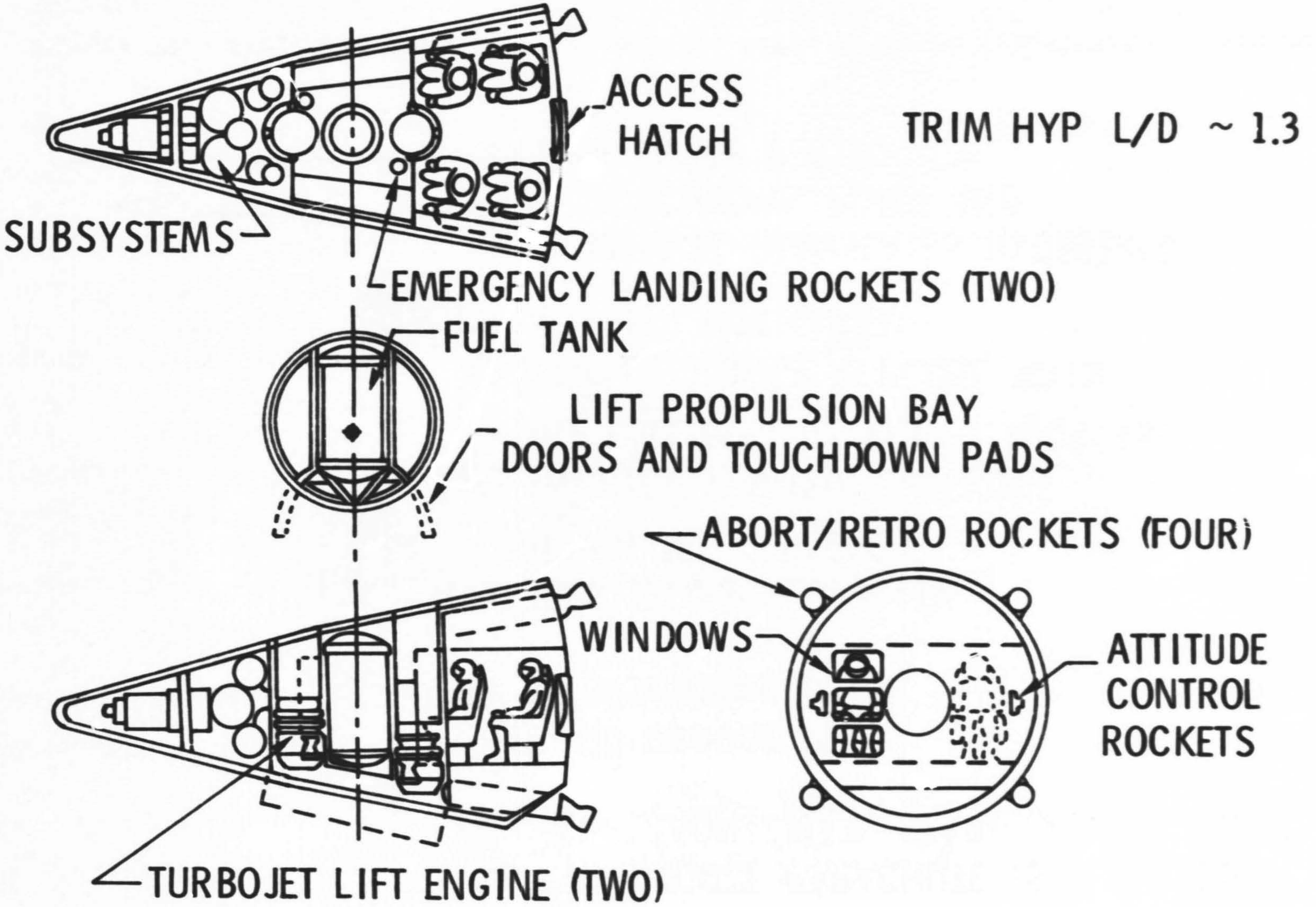


Figure 28.- Decoupled landing: propulsive lift vehicle.

TRIM HYP L/D ~ 1.3;

4-MAN VEHICLE; 24-hour NEAR EARTH ORBIT

PROPULSIVE LIFT	HL-10 WITHOUT PARACHUTE	HL-10 WITH PARACHUTE	HL-10 WITH PARACHUTE AND GO-AROUND PROPULSION
HL-10	1.18	1.12	0.99

Figure 29.- Total weight comparison of propulsive lift vehicle with fixed geometry runway landing vehicle (HL-10).