

**LATERAL-RANGE AND HYPERSONIC LIFT-DRAG-RATIO REQUIREMENTS FOR EFFICIENT
FERRY SERVICE FROM A NEAR-EARTH MANNED SPACE STATION**

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Introduction

The operation of any long-term manned space station will require some type of ferry vehicle to transport men and equipment to and from the station with regularity and reliability. Such a vehicle, designed for entry at near-orbital speeds, could also be useful in the return from any deeper space mission if either an earth-orbit rendezvous terminal maneuver or a maneuver combining atmospheric braking and a near-earth parking orbit is used.

This study was undertaken to determine the class of vehicle which could be most efficiently used as a ferry vehicle between a near-earth space station and the earth. One measure of this efficiency is the ability of the vehicle to reach pre-chosen landing sites with some prescribed frequency.

In considering this frequency of return it is necessary to consider not only the normal mode of operation in which only infrequent returns are scheduled at desirable times, but also operation under various degrees of emergency, which dictate quick or even immediate return to earth. In extreme emergencies, when immediate return to earth is necessary, choice of landing site becomes impractical. In most cases, however, although it might be required to abandon the station quickly, the ferry vehicle could remain in orbit for some time before initiating reentry in order to land at a prechosen site. The allowable delay time in orbit would be determined primarily by the capabilities of the ferry life-support system.

This paper will examine the geometry of the ferry ranging problem, that is, the lateral ranges required to reach chosen landing sites from various near-earth orbits, and will investigate and compare several means of achieving these ranges. The particular case considered is that of returning from a space station which is in a circular orbit at an altitude of 200 statute miles, but the results obtained are not sensitive to orbit altitude for orbits within a few hundred miles of the surface. From this orbit the vehicle will retro and reenter at very close to satellite velocity. The down-range problem can be handled by proper timing of the retrofiring, and the desired lateral range can be achieved by aerodynamics, space propulsion to change orbit plane, atmospheric propulsion, or combinations of these methods. The relative cost in terms of weight of using these different methods to achieve lateral range will be discussed.

Lateral Range by Aerodynamics

In order to tie the lateral-range requirements to vehicle aerodynamics, an investigation of the cross-range capabilities of vehicles with various hypersonic lift-drag ratios was undertaken. The

results of this investigation are presented in figure 1.

The maximum lateral range achievable is presented in terms of the vehicle maximum hypersonic L/D. For this investigation a value of $W/C_D S$ of 200 lb/ft² was chosen. At the lower values of L/D a value of 75 lb/ft² was also considered and was not found to have a significant effect on the values presented. To achieve these lateral ranges, the vehicle performs a shallow reentry and holds a constant altitude at the bottom of pullup by rolling about the wind vector until an appropriate equilibrium glide path can be followed. This mode of operation has been discussed previously^{2,3}.

Requirements for "Quick" Return

In the discussion that will follow, "delay time" is taken as the time between decision to reenter and initiation of reentry, and a "quick" return is defined as a return with a delay time of less than one orbit. For a quick return, therefore, the vehicle initiates reentry some time in the first orbit after the decision to reenter.

The maximum lateral range that could be required for quick return from a given orbit to a landing site at a given latitude is determined, as shown in figure 2, to be given by

$$Y_{req} = r_E(\alpha_1 + \lambda_2) \quad \text{or} \quad r_E[\pi - (\alpha_1 + \lambda_2)] \quad (1)$$

whichever is the lesser. Here α_1 is the orbital inclination to the equator, λ_2 is the latitude of the landing site, and r_E is the radius of the earth. These range requirements are shown in figure 3. Also shown are the values of hypersonic L/D required to achieve these ranges. Several geographic points are shown to indicate the limits of the United States and of the U.S. Mainland.

The ability to reach any point on the globe once each orbit from any orbit inclination is seen to require a hypersonic L/D of about 3.6. For equatorial or polar orbits no lateral range is required to reach points on the equator or the poles, respectively, once each orbit. Although such landing sites are usually impractical, they do serve to point out the fact that the minimum lateral ranges required for quick return from equatorial or polar orbits approach zero as the location of the landing sites approaches these points. For other inclinations no choice of landing site can assure quick returns with zero lateral-range capability.

Effects of Delay Orbits on Range Requirements

For an equatorial orbit the range requirements to reach a base at a given latitude are fixed. For orbits of other inclinations, the requirements can be reduced through use of delay orbits or multiple landing sites.

The effect of delay orbits on lateral range and associated L/D requirements is illustrated in figure 4, which presents the maximum holding time required to reach a landing site near Edwards AFB from orbits of various inclinations and for several values of the hypersonic L/D. The solid curves represent boundaries or discontinuities in the picture, while the dashed curves are representative of the members of the family. As seen in figure 4, a vehicle with an L/D of 3.6 could reach Edwards AFB within one orbit for any orbital inclination. This quick return is possible for a vehicle with L/D = 2.7 from orbits inclined at less than 22° to the equator or from a polar orbit. With less L/D some holding time is required for a polar orbit and the orbits for which quick return is possible are limited to low inclination orbits as illustrated by the L/D = 2 curve. With an L/D of greater than 1.9 quick return from an equatorial orbit is possible, while with less L/D the landing site cannot be reached from an equatorial orbit. The curve for L/D = 1 shows that at least daily return is possible to a base such as Edwards for all orbits which pass over the continental U.S. As L/D is decreased further, the holding times for all inclinations increase and the band of low inclinations, for which no return is possible, grows wider. With values of L/D greater than 0.84, holding times of less than 12 hours are required to reach the site from a polar orbit, but for values of L/D less than 0.84, the delay time for a polar orbit jumps to 24 hours and remains there for values of L/D down to 0.66 after which no regular return to Edwards from a polar orbit can be counted on.

These discontinuities are shown more clearly in figure 5 where a cross plot of maximum delay time to reach Edwards AFB is plotted against L/D for three orbital inclinations. As can be seen, from an equatorial orbit it is a quick-return or no-return proposition, with the break point coming about L/D = 1.9. For the polar orbit, quick return is possible down to an L/D of 2.7, after which there is a steady increase of holding time with reduction in L/D down to an L/D of 0.84 where a holding time of about 12 hours can be required. For values of L/D between 0.84 and 0.66 once daily return is possible, and for lower values of L/D, no regular return is assured. The curve for an inclination of 30° shows some of the characteristics of each of these limiting curves.

We must keep in mind that in discussing these delay times we have made no restriction as to the time of day the return is to be made. If we restrict our landing to the daylight hours, approximately 12 hours or more additional delay time could be required for single site landings.

Return From Polar Orbits

Choice of landing site. In considering space stations for reconnaissance, surveillance, weather-watching, or other applications, the complete earth coverage provided by polar or near-polar orbits is attractive. In considering return from such orbits, proper choice of landing site location and use of

multiple landing sites can serve to alleviate ranging requirements for either quick or delayed returns.

The effect of landing site choice on the L/D requirements for return from a polar orbit is shown in figure 6. The interior of the table presents the values of L/D required to assure reaching the representative landing sites shown on the left utilizing various numbers of delay orbits. The values presented for zero delay orbits are those for quick return, that is, ability to return once each orbit. The sites at Alaska and Thule were included on this chart for purposes of emphasizing the decrease in L/D requirements with increasing latitude of landing site. Although the unfavorable climates at these latitudes might preclude their use as prime landing sites, their possible use as emergency landing sites might warrant consideration. As may be seen from this chart, for return from a polar orbit, the L/D required can be reduced considerably by proper choice of landing site when a number of delay orbits are allowed.

Use of multiple sites. While still considering polar orbits, it is obvious that considerable reductions in lateral-range requirements can be obtained through use of multiple landing sites as illustrated in figure 7. In this figure we are looking down on the northern hemisphere, with the orbital plane appearing as a straight line. The landing sites are placed on the equator for figure simplicity.

If we have one landing site, it can be as much as 90° in longitude away from the plane of the orbit. If two sites are considered, chosen so that they are separated by 90° in longitude, one of the sites will always be within 45° of the orbit plane. This distance is reduced to 30° for three sites and 22.5° for four sites spaced as shown.

The decrease in maximum possible separation from the orbit plane is, of course, directly reflected in a decrease in the lateral-range requirements to reach at least one of these sites, and, therefore, a decrease in the vehicle L/D requirements. In figure 8 the L/D required to reach several landing site combinations are shown for various numbers of delay orbits. Edwards AFB is included as a single site for comparison purposes. The other combinations of sites shown, reading downward, are two bases within the continental United States, two bases with near optimum spacing, three bases across the continental United States, three near optimally spaced bases, and four bases approaching optimal spacing. The degree to which multiple bases properly spaced can reduce vehicle L/D requirements is apparent.

Interim Stations and Relaxed Return Requirements

The discussion to this point has dwelt on the requirements for quick returns and returns with delay times up to one-half day and has been primarily concerned with polar orbits. The values of L/D that have evolved from this analysis represent what we would like to have for efficient, regular service to a future space station. If we consider ferry requirements for an earlier space station, the questions that arise are how much do we have to relax our return requirements in order to use the low L/D and ballistic vehicles which will be available, or, conversely, just how much L/D or how large a landing area is required to meet minimum return requirements.

The minimum lateral-range angle η_y which will allow twice daily return from a polar orbit is given by

$$(\eta_y)_{II} = \frac{\omega_E \tau_S}{2} \cos \lambda \quad (2)$$

where ω_E is the earth rotation rate, τ_S is the orbital period, and λ is the latitude of the landing site. For the near-earth orbits considered in this paper, $\omega_E \tau_S$ is taken as 22.5° . For the ability to return once daily the minimum lateral-range angle required is given by

$$(\eta_y)_I = \left(\frac{\pi + 2\lambda}{2\pi} \right) \left(\frac{\omega_E \tau_S}{2} \right) \cos \lambda \quad (3)$$

These lateral-range requirements and their associated hypersonic L/D values are presented in figure 9. As was shown previously, a vehicle with an L/D of about 1 can reach any point on earth twice daily from a polar orbit, while an L/D of about 0.7 would give the capability of daily return to any site. The approximate limits of the U.S. Mainland are indicated to show the ranges that would be required for return to mainland landing sites on a daily or twice daily basis from a polar orbit.

Early space station orbits may well be other than polar, inclined so as to take advantage of existing launch and tracking facilities. For such orbits we can determine the minimum range which will assure the ability to return to a properly positioned base at least once daily by the method illustrated in figure 10. Shown as solid lines are three consecutive orbit traces mutually separated by a distance $\omega_E \tau_S$. The maximum latitude of these orbits is given by $\lambda_1 = \alpha_1$ and the intersection of the traces can be shown to occur at λ_2 which is given by

$$\tan \lambda_2 = \cos \left(\frac{\omega_E \tau_S}{2} \right) \tan \alpha_1 \quad (4)$$

If a landing site is located at a latitude λ^* halfway between λ_1 and λ_2 , then this site will

always be within an angular distance of $\frac{\lambda_1 - \lambda_2}{2}$ from one or other of these traces. The maximum lateral range required to reach this site at least once a day is therefore given by

$$Y_{\text{req}} = r_E \eta_y = r_E \left(\frac{\lambda_1 - \lambda_2}{2} \right) \quad (5)$$

These values are shown in figure 11 for all orbital inclinations.

It should be borne in mind that these values apply for a landing site at the latitude λ^* which is located slightly under the maximum latitude which the orbit reaches. For a polar or equatorial orbit,

λ^* becomes 90° and 0° , respectively, and no lateral range is required as was indicated in an earlier figure. For other inclination angles the ranges required are small, reaching a maximum value of less than 20 miles for an inclination of 45° . These small ranges should be within the capability of any controllable landing device, such as a paraglider, or could be achieved through use of a small amount of space propulsion, thus placing the landing sites within the reach of nonlifting reentry vehicles. These small range requirements also serve to indicate the size of landing area that would be required if the vehicle had no control over its set down.

On the right of figure 11 are presented the fuel requirements which would be required to achieve these cross ranges by use of space propulsion to change the inclination of the orbital plane. These values were obtained assuming a specific impulse of 300 seconds. It can be seen that the weight of propulsive fuel required for bases within the continental U.S. is about 2 to 3 percent of the reentry vehicle weight.

Weight Penalties Associated With Lateral Range

As mentioned previously, the lateral ranges required may be obtained by several methods in addition to the use of aerodynamic glide which has been discussed to this point. The other methods considered here are:

1. The use of space propulsion
2. The use of combinations of space propulsion and aerodynamic glide
3. The use of aerodynamics and atmospheric propulsion

Structural or fuel weight penalties are, of course, associated with these various methods and one purpose of this paper is to evaluate the cost in terms of weight of these approaches.

The weight of vehicles capable of reentering the atmosphere with high values of L/D will, of course, be greater than that of vehicles capable of only ballistic reentry. Some data to this effect are presented by E. S. Love¹ and have been used to obtain figure 12. The abscissa on figure 12 is the lateral range that could be obtained aerodynamically by the vehicles and the upper nonlinear scale presents the vehicle hypersonic L/D. The shaded area encompasses the majority of the data presented in reference 1. The weight increase is very rapid for the first few hundred miles of lateral range, primarily because of the ineffectiveness of the low L/D vehicles in obtaining lateral range. The exact weight values will, of course, change for each study, and the solid line which was chosen for use in the remainder of this paper represents a mean of all the data rather than a curve of minimum weights.

Space Propulsion

Propulsion can be applied either in the atmosphere or in space to obtain the desired range. If atmospheric propulsion is to be used, it is most efficient to use air-breathing engines with their relatively high values of specific impulse. If pure rocket propulsion is to be used, this can be used best in orbit where the fuel and propulsion systems

do not have to execute the reentry. The initial weight in orbit then consists of the normal reentry vehicle, the fuel for orbital transfer, the tanks, engine, and any special guidance system required for the orbital transfer.

Assuming a circular orbit with an impulse applied 90° before the point at which maximum range will be required, the ratio of the initial to final weight will be given by

$$\log \frac{W_i}{W_f} = \frac{2r_E \sin \frac{Y}{2r_E}}{I_{SP} \sqrt{g_E r}} \quad (6)$$

where

W_i initial weight

W_f final weight

g_E acceleration due to gravity at r_E

r_E radius of the earth

r orbit radius

Y lateral range

I_{SP} specific impulse of rocket

The weight ratio W_i/W_f is plotted against range for several orbit altitudes in figure 13. The effect of specific impulse is also shown in this figure. A value of I_{SP} of 300 seconds will be used for the remainder of the study of space propulsion. Because of the lower orbital velocity at the high altitudes, the energy required to change the orbit is lowered. For low orbits, however, a change of several hundred miles in altitude has little effect on the weight ratio.

In actual practice the initial weight W_i should be increased by the weight of the tankage, engine, and associated control system. No detailed study has been made of this weight; however, a preliminary review indicated that 20 percent of the fuel weight should be more than enough to cover these items. The dashed curve in figure 4 shows that this is not a very large factor in the total weight.

In this analysis it has been assumed that the orbit change is independent of any retroimpulse used to initiate reentry. For small amounts of lateral-range change (on the order of 200 to 300 miles) the retro-rocket, when properly oriented, may be able to supply a large part of the energy required to obtain the desired lateral range; however, for lateral-range requirements over 1,000 miles, its effect is small. The exact effect of the retro-rocket on these curves would, however, be a strong function of the initial orbit and reentry conditions required which make the inclusion of these effects impractical as they are beyond the scope of the present investigation.

Aerodynamic-Glide-Plus-Space Propulsion

Combinations of space propulsion and aerodynamic glide might be practical in some cases. The weight required can be found by

$$\frac{\text{Weight in orbit}}{\text{Weight in orbit for zero lateral range}} = \left(\frac{W_i}{W_f} \right) \left(\frac{W \text{ in orbit}}{\text{Weight in orbit for zero lateral range}} \right)_{L/D} \quad (7)$$

and

$$\begin{aligned} \text{Lateral range} &= (\text{Lateral range})_{L/D} \\ &+ (\text{Lateral range})_{\text{propulsion}} \end{aligned} \quad (8)$$

These relations give the curves shown in figure 14. For large lateral ranges, L/D appears the more economical approach and combinations of the two would not be designed into the system just to obtain range capability. For small values of lateral range, space propulsion appears to be more economical and should be studied further for the specific configurations and tasks considered.

Atmospheric Propulsion

The use of propulsion in the atmosphere allows the higher specific impulse of air-breathing propulsion systems to be utilized. However, the efficient use of propulsion in the atmosphere requires aerodynamically efficient configurations since

$$R = I_{SP} V (L/D)_{\text{eff}} \log \left(\frac{W_i}{W_f} \right) \quad (9)$$

where

R range

V velocity

$$(L/D)_{\text{eff}} = \frac{\text{Weight}}{\text{Drag}} = L/D \frac{1}{\left(1 - \frac{V}{V_{\text{orb}}} \right)^2}$$

The specific impulse values that can be expected in the atmosphere with ram jet, turbojet, or combinations of various jet engines are shown in figure 15. The shaded area represents the current predictions for the performance of future engines.

Propulsion in the atmosphere can be applied either at subsonic or supersonic speeds. For the purposes of this paper it is assumed that the L/D is constant throughout the supersonic speed range. While this is not strictly true, it will be seen later that secondary variations in L/D will not alter the conclusions. For the subsonic speeds, the L/D corresponding to a given hypersonic L/D class of vehicles is not easily determined since it depends strongly on the design philosophy.

Since range is proportional to L/D , it appears unattractive to consider atmospheric propulsion for very low values of L/D . On the other hand, because of the inherent range capability of very high L/D vehicles, they will not require the use of propulsion. The analysis has therefore been carried out only for an L/D of 1 vehicle with the expectation that the analysis could later be extended to higher L/D values if atmospheric propulsion looked promising. It was found that for this vehicle it is more efficient to use atmospheric propulsion supersonically than subsonically for subsonic L/D values up to about 8.

A maximum range is obtained for a given weight ratio at about 11,000 feet per second for the high I_{sp} values and at 7,000 feet per second for the low I_{sp} values. Solving the range equation for these values gives two sets of weight ratios which do not make any allowance for containing the fuel or the weight of the engine and other associated equipment. The effect of these factors is very strong on the overall weight ratio since the vehicle must reenter the atmosphere with all of this weight. However, it is interesting to compare these weight ratios (starting at an $L/D = 1$ vehicle) with the weight predicted for range obtained by the L/D alone. The area between the two curves just above the L/D alone curve in figure 16, therefore, is the band of the weight ratio including only the original $L/D = 1$ vehicle and the fuel. Even this area is well above the L/D alone curve and indicates that, neglecting the increase in vehicle empty weight, this approach is still uneconomical from the weight standpoint.

In order to show the effect of the vehicle modifications required to reenter with the extra fuel and equipment, an elaborate but approximate weight analysis was made. This analysis attempted to account for variations in the percentage of weight tied up in heat protection and structures as the vehicle becomes larger to include fuel and propulsion equipment. The analysis is subject to much question concerning the exact values used, but since the use of atmospheric propulsion does not look promising even in the case where this added weight is neglected, the details of the weight analysis are not of importance and therefore have not been included in this paper. The results of this analysis, however, are included in figure 16 as the band between the upper two curves to illustrate the large effect that can result from modifying the vehicle so that it is capable of reentering with the fuel and associated equipment.

Conclusions

It has been shown that the lateral range required for return is strongly dependent on the location and number of landing sites, on the inclination of the orbit to the equator, and on the amount of delay time that can be tolerated. For the ability to reach any point on earth once each orbit from any orbit, a vehicle with a hypersonic L/D about 3.6 is required. Although it would be nice to have this capability, it is questionable whether it is actually needed, and in any event it is probable that such a vehicle will remain beyond our grasp for quite some time to come. If we are satisfied with selected single or multiple bases and are willing to accept reasonable delay times in orbit prior to initiation of reentry, the hypersonic L/D requirement for return from a polar orbit can be reduced to the neighborhood of one. For other than polar orbits, larger ranges are, in general, required for returns with delay times of one-half day or less, but for properly selected landing sites, very small lateral ranges are necessary to assure daily return.

This study has also shown that for large lateral ranges, the use of space propulsion is very expensive and not competitive with L/D alone. A combination of space propulsion and L/D is not attractive and such a combination should not be considered for the sole purpose of obtaining lateral range. For small amounts of lateral range space propulsion with an $L/D = 0$ vehicle appears to achieve lateral range more economically than aerodynamic glide. The differences, however, are not great enough to eliminate the possibility that efficient L/D vehicles can be made competitive with space propulsion in this range.

References

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2. Becker, J. V., Baradell, D. L., and Pritchard, E. B.: Aerodynamics of Trajectory Control for Re-Entry at Escape Speed. Paper presented at the International Academy of Astronautics Symposium, Paris, France, June, 1961. Also published in *Astronautica Acta*, Vol. VII, Fasc. 5-6, 1961, pp. 334-358.
3. Baradell, D. L.: Lateral Range Control by Banking During Initial Phases of Supercircular Reentries. NASA TN D-1511, 1962.

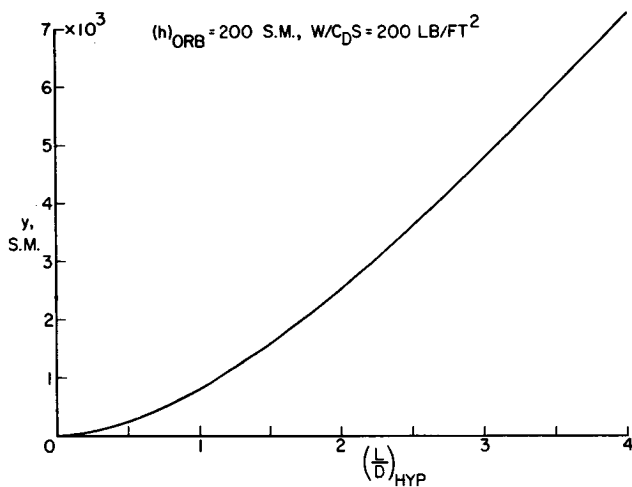


Figure 1.- Lateral range obtainable by aerodynamics.

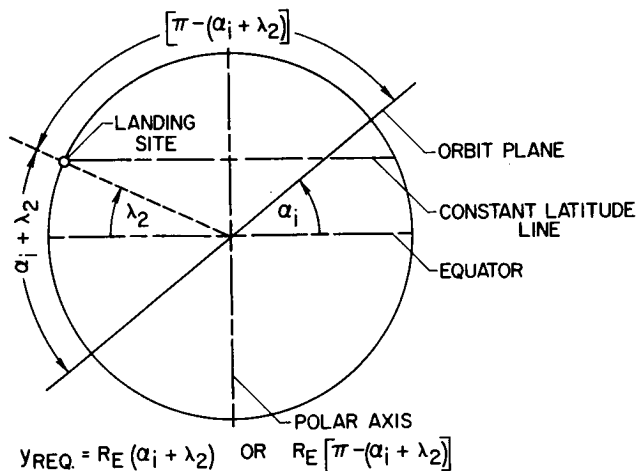


Figure 2.- Maximum lateral range required for "quick" return.

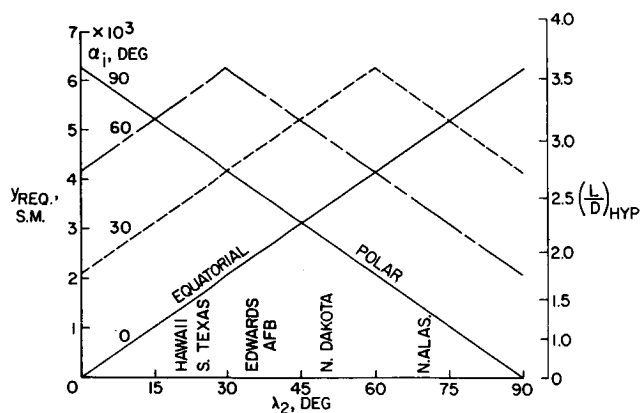


Figure 3.- Lateral range required for "quick" return from space station orbit.

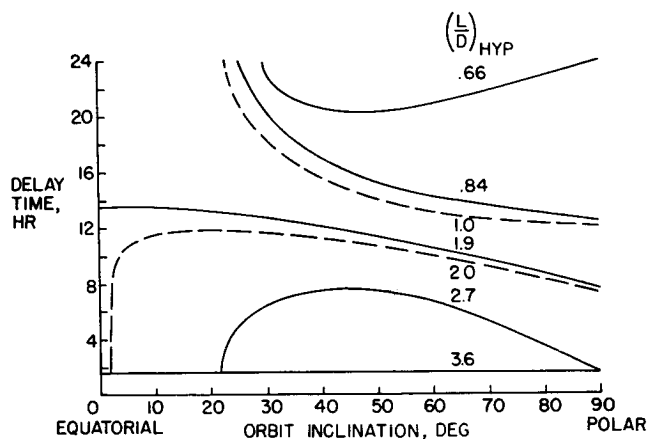


Figure 4.- Maximum delay time for return to Edwards AFB.

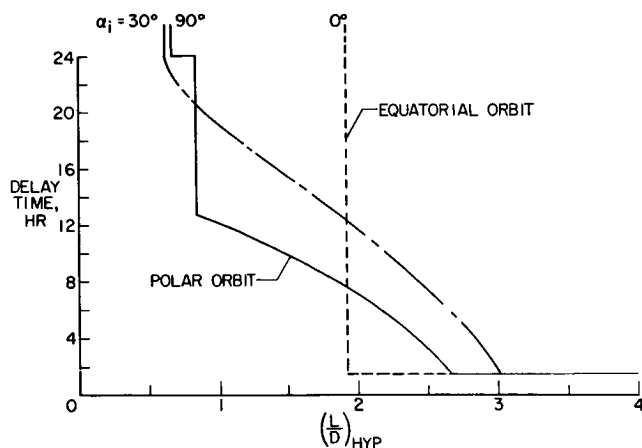


Figure 5.- Maximum delay time for return to Edwards AFB.

		NUMBER OF DELAY ORBITS							
λ_2	LANDING SITE	0	1	2	3	4	5	6	7
35°	EDWARDS AFB	2.7	2.6	2.4	2.2	1.9	1.6	1.3	.8
42°	NEW YORK STATE	2.4	2.3	2.2	2.0	1.8	1.6	1.2	.8
50°	NORTH DAKOTA	2.2	2.1	2.0	1.8	1.7	1.5	1.1	.7
70°	ALASKA	1.4	1.4	1.3	1.2	1.1	1.0	.8	.5
77°	THULE	1.1	1.1	1.0	1.0	.9	.7	.6	.4

Figure 6.- Hypersonic L/D required to reach various landing sites from a polar orbit.

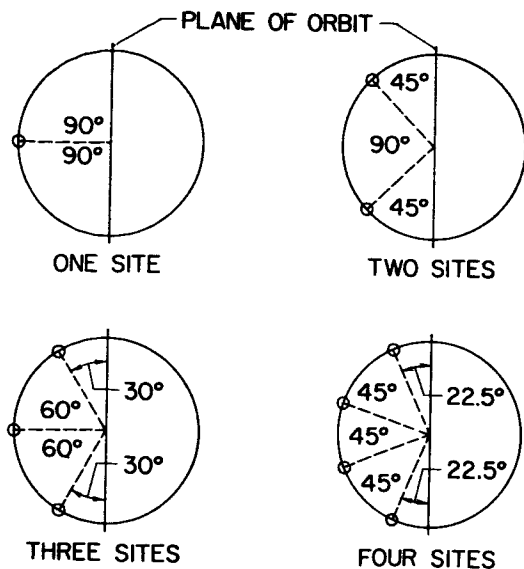


Figure 7.- Optimal spacing of multiple landing sites for return from polar orbit.

LANDING SITE	NUMBER OF DELAY ORBITS							
	0	1	2	3	4	5	6	7
EDWARDS AFB	2.7	2.6	2.4	2.2	1.9	1.6	1.3	.8
EDWARDS + NEW YORK	2.4	2.3	2.1	1.8	1.6	1.2	.8	.8
* EDWARDS + S.E. AUSTRALIA	2.1	1.9	1.6	1.2	.8	.8	.8	.8
EDWARDS + HOUSTON + NEW YORK	2.4	2.3	2.1	1.8	1.6	1.2	.8	.8
* EDWARDS + HAWAII + S.E. AUSTRALIA	1.8	1.3	1.0	1.0	1.0	1.0	.9	.8
* NEW YORK + EDWARDS + HAWAII + S.E. AUSTRALIA	1.6	1.1	1.0	.8	.8	.8	.8	.8

* NEAR OPTIMAL SPACING

Figure 8.- Hypersonic L/D required to reach multiple landing sites from a polar orbit.

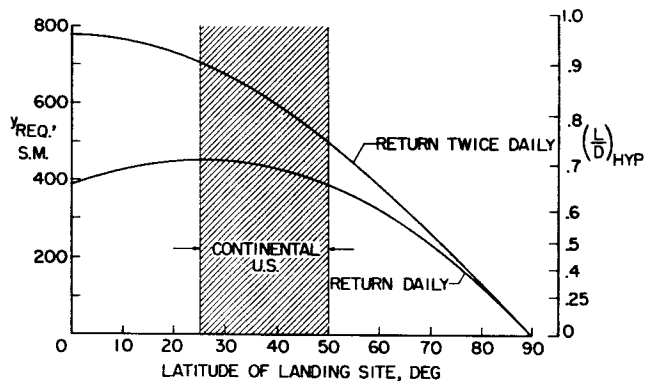


Figure 9.- Lateral range required for daily or twice daily return from a polar orbit.

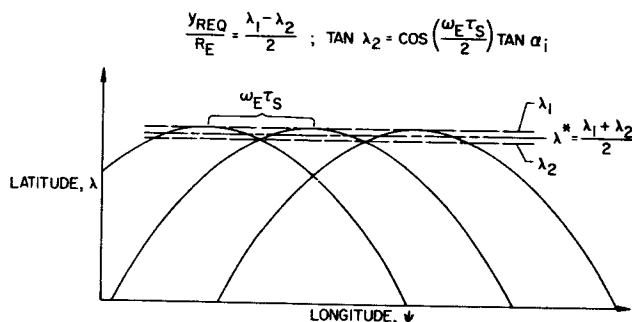


Figure 10.- Location of landing site to achieve daily return with minimum ranging capability.

$$\text{LATITUDE OF LANDING SITE} = \lambda^* = \frac{1}{2} \left\{ \tan^{-1} \left[\cos \left(\frac{\omega_E T_S}{2} \right) \tan \alpha_i \right] + \alpha_i \right\}$$

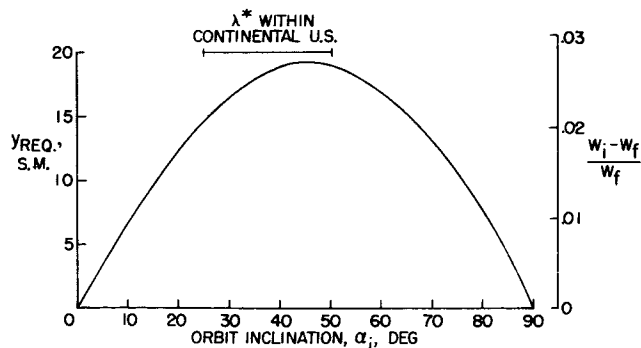


Figure 11.- Minimum lateral range required for daily return from inclined orbits.

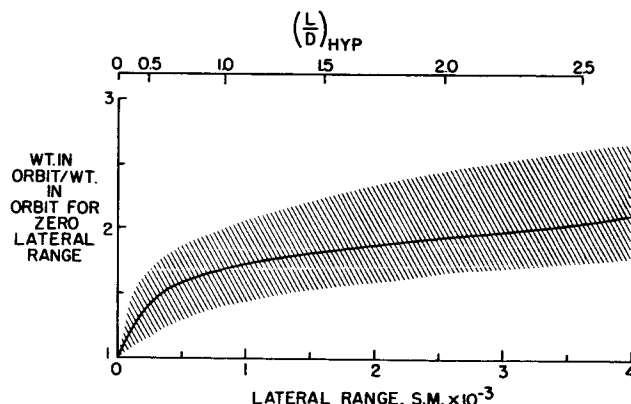


Figure 12.- Weight required to achieve lateral range by aerodynamics.

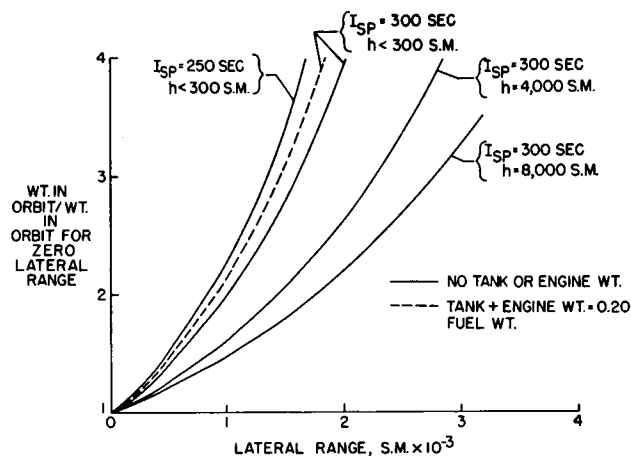


Figure 13.- Weight required to obtain lateral range by space propulsion.

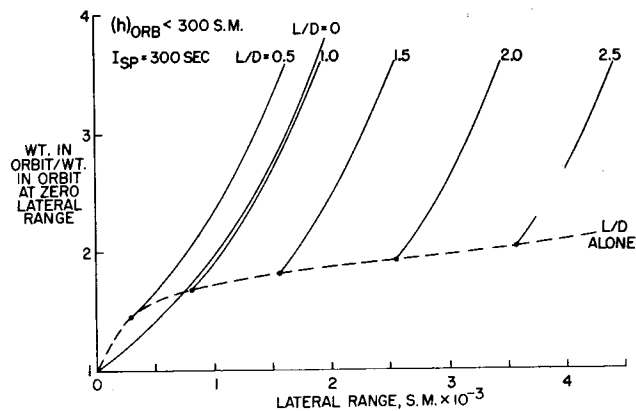


Figure 14.- Weight required to achieve lateral range by aerodynamics plus space propulsion.

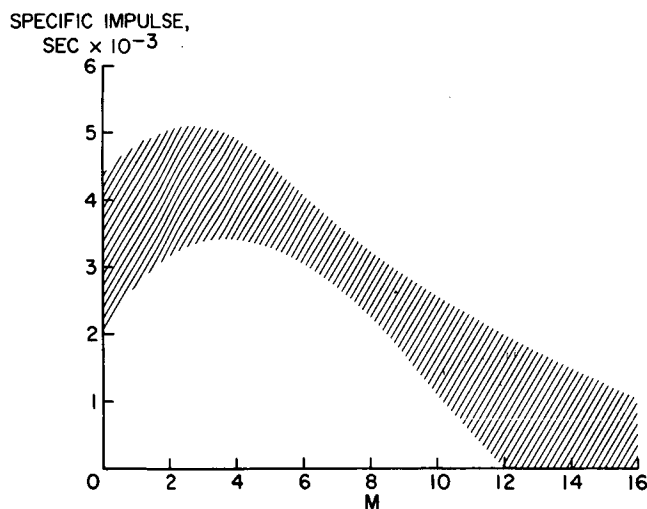


Figure 15.- Estimated specific impulse of air breathing engines.

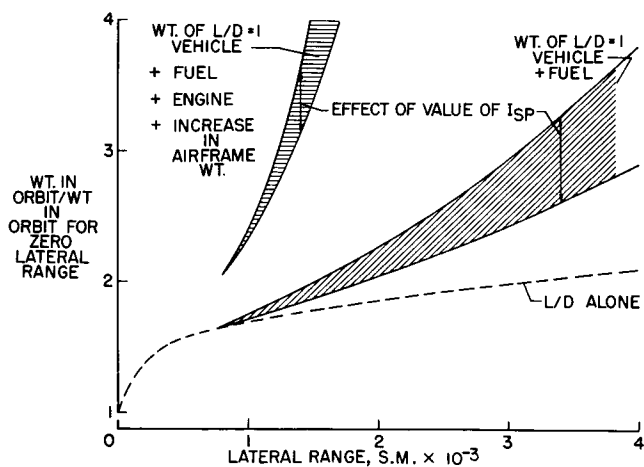


Figure 16.- Effect of lateral range on weight using atmospheric propulsion - vehicle $L/D = 1$.