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SOME FACTORS AFFECTING THE USE OF LIGHTER THAN AIR SYSTEMS

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SUMMARY

The uses of lighter-than-air (LTA) vehicles are examined in the present day transportation environment. Conventional dirigibles are examined and found to indicate an undesirable economic risk due to their low speeds and to uncertainties concerning their operational use. Semi-buoyant hybrid vehicles are suggested as an alternative which does not have many of the inferior characteristics of conventional dirigibles. Economic and performance estimates for hybrid vehicles indicate that they are competitive with other transportation systems in many applications, and unique in their ability to perform some highly desirable emergency missions.

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INTRODUCTION

In recent years a renewed interest in airships has arisen and numerous proposals have been brought forward to develop very large dirigibles (payloads of hundreds of tons) to supplement current transportation systems. It has been suggested that technological advances since such vehicles were last used commercially would permit the development of new airships which are both safer and more efficient. It is claimed that power requirements will be low relative to heavier-than-air-craft because the vehicle weight is lifted buoyantly without requiring power, and thus such vehicles will conserve fuel and pollute less. It is also claimed that such vehicles taking off and landing vertically will not require the elaborate facilities of modern airports which are associated with aircraft, and can therefore operate effectively into and out of remote undeveloped areas.

A series of studies have been conducted recently at the Ames Research Center to examine the claims of the dirigible proponents and to assess the potential of LTA systems to supplement other systems in the current transportation environment. This report presents the results of these studies. These results indicate that sufficient uncertainty exists regarding the ability of large conventional dirigibles to perform general transportation missions effectively, and as a result the cost of developing them would entail too much risk. However, if practical applications are found for much smaller LTA vehicles, then the lesser funds required for their development could be justified, and experience obtained in their use would provide valuable information for deciding whether later development of large vehicles would be justified.

The performance of small semi-buoyant hybrid LTA vehicles has been found to be generally superior to both conventional dirigibles and to other transportation systems in many applications. In these applications they may be superior to other systems from the standpoints of energy conservation, reduced pollution, and improved economy. They may also be effective in missions not using air vehicles at the present time, and in particular they should be the most effective vehicle available for emergency use during natural catastrophes such as earthquakes, fire, floods, and storms.

OBSERVATIONS CONCERNING THE DIRIGIBLE

By definition a dirigible is an airship which can be directed toward a pre-established destination. It can have either a rigid structure or a pressure stabilized structure such as does a blimp. It consists of a large volume containing a buoyant fluid, a propulsive system, a directional control system, and compartments containing other subystems, crew, expendables, and payload. The gross weight which a dirigible will support in excess of the weight of the buoyant fluid is the product of the buoyant fluid volume and the difference between outside air density and buoyant fluid density. This weight is referred to as static lift. Empty weight is the complete weight of the vehicle less lifting gas, crew, payload, fuel and other expendables.

Scale Size

A statement similar to that in Reference 1, "The ratio of useful lift (payload) to gross lift rises steadily as size increases," is found in almost every dissertation written on airships. It is usually used to foster the idea that the largest dirigibles produced (Hindenberg, Akron, Macon) were just getting into a size range where airships become efficient, and that further size increases to 20 – 100 million cubic feet ($5.66\text{X}10^5 - 2.83\text{X}10^6$ m^3) would produce much more efficient vehicles. This is undoubtedly the most widespread myth that has been circulated about airships, and it is difficult to understand why it has not been challenged. It is well known that conventional aircraft obey, to a first approximation, the "square-cube" law. This refers to the fact that the lifting capability increases with the square of reference dimension while the weight of bending critical structure increases with the cube. Thus conventional aircraft tend to become less efficient as size increases. For a buoyant vehicle, the lifting capability increases with the cube of the dimension while the structural weight increases with the cube regardless of whether the structure is designed by bending or pressure loads. Thus, to a first approximation, airships obey a "cube-cube" law and their efficiency may be expected to be to a large extent independent of size. This conclusion tends to be validated by data on existing airships.

Data showing the variation in empty weight-to-volume ratio (W_e/V) with volume (V) for a large sample of the airships built between 1918 and 1967 are presented in Figure 1. (These data were obtained from tabulated information in Reference 2.) Included in Figure 1 are dashed lines showing the required data trend if airships followed a "cube-square" law. The data, covering a size range of more than an order of magnitude for non-rigid airships and almost an order of magnitude for rigid airships, indicate that (W_e/V) is close to being constant and airships do not tend to increase in efficiency as size is increased.

Power and Economic Performance

The second most common misconception about dirigibles is that they are more efficient because they require less power. The fact that dirigibles can use less power than other aircraft is true, but not necessarily meaningful. A motorcycle requires less power than a large truck, but is not a more efficient transportation system because of its lower payload. Power can only be a value parameter when the same or equal performance is assumed for the vehicles being evaluated. It is indirectly inferred that less power means less pollution and resource conservation (less fuel used) but this is not necessarily true. The proper value parameter to measure pollution and resource conservation is the quantity of fuel used to transport a unit weight through a unit distance (frequently given as pounds of fuel per ton-mile).

Another misconception about power is the inference of greater economy. Lower power will probably mean lower propulsion systems costs and may mean lower fuel costs. However, these costs are only a portion of the total operating costs associated with a transportation system. Furthermore, costs are only one side of the economic picture and are meaningless without considering productivity (ton-mile/hr). Any economic evaluation must weigh dollars/hr total operating costs against ton-miles/hr productivity.

Operational Problems

Cruise Altitude – There are a number of operational problems associated with dirigibles, and solutions have been found or proposed for all of them. However, the influence of the solutions on mission performance and economic viability needs to be examined more thoroughly. One problem which has been neglected somewhat is the problem of maximum permissable altitude. If conservation of the buoyant fluid is a necessity, as with helium, then it must be contained, and maximum altitude is established by the ambient pressure at which the buoyant fluid expands to fill the buoyant envelope.

If an altitude capability of about 20,000 feet (6096 m) is required, with ambient pressure only half that at sea level, then at sea level the hull can only be half filled with buoyant fluid, and will only have half the gross lift of a vehicle operated only at sea level. The variation of useful lift as a function of altitude capability can be obtained using the following equations:*

$$W_g = (\rho_a - \rho_f)\, V_f \tag{1}$$

$$W_e = (W_e / V_H)\, V_H \tag{2}$$

$$W_u = W_g - W_e = (\rho_a - \rho_f)\, V_f - (W_e / V_H)\, V_H \tag{3}$$

The ratio of fluid volume at sea level (V_{fh}) for a vehicle designed to cruise at altitude h, to the vehicle hull volume V_H is:

$$\frac{V_{fh}}{V_H} = \frac{\rho_{ah}}{\rho_{aSL}} \tag{4}$$

$$\therefore\ W_{uh} = (\rho_{aSL} - \rho_{fSL})(\rho_{ah}/\rho_{aSL})\, V_H - (W_e / V_h)\, V_H \tag{5}$$

Therefore, the ratio of useful lift for a vehicle designed with a maximum altitude h, to one which operates only at sea level is:

$$\frac{W_{uh}}{W_{uSL}} = \frac{(\rho_{aSL} - \rho_{fSL})(\rho_{ah}/\rho_{aSL}) - \left(\dfrac{W_e}{V_H}\right)}{(\rho_{aSL} - \rho_{fSL}) - (W_e / V_H)} \tag{6}$$

For helium the ideal value of $(\rho_{aSL} - \rho_{fSL})$ is 0.066 lb/ft^3 (1.06 kg/m^3), but due to normally expected impurities, a more practical value is 0.062 lb/ft^3 (0.099 kg/m^3). Using the latter value along with the value $(W_e / V_H) = 0.0325$ from Figure 1, values for the ratio were computed as a function of altitude and are presented in Figure 2. Also shown in Figure 2 is the variation assuming a more optimistic value $(W_e / V_H) = 0.020$ which might be achieved with current technology.

While the data in Figure 2 indicates that dirigibles can be designed for altitude capabilities of around 20,000 feet (6096 m), the price in reduced performance will be severe. It is obvious

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*Symbols defined beginning on page 22.

that the indicated performance reduction would not occur if a disposable fluid were used. In such a case the vehicles would take off with the hull volume filled, and as altitude increased fluid would be released. Therefore, if an appreciable altitude capability is desired, a disposable fluid such as hot-air might be more efficient than helium even though its lifting capability is less. If it is assumed that any decrease in buoyant lift due to increasing altitude or allowing the buoyant fluid to cool in flight will be carried aerodynamically, then the computation of buoyant lift at takeoff will suffice for comparing the performance of a disposable fluid to helium. The gross lift for a hot-air vehicle at sea level is:

$$W_{gHA} = (\rho_{aSL} - \rho_{HA})\, V_H \qquad (7)$$

and hot-air density, ρ_{HA}, is proportional to the ratio of standard sea level absolute temperature to the absolute temperature of the hot air, or:

$$\rho_{HA} = \rho_{aSL} \left(\frac{520}{T_{HA}{*}} \right) \qquad (8)$$

Giving for useful lift at sea level

$$W_{uHA} = \rho_a V_H \left(1 - \frac{520}{T_{HA}} \right) - \left(\frac{W_e}{V_H} \right) V_H \qquad (9)$$

The hot-air temperature, T_{HA}, at which this useful lift will be equal to that of a helium dirigible with an altitude capability h, can be obtained by setting W_{uHA} equal to the previously obtained equation for W_{uh}:

$$\rho_a V_H \left(1 - \frac{520}{T_{HA}} \right) - (W_e / V_H) V_H = (\rho_{aSL} - \rho_{fSL}) \left(\frac{\rho_{ah}}{\rho_{aSL}} \right) V_H - \left(\frac{W_e}{V_H} \right) V_H \qquad (10)$$

which reduces to

$$T_{HA} = 520/1 - [(\rho_{aSL} - \rho_{fSL})/\rho_{aSL}] \left(\frac{\rho_{ah}}{\rho_{aSL}} \right) \qquad (11)$$

where ρ_{fSL} is the standard density of helium as before.

Hot-air temperatures for equal performance with a helium vehicle were computed using the foregoing equation and are presented in Figure 3. Also shown are comparable data for steam, which is another good candidate for a disposable buoyant fluid. Water vapor density was assumed equal to

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*Degrees Rankine $t_K = \left(\frac{5}{9}\right) t_R$

the product of hot-air density with the ratio of their molecular weights, and the minimum steam temperature of 600° F (315.5° C) will be superior in terms of lifting capability for an altitude requirement greater than 5000 feet (1524 m). Also hot-air at 600° F (315.5° C) or steam above 212° F (100° C) will have greater lift than helium at altitudes greater than 15,000 feet (4572 m).

It should be noted that another alternative would be to use heated helium for takeoff which is then allowed to cool when altitude is increased. In this way takeoff useful load would be increased somewhat instead of decreased. However, it is problematical whether the double complexity of fluid conservation and high temperatures would be competitive with systems including only one of these complexities, even though the more complex system has superior lifting capability.

A problem in the use of heated fluids for achieving high altitude capability is decreased flight efficiency at those altitudes. When flying at an altitude where air density is only half the sea level air density, (about 20,000 feet (6096 m), the available gross static lift is only one-half what it is for sea level flight. Therefore if such a vehicle is loaded to capacity at takeoff, one-half of its gross weight must be carried aerodynamically at altitude. The aerodynamic efficiency (lift-drag ratio) of conventional dirigible configurations is so poor that such a procedure would not be competitive with other transportation systems. This problem can be minimized, however, if unconventional dirigible configurations are developed with appreciable improvement in aerodynamic lift-drag ratio.

The foregoing discussion addresses the problems of including high altitude capability in dirigibles without considering reasons why such capability is desired. Three primary reasons for desiring increased altitude capability are to fly over mountains, to fly above storms, and to fly faster in regions of reduced air density. A dirigible with a mission range of several thousand miles will not be too constrained by low altitude flight because it can find pathways through the mountains and fly around storms without being greatly inhibited by the increased flight distance. However, for short mission ranges, flight deviations due to weather and terrain will seriously hamper schedules and flight times. Since reductions in effective utilization of a transportation system might be greater for a system which is only efficient at long ranges than for a system limited to short ranges, in the interest of operational flexibility there are strong reasons for including high altitude capability in dirigibles.

Weather and Zero Wind Conditions – There is a large family of problems associated with the practical utilization of dirigibles which do not appear in an evaluation of general dirigible performance capability. It is interesting to note that the critics attempt to eliminate consideration of dirigibles by suggesting they will be too sensitive to severe weather conditions, while from the standpoint of practical utilization the opposite may be true. Among those who have studied the situation, there seems little reason to suppose that dirigibles cannot be designed to operate safely and effectively in extreme weather. However, the problems associated with landing in zero wind may seriously limit the practical utilization of such vehicles. The orientation of a dirigible is established with aerodynamic control surfaces, so some relative air motion must be present for control. If no wind is present during landing, then control of the vehicles orientation will be lost by the time its speed approaches zero. In earlier times, this problem was solved by dangling ropes from the vehicle and having a large ground crew assume control when the vehicle speed became too low. Such a procedure would not be economically viable today because of the relatively higher level of labor costs. Instead, it would be necessary to establish complex ground support equipment at each landing point or establish propulsion systems on the vehicle which include thrust vector control capability. The former would inhibit operational flexibility by limiting destinations to established dirigible ports, while the latter might be complex and expensive. Since one of the principal advantages of dirigibles is their potential to transport material to out of the way destinations without elaborate port facilities, the thrust vector control technique would appear to be most desirable. However, if such systems are to be included, dirigible designs should be established to take complete advantage of the additional capability.

Airfield Requirements – In addition to questions discussed previously concerning the variation of airship efficiency with size, some other misconceptions concerning size exist as a result of operational problems. In discussing a 980 foot (299 m) long proposed airship with a payload capacity of about 150 tons (136×10^3 kg), Reference 1 states:

> . . . it requires none of the elaborate and expensive terminal facilities which characterize heavier-than-air craft operations. No 10,000-foot runways are needed. Essentially, all the airship requires is a level clearing with a radius only little more than the length of the airship.

For safe operation under a variety of weather conditions, the minimum radius for such a circle would probably be at least twice the ship's length, giving an area of 12 million square feet (1.1148×10^6 m^2). This is equivalent to 8 runways 150 feet (45.7 m) by 10,000 feet (3048 m). The runways will handle 10 or 15 aircraft/hour while the dirigible port will be filled by one vehicle. While the airship may require only a level clearing, a good supporting base will be required by the 150 ton (136×10^3 kg) payload after it is unloaded, and ballast before it is loaded, and all vehicles used in the loading and unloading process. Finally, required terminal facilities are not established by the vehicle, but by the payloads arriving and departing. There is no reason to assume that a 150 ton (136×10^3 kg) payload arriving on an airship will require any less facilities than the same payload arriving on a heavier-than-air craft. The only difference appears to be between the aircraft landing strip and the airship mooring area, and that is shown to favor the aircraft, at least in size.

Unique Mission Considerations – Large sizes in airships are considered desirable to carry large bulky loads to out of the way places. Examples are transporting power generators from factory to remote reservoirs, transporting power transmission towers to remote areas with limited accessibility, and transporting and installing power transmission cables. In addition to the question of whether enough such missions would be available to justify manufacture of a large airship, there are serious questions concerning the efficiency with which large expensive systems could be used for such missions. Generally payload will have to be reduced for transporting large loads to remote areas because additional fuel must be carried to return the vehicle to a base where fuel is available. Also, the logistics of providing ballast at a remote location for the return trip may become expensive.

SUMMARY FOR DIRIGIBLES

Discussions above indicate that useful load fraction will not increase with size, and large size carries with it a number of potentially detrimental effects which are difficult to evaluate until such vehicles have been built and operated. However, there are a number of ways in which size can have beneficial effects. While the square-cube law does not appear to apply to useful load percentage, it does apply to power requirements. Useful load increases with volume, but aerodynamic drag only increases as the two-thirds power of volume. Therefore, for the same flight speed and altitude, an increase in size will increase payload capacity more rapidly than it increases power requirement. Conversely, if the same power to weight ratio is installed on a larger vehicle, speed will be increased providing an increase in productivity. Another positive effect of size increase is a decrease in relative crew size. A vehicle twice as big, carrying twice the useful load, may require an increased crew, but doubling of the crew size would not be expected. Finally, a distinct advantage of larger size is ride comfort, or motion stability. Due to their rolling motion, blimps of a few hundred thousand cubic feet would probably not receive widespread acceptance for passenger transportation, but the German Zeppelins of the thirties were reported to be the smoothest riding transportation system ever devised by man. The reason for this difference is again associated with the square-cube law. Intensity of motion will be related to the ratio of imposed force to inertia. Gusts acting on a vehicle produce a force proportional to its surface and area, or the two-thirds power of volume, while inertia increases directly with volume. Therefore, as vehicle volume increases, the ratio of force to inertia decreases.

OBSERVATIONS CONCERNING THE HYBRID AIRSHIP

The hybrids considered here are semi-buoyant vehicles with the buoyant system lifting only a fraction of the vehicle gross weight. For takeoff, landing, and hovering, the balance of vehicle weight is lifted by large diameter propellers oriented in a vertical direction. For horizontal flight the propellers are rotated horizontally and the balance of vehicle weight is borne on aerodynamic lift supplied by the body. The difference between these flight modes illustrates that the hybrid is actually two hybrids. During takeoff, landing, and hovering, it is a hybrid between a buoyant vehicle and a helicopter. During horizontal flight, it is a hybrid between a buoyant vehicle and an airplane. Two optimization requirements exist for such vehicles, which are not present with dirigibles. The optimal distribution of gross weight between buoyant lift and propeller lift requires the establishment of an optimal relationship between engine power and buoyant fluid volume. The second optimal consideration involves shaping the body to achieve both high aerodynamic efficiency (lift-drag ratio) and high volumetric efficiency (volume/surface area). An obvious disadvantage of the hybrid airship compared to the dirigible is the higher ratio of empty weight to volume that will probably result from takeoff thrust requirements and from the structural design requirements of a vehicle with non-circular cross section. The question discussed in the preceding section concerning the influence of scale size on weight will also apply to hybrid vehicles. The question that remains is whether operational and other design considerations for a given set of mission requirements will result in an overall advantage for the hybrid vehicle. The remainder of this section discusses attributes of the hybrid airship from a qualitative standpoint, and these attributes will be supported to a degree in the following section on performance.

1. Conventional dirigibles, when operated at a sufficiently low speed, will require less power per ton of payload and use less fuel per-ton-mile of payload transportation than a hybrid vehicle. However, at the low speed required to achieve these advantages, its productivity will be much less than that of the hybrid, which is designed for much higher speeds, very likely making the dirigible commercially non-competitive.

2. Relatively high altitude capability can also be achieved by hybrids, which is not possible with conventional dirigibles without a complete reversal of its power and fuel consumption advantages. High altitude capability will permit hybrids to be designed for and used in short range missions as well as long range missions without schedule interruptions and decreased efficiency which would occur with conventional dirigibles in short range missions.

3. A hybrid with 30% buoyancy will have three times the ratio of inertia to wind force as a dirigible the same size, thus providing much better motion stability and stability on the ground. The higher inertia and smaller ratio of side area to frontal area for a hybrid will allow such a vehicle to sit on the ground in a cross wind without requiring a weather cocking mooring mast as does the dirigible.

4. A hybrid will not lose control as zero speed is approached during landing, and thus will not require complex ground or flight equipment or a large ground crew, as does the dirigible.

5. A hybrid will not require a complex ballasting system, including facilities for providing and handling ballasts at all origins and destinations, as does a dirigible.

6. Even if cruise conditions are optimized for productivity, the productivity of a conventional dirigible will only be about one-fourth that of a representative hybrid.

7. Helicopters may be more maneuverable than hybrids in confined areas, and thus may have some applications for which hybrids are not suitable. However, this cannot be stated with certainty until experimental hybrids have been produced and tested. In all other non-military applications, hybrids are potentially superior. They will have a greater lifting capacity for the same power, they will have better performance, lower fuel consumption, decreased noise and pollution, less cost and complexity, and decreased vibration with a smoother ride.

8. Due to its relatively low speed, a hybrid will not be generally competitive with fixed wing commercial aircraft on such missions as long range passenger transportation where flight time is very important. However, for shorter ranges where speed is of lesser importance, the hybrid appears to be distinctly superior to commercial fixed wing aircraft. Even though the aerodynamic efficiency (lift-drag ratio) of a hybrid is less than that of commercial fixed wing aircraft, consideration of other factors reverses the comparison. The classical Breguet range equation is:

$$R = C_1 N_t N_p \left(\frac{L}{D}\right)_{max} \ln\left(\frac{W_e + W_f + W_{PL}}{W_e + W_{PL}}\right) \tag{12}$$

which when solved for pounds of fuel per lb-mile of payload transportation gives

$$\left(\frac{W_f}{R W_{PL}}\right) = \left(\frac{1}{R}\right)(e^f - 1)\left(1 + \frac{W_e}{W_{PL}}\right) \tag{13}$$

where

$$f = \frac{R}{C_1 N_t N_p (L/D)_{max}}$$

The larger diameter propellers which are possible with LTA vehicles may result in slightly higher values of N_p, and thus greater fuel efficiency, but the main advantage of LTA vehicles over fixed wing aircraft will be due to lower values of the ratio (W_e/W_{PL}). For fixed wing aircraft, this ratio might be 2 – 4 times as great as it is for LTA vehicles. Thus, the fuel consumption of hybrids will be about 1/2 to 1/3 of fixed wing aircraft.

9. In terms of required power per unit payload weight or ton-miles/hr of productivity, hybrids potentially are about equal to fixed wing aircraft.

10. A hybrid will not only have a lower noise level due to its lower disc loading, and lower pollution due to lower fuel consumption, but both these characteristics will be further improved if Rankine or Stirling cycle engines are used. Due to the large volume capacity available, a hybrid is more suitable for Rankine or Stirling cycle propulsion systems than other air transport vehicles. Stirling cycle engines can be made more efficient than any other combustion engine, resulting in considerable advantage from the standpoints of resource conservation and pollution.

11. By far the most significant advantage of hybrids over fixed wing aircraft, however, is their VTOL capability. The benefits of this capability are too complex to be evaluated accurately, but they are sufficiently significant to have justified a major effort spread over many years to develop VTOL aircraft.

In summary, the following hypotheses are made regarding the relative characteristics of hybrid airships compared to other aircraft.

1. Relative to conventional dirigibles, hybrids will have a higher ratio of empty weight to volume, will require more power and fuel per ton of payload, will have appreciably greater productivity, can be more effectively designed for high altitude capability, will have greater ride comfort in smaller sizes, will not require systems for buoyancy control, and will have more desirable ground handling characteristics.

2. Relative to helicopters, hybrids may not be as maneuverable and will be inferior in missions where their larger size will be detrimental, but in all other non-military applications they are potentially superior. They will have better performance, lower fuel consumption, decreased noise and pollution, less cost and complexity, and decreased vibration with a smoother ride.

3. Relative to fixed wing aircraft, hybrids will be less desirable for long range passenger transportation due to their lower cruise speeds, but will have lower energy consumption, decreased noise and pollution, and will be able to take off and land vertically.

PERFORMANCE ANALYSES

Energy Requirements

The energy efficiency of a flight vehicle is a function of its aerodynamic efficiency (lift-drag ratio), its propulsor efficiency in converting engine power to propulsive thrusting force, and its engine thermal efficiency in converting fuel to engine power.

Aerodynamic Efficiency – Considering aerodynamic efficiency first, an airship has two sources of lift, aerodynamic and buoyant. Therefore, aerodynamic efficiency will consist of the sum of buoyant and aerodynamic lift divided by aerodynamic drag. Lift drag was computed for two configurations, a conventional dirigible shape, and a NASA M-2/F-2 lifting body reentry vehicle shape. The M2/F2 configuration is shown in Figure 12. Aerodynamic drag polars were obtained for the two configurations from References 3 and 4, and are shown in Figure 4. In the absence of better data, the coefficients shown were used in the evaluation of aerodynamic efficiency. However, it should be noted that these data appear to be optimistic, especially in the case of dirigibles. Studies of lifting dirigible configurations by the Goodyear Aerospace Corporation lead one to believe that a conventional symmetric dirigible might not have a maximum aerodynamic lift drag ratio more than about half that shown. Also, what limited information is available from flight tests of the M-2/F-2 indicates that its maximum lift-drag ratio will be less than that shown. However, research done by the Aereon Corporation on lifting body airships indicates that with optimization such configurations might achieve lift-drag ratios between 8 and 10.

Using the data from Figure 4, a vehicle hull volume of 373,000 ft^3 (1.056×10^4 m^3) was assumed with buoyant fluid volume equal to 90% or 335,000 ft^3 (9.48×10^3 m^3). A cruise altitude of 3000 feet (914.4 m) was assumed with speeds of 50, 100, and 150 mph (22.3, 44.7, and 67.1 m/s). And, the calculations were performed for variations in the percent buoyant lift (buoyant lift/gross weight X 100) from 15% to 100%. The results presented in Figure 5 clearly show the superiority in terms of lift-drag ratio of conventional dirigibles and full buoyancy at a flight speed of 50 mph (22.3 m/s). At 100 mph (44.7 m/s), peak efficiency for the dirigible is still superior to the hybrid, but only when buoyancy has been decreased. Also note at this flight speed that the 100% buoyant dirigible has a lift-drag ratio only slightly less than the peak value (at 33% buoyancy) for the hybrid. Finally, peak lift-drag ratio for the hybrid with 18% buoyancy is superior to the dirigible with any percent buoyancy at 150 mph (67.1 m/s).

It can be argued that the poor high speed performance of the fully buoyant dirigible is due to the small size assumed. At 100% buoyancy, lift is proportional to hull volume and drag is proportional to the products of the 2/3 power of volume with the square of velocity.

$$\frac{L}{D} = K\left(\frac{V_H}{V_2}\right) \tag{14}$$

Therefore, if volume is increased, higher cruise speeds can be used while maintaining the same lift-drag ratio. However, the effect of increased size on allowable speed is small. Assuming different sized vehicles with the same lift-drag ratio, consideration of the equation for vehicle drag leads to the relationship:

$$\frac{V_2}{V_1} = \left(\frac{V_1}{V_2}\right)^6 \tag{15}$$

Therefore, doubling the speeds shown in Figure 5 and maintaining the same lift-drag ratio, requires a size increase by a factor of 64, or a volume increase from 373,000 ft^3 (1.056×10^4 m^3) to almost 24 million ft^3 (6.8×10^5 m^3). Even at such large size, speed would have to be limited to around 100 mph (44.7 m/s) to maintain an appreciable superiority in lift-drag ratio.

It is apparent that for the vehicles assumed for Figure 5, even at 50 mph (22.3 m/s) a dirigible has a lower lift-drag ratio than commercial aircraft when percent buoyancy decreases below about 70%; also, at the higher speeds, the same is true at any percent buoyancy. Therefore, if such vehicles are to be superior to aircraft from an energy efficiency standpoint, that superiority must arise from factors other than lift-drag ratio.

As discussed previously, the Brequet range equation indicates an appreciable superiority in terms of fuel efficiency for vehicles with a lower ratio of empty weight to payload weight. The value of this ratio for airships will be only 1/2 to 1/4 that of heavier than air craft, and the resulting increase in fuel efficiency will more than make up for the decreased lift-drag ratio.

Propulsion System – An advantage of LTA vehicles with regard to propulsive efficiency is the type of engine which is suitable. Due to the very large body size, engines which utilize a volume much greater than is acceptable for normal aircraft can be effectively used in LTA vehicles. More specifically, such vehicles are ideally suited to external combustion engines, and in particular, Stirling cycle engines. In addition to their extremely low pollution and noise characteristics, such engines could be used to assist in heating a hot buoyant fluid and can be much more efficient.

Comparison of Fuel Requirements – A brief study was made to compare the fuel requirements of dirigibles and hybrids with each other and with conventional aircraft. Since performance and cost estimates for external combustion engines such as the Stirling cycle engine are uncertain, the advantage they might impart to LTA vehicles was neglected and standard turboshaft engines such as those used in helicopters were assumed, and performance and weight characteristics were estimated from empirical data for conventional dirigibles. For the hybrid vehicles, inert weight was divided between propulsion system weights and all other inert weights. The propulsion system weights were estimated from data in References 6, 7, and 8. The fuel tankage weight was assumed to be included in the non-propulsive weights. The non-propulsive weight-to-volume ratio was assumed to be 0.03 lbs/ft^3 (0.48 kg/m^3) for the purposes of this study. The resulting estimate for empty weight-to-volume ratio (W_e/V) is shown as a function of total installed engine power in Figure 6.

Propulsive thrust at zero speed was derived from empirical data for helicopters in Reference 5 and is shown in Figure 7. The variation in propulsive thrust with speed was estimated from data presented in Reference 10.

Helium was assumed to be the buoyant fluid for the dirigible while two fluids were considered for the hybrid airship, helium and hot air; fluid temperatures at takeoff were assumed to be either 300° F (149° C) or 600° F (315.5° C) for the hybrid. For the helium vehicles, cruise altitude was established as that altitude where the buoyant fluid having cooled to ambient temperature would fill the buoyant volume, provided that sufficient thrust was available to cruise at a speed corresponding to maximum lift-drag ratio for the configuration. If insufficient thrust were available then cruise altitude was reduced to a point where the maximum lift-drag ratio condition could be met with the available thrust. For the hot-air vehicles there was no altitude limitation due to fluid expansion. Thus, fluid temperature was assumed reduced to ambient and cruise altitude adjusted for the available thrust and the maximum lift-drag ratio condition. The symbol key identifying the performance curves of Figures 8 through 11 is shown on Table III.

The weight of fuel required per ton-mile of payload transported at the cruise condition is shown as a function of cruise speed in Figure 8. In addition to hybrids and conventional dirigibles, data are shown for a number of other aircraft with empty weights in the same general category as the LTA vehicles. The latter data were obtained from Reference 6. It is apparent from Figure 8 that at low enough speeds conventional dirigibles will be more energy efficient than any of the other vehicles. However, at 70 mph (31.3 m/s) they become less efficient than helium filled hybrids, at 100 mph (44.7 m/s) they become less efficient than hot-air hybrids operating at higher speeds, and at 150 mph (67.1 m/s) they will be less efficient than most heavier-than-air vehicles. While the helium filled hybrids are more efficient in energy use than the hot-air hybrids, they are limited to lower cruise speeds because of the limitation on cruise altitude. Both types of hybrids at either buoyant fluid temperature are well over twice as efficient as the best heavier-than-air vehicle, and this is without the potential advantage of Stirling engines which are suitable for the hybrids.

Productivity

In addition to establishing the fuel used per ton-mile of payload transported, the foregoing study also examined payload, required power, and productivity. The latter quantity is defined as the ton-miles per hour of payload transported. These quantities are important because of their effect on the economic viability of a transportation system. Increases in productivity imply increased revenues, while increases in required power for the same payload implies increased development, procurement, and operating costs.

For the dirigibles and hybrids, gross payload was divided between payload and required fuel in a manner to achieve a 500 mile (805 km) range. This would be somewhat greater than the range of helicopters used for comparison, and somewhat less than range of the fixed wing aircraft. For the vehicles considered previously, payload and horsepower per ton of payload are shown as function of design cruise speed in Figures 9 and 10, respectively. The hull volume for both the dirigible and the hybrid was 373,000 ft^3 (1.053×10^4 m^3).

Payload – Figure 9 illustrates an interesting aspect of hybrids relative to the other vehicles: for a given vehicle size, payload will increase as the design cruise speed increases. This occurs because larger engine powers will be required for higher speeds, and with higher engine power the takeoff gross weight will be higher since it is the sum of static lift and propulsive lift. For conventional dirigibles propellers would not be rotated vertically, increasing takeoff gross weight, because the vehicle would then have to carry the excess weight aerodynamically during cruise, and the lift-drag ratio of a dirigible is too low for this to be efficient. Therefore, the increased power required by dirigibles at higher speeds simply means a greater fuel requirement for a given range, and as indicated in Figure 9, at some speed payload is reduced to zero with all the lifting capacity required for fuel.

Figure 9 also shows that for the heavier-than-air vehicles used for comparison, payload is not as great as that possible with the hybrids, but is greater than conventional dirigibles. These vehicles of course would also have increased payloads if their power were increased, but the increase would probably not be large. With helicopters, propulsion systems weight is a larger percentage of vehicle inert weight, and with fixed wing aircraft the only increase in payload, due to an increase in engine power, would be that resulting from accelerating to a higher speed during takeoff with the same lift coefficient.

Power to Payload Ratio – One might think that the increased payload is simply the result of an undesirably excessive use of power but this is not the case. Figure 10 shows that the required power per ton of payload is less than or about the same as that required by heavier-than-air vehicles. At sufficiently low speeds, dirigibles and helium filled hybrids require less power than hot-air hybrids due to the lifting capacity of helium in the former. However, if higher speeds are desired the power advantage is reversed. An interesting point illustrated in Figure 10 is the low power requirement of the Skycrane helicopter which has neither buoyant lift nor a fixed wing to provide high aerodynamic efficiency. The reduced power requirement is due to the large diameter low disc loading rotor which converts engine power to thrust with much greater efficiency. This illustrates that large vehicles such as LTA systems should take advantage of their large size by using large diameter propellers with low disc loading.

Payload Productivity – While fuel use data such as that in Figure 8 is of interest with regard to energy conservation and pollution, it is only one of the elements of operating economy. While economy must be sacrificed to some extent in the light of the current energy and pollution picture, it remains the most important criterion. Therefore, the factors affecting economy are significant, and one of the most important of these is productivity. To a first order of approximation, the costs of developing, procuring and operating a commercial air transport vehicle will be proportional to vehicle empty weight. Therefore, if several vehicles of roughly the same empty weight are compared, then that one which will perform the greatest amount of transportation will probably be most economical. Productivity, defined as payload ton-miles/hr of transported goods is the best general measure of quantity of transportation.

Productivity for the various vehicles being considered is presented in Figure 11. It is apparent that at this size and range, conventional dirigibles will not be able to compete economically with other flight systems. Their productivity is only about one-third that of helicopters, one-fifth that of air transports, and as little as one-eighth that of hybrid vehicles. Since the empty weights (and hence procurement costs) of these vehicles are about the same, profits will vary linearly with productivity. The argument that large increases in size and range would eliminate this deficiency is not valid. As discussed previously, there is little reason to suspect that increases in size will produce increases in performance. This then is the problem of conventional dirigibles. Unless it can be shown that the costs per pound for procuring and operating them is only a small fraction of that for other flight systems, or that sufficient missions are available that they alone can perform, then they will not be economically viable.

Perhaps of greater interest is the fact shown by the data in Figure 11 that for hybrids the situation with conventional dirigibles is reversed. Both helium and hot-air hybrids have a potential productivity which is superior to all other air transport systems examined. It is of further interest that since the upper limit of the hybrid curves all represent the same power levels for vehicles of the same size, then the indication is that hot-air vehicles will be more productive than helium filled vehicles. While an anlysis has not been performed, the indications are that even further increases in productivity would be achieved if steam were used as the buoyant fluid. In view of other advantages such as reduced costs and elimination of extreme containment requirements, it appears that future evaluations of hybrid vehicles should concentrate more in the disposable fluids such as hot-air or steam.

PERFORMANCE OF A SPECIAL PURPOSE HYBRID AIRSHIP

The uncertainties involved in the operation of the airships make it inadvisable to gamble the large sums of money required for the development of very large vehicles if much smaller vehicles can be developed first and will have a practical application. By developing smaller vehicles and using them, the problems associated with airships will become more clearly understood and the initial monetary outlay will be greatly reduced. However, there is one exception to this approach and that is the special purpose vehicle. The advantage of large special purpose vehicles is illustrated by the difference between large oil tankers and cruise passenger ships. Development, manufacturing, and operating costs for the tanker are extremely low relative to the cruise ship, because of its much greater simplicity and its use in a single type of mission.

For airships, the advantages of large special purpose vehicles can be even greater if the mission involves certain types of payloads. A major factor establishing the inert weight and design difficulty of an airship is the necessity to distribute a concentrated load over a large lifting area. If the payload itself could be distributed throughout the vehicle, then the difficulty of design and manufacture would be greatly reduced. Such a procedure might be feasible for an airship designed to transport crude oil and natural gas from its source to its market. If a semi-rigid structure consisting of large diameter flexible tubes pressurized to achieve rigidity were designed to such a vehicle, then oil could be pumped into the tubes, thus distributing the payload weight over the surface of the vehicle. The other payload, natural gas, would automatically be distributed throughout the vehicle, and would provide its buoyant lift. Such a vehicle would be considerably lighter, and cost less to develop and manufacture than conventional airships.

Lifting Body Hybrid Configuration – A study was performed to assess the performance of a large M-2/F-2 lifting body as an oil transportation airship. The mission consists of transporting oil and natural gas from Prudhoe Bay to Seattle with an estimated range of 1500 miles (2414 km). The fuel requirement was based on a round trip. It was assumed that all of the natural gas would be delivered and the vehicle flown back on hot-air if it were required to assist in lifting the empty vehicle. A vehicle length of 1200 feet (366 m) was assumed, consistent with a number of airship proposals in recent years. Vehicle hull volume for this length is:

$$V_H = 80.6\times10^6 \text{ ft}^3 \ (2.28\times10^6 \text{ m}^3)$$

Assuming that 95% of the hull volume was available for natural gas, and a natural gas density of 0.05 lb/ft^3 (0.8 kg/m^3), the buoyant lift is 2.03×10^6 lb (9.03×10^6 N). Since the study covered a range of engine power, vehicle empty weight was separated into two components: total propulsion system weight, W_e, and total remaining weight, W_u. Due to the vehicle's simplicity and the structural design, it was assumed that:

$$W_H = 0.015\ V_B = 1.15\times10^6 \text{ lb} \ (5.22\times10^5 \text{ kg})$$

Total propulsion system weight was estimated as:

$$W_P = 0.3\ F_{SL}$$

where F_{SL} is the rated sea-level thrust.

Data from Reference 5 and 9 were used to develop an empirical relationship between thrust and power for the helicopter type rotors.

Horizontal takeoff was assumed at a takeoff speed of 100 ft/sec (30.5 m/s). Vehicle gross weight at takeoff is given by:

$$W_g = F_o \sin\theta + L_{ao} + L_B \tag{16}$$

$$L_{ao} = \left(\frac{L}{D}\right)_{ao} D_o = \left(\frac{L}{D}\right)_{ao} F_o \cos\theta \tag{17}$$

or:

$$W_g = F_o \sin\theta + 2.2\, F_o \cos\theta + L_B \tag{18}$$

where takeoff is assumed at lift coefficient $C_L = 0.9$, which from data in Reference 4 corresponds to an aerodynamic lift-drag ratio of 2.2.

To obtain the value of θ for a maximum gross weight, the derivative of W_g with respect to θ is set equal to zero, with the following result:

$$\cos\theta_{max} = 2.2 \sin\theta_{max} \tag{19}$$

or the value of θ for maximum gross weight is:

$$\theta_{max} = 24.46^\circ$$

This value was used in the study.

The analytical procedure consisted of assuming various levels of engine power and computing vehicle gross weight and gross payload weight using the equations previously developed. Gross payload weight consisted of oil used for engine fuel during transportation plus oil delivered to the destination. In the event that a power plant is used which will not burn crude oil, then refined fuel would be carried in the same quantity and the weight of crude oil delivered would be the same. To separate these two quantities and thus compute delivered payload, an iterative procedure was necessary for the evaluation of cruise conditions. An initial estimate was made of (ρ_c/ρ_{SL}), the ratio of cruise air density to sea-level air density, and cruise power computed from the relationship:

$$P_c = 0.8\, P_o \left(\frac{\rho_c}{\rho_{SL}}\right) \tag{20}$$

where cruise power is assumed to be 80% of the power available at cruise altitude. For efficient operation, cruise flight was assumed to occur at maximum aerodynamic lift-drag ratio ($L/D = 6.5$ from Figure 4) and this assumption along with gross weight and cruise air density provided inputs necessary for computation of cruise speed and cruise thrust.

During the foregoing calculation, gross weight was modified to account for the fact that the volume of buoyant fluid, and thus buoyant lift, must be reduced as cruise altitude is increased. For computing the quantity of oil used for fuel, an energy requirement of 9500 Btu/hp-hr (3.733 J/W·s), and an energy availability of 17,000 Btu/lb (39.516 MJ/kg) were assumed.

Results of the evaluation are presented in Table I for a power range from 100,000 hp (74.57 MW) to 300,000 hp (223.7 MW). At all power levels except the lowest, payload in terms of pounds of oil is greater than the vehicle empty weight. If the weight of natural gas is included in the payload, then it is 2.99 to 3.29 times the vehicle empty weight, a remarkable achievement for an air transport vehicle. Cruise speeds of 118.1 mph (52.8 m/s) to 174.1 mph (77.8 m/s) are achieved at cruise altitude varying from 8900 feet (2712 m) to 4900 feet (1493 m). A fleet size is shown based on utilization of the vehicles 90% of the time, to achieve the transportation of one-million barrels of oil per day, assuming 4 hours for loading and unloading at each end of the trip. At the maximum power level the fleet size is only 115 vehicles, and would be even lower if higher powers were used. While one-million barrels per day (0.159 Mm^3/day) is only one-half the maximum capacity of the currently planned Alaskan pipeline, when all factors are considered, the pipeline's average oil transportation might not be much greater than the million barrel per day figure (0.159 Mm^3/day).

A factor which does detract from the use of dirigibles in the manner discussed is the ratio of natural gas to oil. For the range of power shown in Table I, the vehicles will transport between 3940 and 7740 cubic feet (111 and 219 m^3) of natural gas for every barrel of oil taken from the well. Reference 10 indicates that in the Prudhoe Bay field the ratio of natural gas to oil is only 2600 ft^3 per barrel (463 m^3/m^3). Therefore, engine horsepowers beyond the maximum level in Table I, possibly as high as 600,000 to 700,000 (0.447 GW to 0.522 GW), would have to be used to bring the ratio of gas to oil to the value available. However, this is not absolutely necessary since part of the oil could be transported using hot air buoyancy instead of natural gas buoyancy. To achieve the same buoyant lift, air would have to be heated to a temperature of only 336° F (169° C), and this temperature would only have to be maintained during takeoff.

HANDLING PROBLEMS

The handling problems associated with airships are among the principal reasons for not developing modern airships in large sizes until commercial experience is available in small sizes where the economic investment is not prohibitive. The use of very large ground crews to control the ship on landing and takeoff is not economically viable in the commercial environment of today. While systems have been suggested to minimize ground crews with specialized equipment, the requirements for such equipment negate one of the often quoted advantages of airships, i.e., their ability to operate in and out of remote areas with a minimum of airport facilities. Another problem is the inability of an airship to land at all during severe weather.

While the handling problems of a hybrid cannot be described with confidence since such vehicles have not been operated, one can conclude that they will be appreciably improved over those of conventional dirigibles. A hybrid with only 25% buoyant lift will have 3 to 4 times the inertial mass as a fully buoyant vehicle with about the same surface area. The effect of wind forces on the larger mass will be appreciably reduced, and handling will be appreciably improved. While one might expect the handling problems of a hybrid to be appreciably greater than those of heavier than air craft, the deficiency, if it exists, might well be less than believed. It must be noted that the inertial mass which resists aerodynamic forces includes the mass of the buoyant fluid, that the effective mass is considerably increased by air in the immediate vicinity of the airship hull, and that moments of inertia are considerably increased by the long lever arms from the center of rotation. These factors support the contention that there may not be many heavier than air craft missions which hybrid vehicles cannot perform because of handling problems.

SAFETY

Semi-buoyant lifting body hybrid vehicles with 20 to 40% buoyancy may be inherently the safest mode of transportation ever devised by man. The hazards of sea-going ships are well known with even supposedly unsinkable ships occasionally sinking. Surface land transportation will not fall out of the sky or sink in the sea, but is confined to narrow corridors with many vehicles operating in the same corridor. The result of this concentration of vehicles is reflected in accident statistics Normal aircraft can be made relatively safe with sufficient attention to quality control and maintenance. Conventional dirigibles will not fall out of the sky at dangerous speeds or sink in the sea, and they are not confined to narrow high density corridors. However, their large size makes them susceptable to bad weather, and history indicates that a loss of power or control during high and gusty winds can lead to disaster.

The degree to which the foregoing hazards are inherent in a hybrid vehicle is minimal. The hybrid will not normally operate in high density corridors, but even if a collision occurs it should not be catastrophic. High speeds are not required for it to become airborne, so the hazard of takeoff and landing will be almost eliminated. The higher ratio of inertial mass to surface area will make a hybrid much less subject to destruction by bad weather than a conventional dirigible. If a hybrid loses power, control, and all its buoyant fluid in flight, it will drop to the surface but its large platform area and the associated drag will limit its impact to speeds under 50 mph (22.3 m/s). By proper location of compartments containing passengers and/or crew, deceleration can be cushioned and limited to safe levels at such impact speeds.

ECONOMIC FACTORS

There is no way at the present time to estimate the costs associated with lighter-than-air vehicles with any confidence. Due to materials and technology changes, costs associated with dirigibles of former decades would not be indicative even of conventionally designed dirigibles today. Also, cost estimations associated with hybrid vehicles would be considerably less reliable since no such vehicle has ever been produced and operated commercially. However, due to the relationships of costs with various technical factors, some valid comments can be made concerning the costs of such vehicles relative to other transportation systems.

To a first approximation, vehicle costs will be roughly proportional to empty weight. Empty weight for conventional dirigibles is about equal to gross payload weight (payload plus expendables), while empty weight for heavier-than-air-craft is much greater than payload weight, about twice as great in some cases. Therefore, on the basis of a constant cost per pound of empty weight, the costs of a conventional dirigible per pound of payload capacity may be only about half that of heavier-than-air-craft. For hybrids, the advantage is much greater since empty weight is only one-fourth to one-half the payload weight, resulting in a cost per pound of payload weight less than that of heavier-than-air-craft by a factor of 4 to 8.

The cost associated with weight minimization is difficult to evaluate, but it does exist, and it will become larger as the effort to minimize weight becomes greater. Therefore, one can say generally that this element of cost will be decreased if the importance of minimizing weight is decreased. Since the ratio of payload weight to vehicle empty weight for LTA vehicles is around

2 to 8 times as great as for HTA vehicles, a percent decrease in inert weight of the former results in a percent increase in payload weight only 1/8 to 1/2 that which would be achieved in the latter. Therefore, the importance of minimizing weight is considerably decreased with LTA vehicles, and costs associated with such an effort would be less.

In many systems, the requirements of precision and reliability are related to performance and maintenance requirements, but in air transportation systems they are related more strongly to safety requirements. Operational safety of an air vehicle is a function of inherent configurational safety and of the effort in the manufacturing process to produce high quality reliable systems. In the light of previous discussions on the higher level of inherent safety of airships, it is reasonable to conclude that a lesser effort on precision and reliability will be required to achieve the same level of safety, and therefore the costs associated with these factors would be reduced.

The foregoing discussion indicates the economic superiority of LTA systems to other aircraft with the same payload capacity. However, payload is not the only important factor in an economic evaluation. For transportation systems, costs must be weighed against revenues, and revenue rate is proportional to productivity, or ton-mile/hr of transportation. Therefore, the low productivity of conventional dirigibles, as indicated in Figure 11, offsets other factors and may cause them to be economically undesirable relative to other aircraft. However, hybrids with their equal or superior productivity appear to have a great deal of economic promise.

Comparisons of Airship with Pipeline for Transporting Alaskan Oil

A somewhat different approach can be taken toward the economic evaluation of a special purpose fuel transportation hybrid because of its simplified mission. An LTA vehicle of the size discussed would cost between one and two billion dollars to develop, and due to the simplified nature of the fuel transportation vehicle, its development cost should be at the low end of this range. The first unit costs of LTA vehicles at this size would be 50 million to 100 million dollars, and again the simplified vehicle should be at the lower end. Applying a conservative 90% learning curve to a procured quantity of 115 vehicles, the average procurement cost would be \$25 million per vehicle, or total development and procurement costs for a fleet of 115 vehicles would be \$3.875 billion. For an economic evaluation this initial cost should be compared to those for an alternative transportation system including the Alaskan oil pipeline. The fleet of LTA vehicles will only transport one-million barrels per day while the Alaskan pipeline has a capacity of 2 million barrels a day (3.18×10^5 m^3/day), but consideration of use factors indicates that the average capacity of the pipeline may not be much over one-million barrels per day. The pipeline will initially transport only 600,000 barrels per day (9.54×10^4 m^3/day) (Ref. 10) and it will take about five years to increase this to maximum capacity. There will also be inoperative periods for repair and maintenance, and there will be a long tailoff period at the end of its life due to diminishing of supplies in the Prudhoe Bay Field.

A recent estimate of the cost for the Alaskan pipeline is \$4 billion, which appears to be about the same as that for development and procurement of an LTA fleet. However, it is not generally pointed out that for various environmental reasons it will be necessary to also remove the natural gas which is present if the oil is removed. Estimates based on data in Reference 11 indicate that a pipeline for this purpose would cost in the vicinity of \$1 billion even when taking advantage of the oil pipeline right-of-way. When one also considers the costs of port facilities at Valdez, a natural gas liquefaction plant, and oil and LNG tankers, the total initial cost of the pipeline transportation system may approach twice that for the LTA system.

To estimate delivery cost for gas and oil, one can assume a crew of 4 with four crews per vehicle at an average cost of \$25,000 per man-year. For 115 vehicles this gives \$46 million/yr. To the degree of accuracy in the estimate of initial capital investment cost, \$3.875 billion, one can also assume an annual cost for everything except crew (e.g., amortization, interest, maintenance, etc.) equal to 20% of the capital invested, or \$775 million/yr. Therefore, the total delivery charges will be \$821 million/yr. The quantity of energy delivered per year is 2.39×10^{15} Btu (2.52×10^{18} J) in the form of natural gas and 1.862×10^{15} (1.964×10^{18} J) in the form of oil, for a total of 4.252×10^{15} Btu/yr (4.490×10^{18} J/yr). For the estimated charges this comes to \$0.193 per million Btu (\$0.183/GJ), or \$0.193/thousand ft^3 (\$0.681/hm^3) of natural gas and \$0.985/barrel (\$6.195/m^3 of oil.

If the previous assumption is valid and the initial cost of pipeline, LNG plant, port facilities, and ships is twice the initial cost of the dirigibles, or 2(\$$3.875 \times 10^9$) = \$7.75 billion, then assuming the same 20% annual operating costs without operating personnel, the annual operating costs will be \$$1.55 \times 10^9$ + operating personnel costs. Neglecting the cost of operating personnel and assuming the same delivered quantities, this results in \$0.364 per thousand ft^3 (\$1.285/hm^3) of gas delivered and \$1.865/barrel of oil (\$11.73/m^3), which is almost twice the corresponding values for airship transportation.

APPLICATIONS

General

Very large general cargo and passenger carrying airships require special consideration of missions they might perform because of their tendency to be non-competitive with alternate modes of transportation. They will fly several times as fast as sea and land transporters, but their relative efficiency and productivity is too low to make them competitive with such systems. They can be more efficient than other types of air transportation but their low speed and productivity severely damages their competitive position. Therefore, one must look for special missions where other modes of transportation have special weaknesses, and generally such missions will not be sufficiently numerous or of sufficient importance to justify a large scale development program.

The case for small semi-buoyant hybrids is more promising. It is unnecessary to hypothesize novel missions for such vehicles since they have the potential to perform more effectively and economically many of the missions currently performed by helicopters and low speed aircraft. There are probably very few helicopter missions which could not be performed as effectively or more effectively by hybrids, and the operational costs for the latter should be considerably less. For higher values of fixed wing aircraft speed and range hybrids would not be competitive except in special cases, because of their relatively low operating speed. However, in the field of short-haul air transport, where speed is of less importance, hybrids will frequently be competitive and will have a special competitive advantage where their VTOL capability is of value. Table II lists a prediction of General Aviation Aircraft use in 1975 obtained from Reference 12. Semi-buoyant hybrid vehicles may be able to perform a large majority of the missions shown with either effectiveness or improved economy.

Special Applications

A possible use for hybrid vehicles is as a replacement for or supplement to high speed ground transportation systems in and around dense population areas. Such a use would be predicated on eliminating some of the problems of existing systems. Transportation requirements vary considerably with time of day, and there are also appreciable changes in transportation patterns with days of the week and seasons of the year. If a tracked or fixed roadbed type of system is sized to provide adequate service during peak requirements, then it must be operated inefficiently during periods of lesser requirements. It is difficult if not impossible to divert vehicles in such systems to other uses in other areas. However, much greater efficiency could be realized if the system were sized for the lower requirement period and then supplemented during peak requirement periods with hybrid vehicles operating over the same routes. The increased efficiency would be due to the fact that during off-peak hours the hybrid vehicles could be effectively used in other transportation missions.

Another special use for hybrids is to bypass the normal interfaces between sea and land transportation. Examples of such uses are removal of cargo from coastwise ships underway and transporting it to inland destinations, and transporting fish to canneries from fishing boats at sea. In each case economic advantages would be derived from utilization of the surface ships in their primary mission for a greater percentage of their operating time, and in the greater speeds available in transporting such payloads to their destination.

The fuel transportation mission has already been discussed, but some mention should be made of secondary missions which such a special purpose vehicle could perform. There is an annual fluctuation in energy demand with peaks in summer and winter. Therefore, if a fuel transportation fleet were sized for a greater capability than the average, part of the fleet could be diverted to other uses during spring and fall. During these periods transportation is needed in the farming industry which could effectively utilize such vehicle operating in the hot-air mode. A specific example would be transportation of the wheat crop to market in the fall. It seems to be a perennial problem for wheat-farmers that when the fall crop is harvested there is insufficient rail transportation available to carry it to market. Finally, such vehicles could be effiectively used by industry in dealing with foreign countries. In the past, oil companies have provided the capital to build pipelines from oil fields to a port area, and build port facilities and gas liquefaction plants. Then at a later date these facilities have too frequently been taken over by the country resulting in a loss in capital investment by the companies. If fuel transportation hybrids were used then only capital invested in the oil field development would be risked.

Emergency Missions

When a natural disaster (such as earthquake, fire, flood, or storm) hits an area one of the serious problems generally is the interruption of transportation corridors. People must be rescued and supplies and equipment must be brought into the area. The only vehicle which can reliably perform such missions under almost all conditions is a vertical takeoff and landing aircraft. Helicopters would be fine for such a mission, but their payload is woefully inadequate when such conditions prevail. LTA hybrids would ideally suit such missions, especially if they were available in a range of sizes. Vehicles would probably not be purchased solely for emergency use, but would be diverted from other applications. If an area has a fleet of hybrids in use for rapid transit or short haul transportation, it automatically has a fleet of the best emergency vehicles available in the event of a major natural catastrophe.

An emergency mission of particular interest is the fighting of wildland fires. When high winds are present in company with high temperatures and low humidities, forest and brush fires cannot be controlled with any currently available equipment. It is necessary in such cases to simply wait until the wind dies down before attempting to block the fire spread in the direction of wind motion. However, such fires could be slowed down sufficiently for normal firefighting techniques to become effective if the area ahead of them could be moistened with a sufficient quantity of water. Unfortunately, current air vehicles used for fighting fires are limited in payload to a few thousand gallons of water, and larger vehicles cannot be used because their speed and controllability are unsafe for such low altitude missions in rough terrain. Conversely, LTA hybrid vehicles will have low speed and low altitude capability along with high payloads. A vehicle sized for a rapid transit mission would have several times the payload of the largest current air vehicles use in firefighting, and if a fuel transportation hybrid of the size discussed earlier were diverted for this use in a hot-air mode it would carry more than a quarter million gallons (9.46×10^2 m^3) of water. It is probable that by this means almost any wildland fire could be slowed sufficiently to be subsequently controlled.

Finally, if the costs associated with hybrid airships are not prohibitive, they will be useful in a vast assortment of missions in emerging non-developed countries where road and rail transportation is minimal.

CONCLUDING REMARKS

A study of conventional dirigibles and more novel LTA hybrid vehicles has been made to evaluate their potential use to supplement existing transportation systems. Arguments are presented to indicate that while conventional dirigibles might be effectively used at some time in the future, there are many uncertainties regarding their potential effectiveness which result in too high a risk to justify the large sums of money which would have to be invested, providing a more promising alternative is available. LTA hybrid vehicles are suggested as such an alternative since they can be produced and used successfully in very small sizes requiring much smaller monetary risk. Hybrids appear to be superior to other modes of transportaiton in terms of energy conservation, reduced pollution and noise, and in transportation productivity. Not only might hybrids be competitive in missions currently performed by heavier-than-air-craft, but they can be useful in a number of unique missions currently not performed by HTA vehicles. Of particular importance is their ideal suitabilit as emergency vehicles to provide much needed transportation to remote areas following a natural catastrophe such as earthquake, fire, flood, or storm.

While it is recommended in the interest of financial prudence that the initial modern development of LTA vehicles should be started with very small vehicles, it is also suggested that special purpose vehicles might be a worthwhile development objective in much larger sizes. An example of such a vehicle to transport oil and natural gas from the North Slope of Alaska to Seattle, Washingto was studied and the indication obtained that it would be more than economically competitive with the currently planned Alaskan pipeline.

NOTATION

C_d	drag coefficient
C_1	constant in Breguet equation
D	drag, lb
F	propulsive thrust, lb
G	acceleration of gravity, ft/sec^2
K	ratio of volume to buoyant lift
K_1	thrust constant
L	lift, lb
l_D	disc loading, lb/ft^2
P	engine horsepower
R	range, miles
S	surface area, ft^2
T	absolute temperature
V	volume, ft^3
v	speed, mph or ft/sec
W_e	empty weight, lb
W_f	fuel weight, lb
W_g	gross weight, lb
W_h	empty weight minus propulsion systems weight, lb
W_p	propulsion system weight, lb
W_{pl}	payload weight, lb
W_u	useful lift, lb
N_p	propeller efficiency
N_t	thermodynamic efficiency

θ	angle between thrust vector and horizontal, degrees
ρ	fluid density, lb/ft^3 or slug/ft^3

Subscripts

0	takeoff
a	air, aerodynamic
B	buoyant
C	cruise
f	buoyant fluid
H	hull
h	at altitude
HA	hot-air
SL	sea level
PL	payload

REFERENCES

1. "Cargo Airships: A Renaissance?", Francis Morse, Handling and Shipping, June, 1972.
2. "Investigation of Powered Lighter-Than-Air-Vehicles," Jerome J. Vorochek, Goodyear Aerospace Corporation, GER 13140, February 1967.
3. "Airship Model Test in the Variable Density Wind Tunnel," Ira H. Abbott, NACA Report No. 394, 1931.
4. "Preliminary Investigation of Modified Blunt 13° Half-Cone Re-Entry Configurations at Subsonic Speeds," George C. Kenyon and George C. Edwards, NASA TMX-501, December 20, 1960.
5. "Janes All the Worlds Aircraft 1969-70," McGraw-Hill.
6. "Q-fan for General Aviation," Rose Worbell, Millard G. Mays, Mark Waters, NASA CR-114665, December 1973.
7. "Generalized Method of Propeller Performance Estimation," Hamilton Standard, United Aircraft Corp.
8. "Parametric Study of Dynamic Lift Aerostats for Future Naval Mission," Goodyear Aerospace Corporation, GER 13564, January 1968.
9. "Characteristics of Shrouded Propellers," Hamilton Standard, United Aircraft Corp.
10. "Energy Statistics: A Supplement to the Summary of National Transportation Statistics," Report No. DOT-TSC-OST-73-34, Dept. of Transportation.
11. "U.S. Energy Outlook," National Petroleum Council, November 1971.
12. "General Aviation: A Study and Forecast of the Fleet and Its Use in 1975," Federal Aviation Administration, July 1966.

TABLE I.– FUEL TRANSPORTATION HYBRID AIRSHIP CHARACTERISTICS

Engine rated horsepower (MW)	100,000 (74.5)	150,000 (111.8)	200,000 (149.1)	250,000 (186.4)	300,000 (223.7)
Propulsion system weight lbs (10^5 kg)	300,000 (1.361)	450,000 (2.041)	600,000 (3.721)	750,000 (3.402)	900,000 (4.082)
Vehicle empty weight 10^6 lbs (10^5 kg)	1.45 (6.58)	1.60 (7.26)	1.75 (7.94)	1.90 (8.62)	2.05 (9.30)
Vehicle gross weight 10^6 lbs (10^6 kg)	3.72 (1.69)	4.56 (2.07)	5.41 (2.45)	6.25 (2.83)	7.11 (3.22)
Gross payload weight 10^6 lbs (10^6 kg)	2.27 (1.03)	2.96 (1.34)	3.66 (1.66)	4.35 (1.97)	5.05 (2.29)
Percent buoyant lift	54.50	44.5	37.5	32.5	28.5
Cruise altitude, ft (m)	8,900 (2713)	8,200 (2499)	7,100 (2164)	6,100 (1859)	4,900 (1493)
Cruise speed, mph (m/s)	118.10 (52.8)	136.70 (61.1)	151.40 (67.7)	163.60 (73.13)	174.10 (77.8)
Cruise power, hp (MW)	61,150 (45.6)	93,900 (70.0)	129,350 (96.4)	167,350 (124.7)	208,350 (155.4)
Roundtrip cruise time, hr	25.40	21.90	19.82	18.33	17.23
Roundtrip time, hr	33.40	29.94	27.82	26.33	25.23
Propulsion fuel, lb (10^5 kg)	868,000 (3.94)	1,151,000 (5.22)	1,434,000 (6.50)	1,714,000 (7.77)	2,007,000 (9.10)
Oil delivered, 10^6 lb/trip (10^5 kg/trip)	1.402 (6.36)	1.809 (8.20)	2.226 (10.09)	2.636 (11.95)	3.053 (13.85)
Oil delivered, barrel/day (m^3/day)	3,360 (534.2)	4,832 (768.2)	6,400 (1017)	8,010 (1273)	9,680 (1539)
90% utilization bbl/day (m^3/day)	3,025 (480.9)	4,350 (691.6)	5,760 (915.8)	7,210 (1146)	8,710 (1385)
Gas delivered 10^6 ft^3/trip (10^6 m^3/trip)	58.60 (1.66)	59.90 (1.69)	62.00 (1.75)	64.15 (1.82)	66.50 (1.88)
Gas delivered 10^6 ft^3/day (10^6 m^3/day)	42.1 (1.19)	48.00 (1.36)	53.45 (1.51)	58.45 (1.65)	63.25 (1.79)
90% utilization 10^6 ft^3/day (m^3/day)	37.90 (1.07)	43.20 (1.22)	48.10 (1.36)	52.60 (1.49)	57.00 (1.61)
Fleet size for 10^6 bbl/day	331	230	174	139	115
Fleet gas del. 10^9 ft^3/day (10^6 m^3/day)	12.55 (355.4)	9.94 (281.4)	8.37 (237.0)	7.31 (207.0)	6.55 (185.5)

TABLE II.– PREDICTED GENERAL AVIATION AIRCRAFT IN 1975

Use	Number of aircraft		Comments
	Fixed wing	Rotary wing	
Aerial application	6,200	350	Crop dusting, seeding, and fertilizing, restocking fish, cloud seeding, etc.
Industrial/special use	1,900	400	Pipeline and highway patrolling, aerial surveying, emergency rescue, advertising, photography, helicopter hoist, firefighting, etc.
Air-taxi	12,100	900	Scheduled air-taxi, non-scheduled air-taxi, charter services
Business	31,250	900	Motives for justifying the acquisition of corporate aircraft are: • Save valuable executive time • Make own schedules • Reliability, safety • Reach off-airline cities • Prestige
Personal	88,450		
Instructional	6,855		
Other uses	3,855		
Totals	149,755	2,550	

TABLE III.– KEY FOR FIGURES 8 THRU 11

Symbol	**Vehicle Type**
	Helicopter
1	Boeing-Vertol M114
2	Siskorsky S-64E
	Transport Aircraft
3	Fairchild-Hiller FH-227D
4	G.D. Convair 600
	Hybrids
– – – –	300° F hot air
———	600° F hot air
– —— –	*Dirigible*

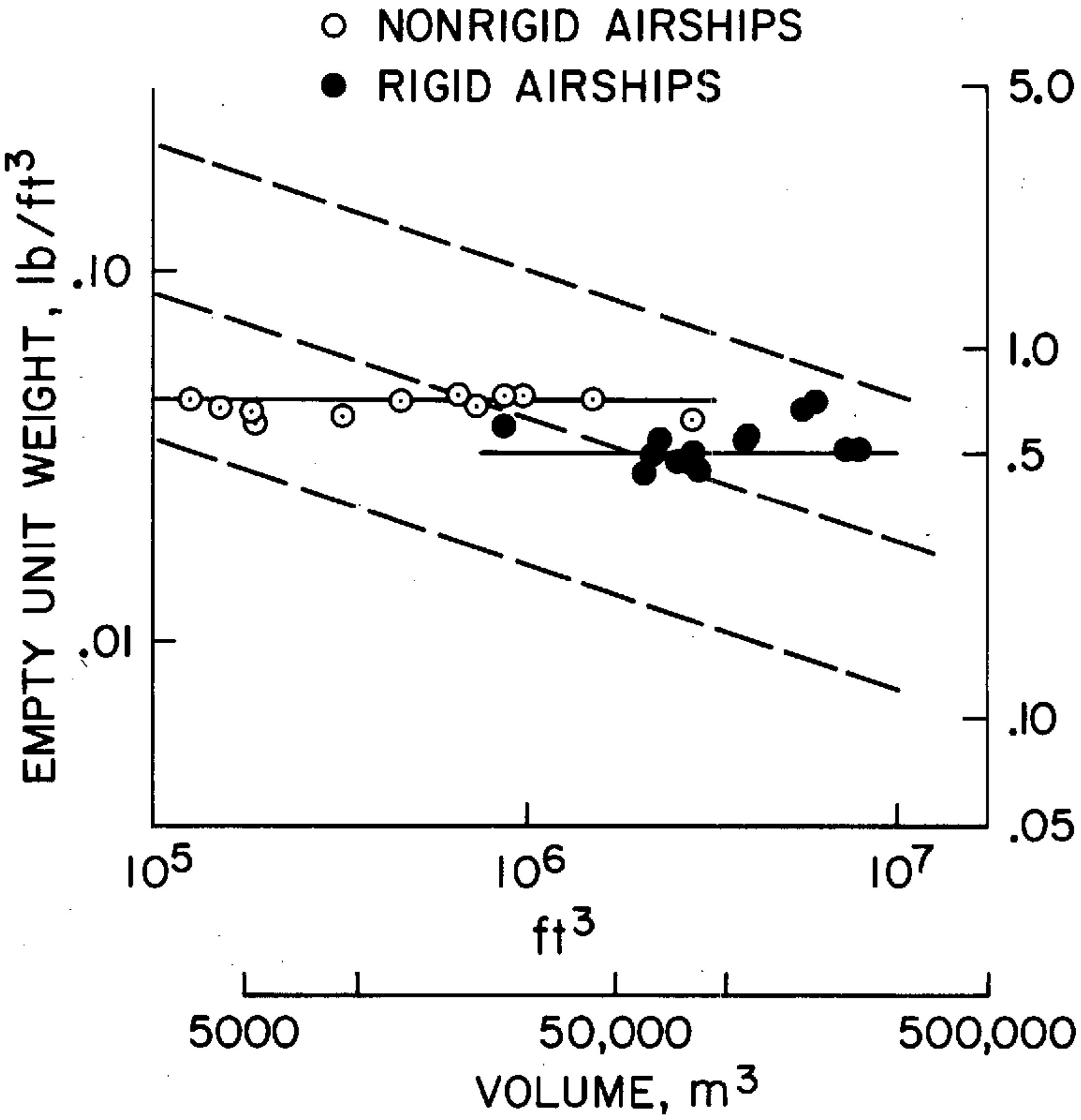

Figure 1.– Empirical weight characteristics of dirigibles.

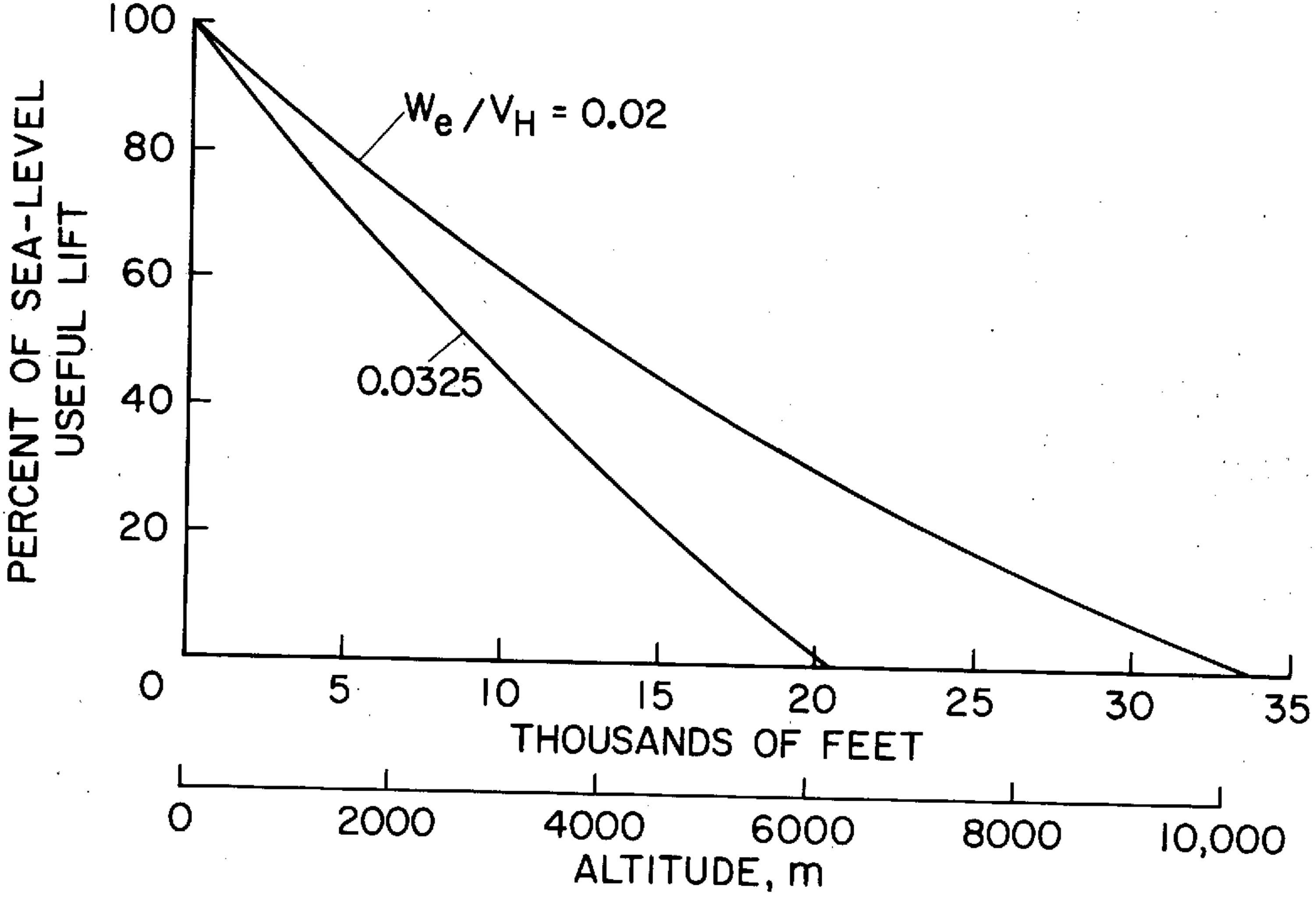

Figure 2.– Lift variation with design maximum altitude.

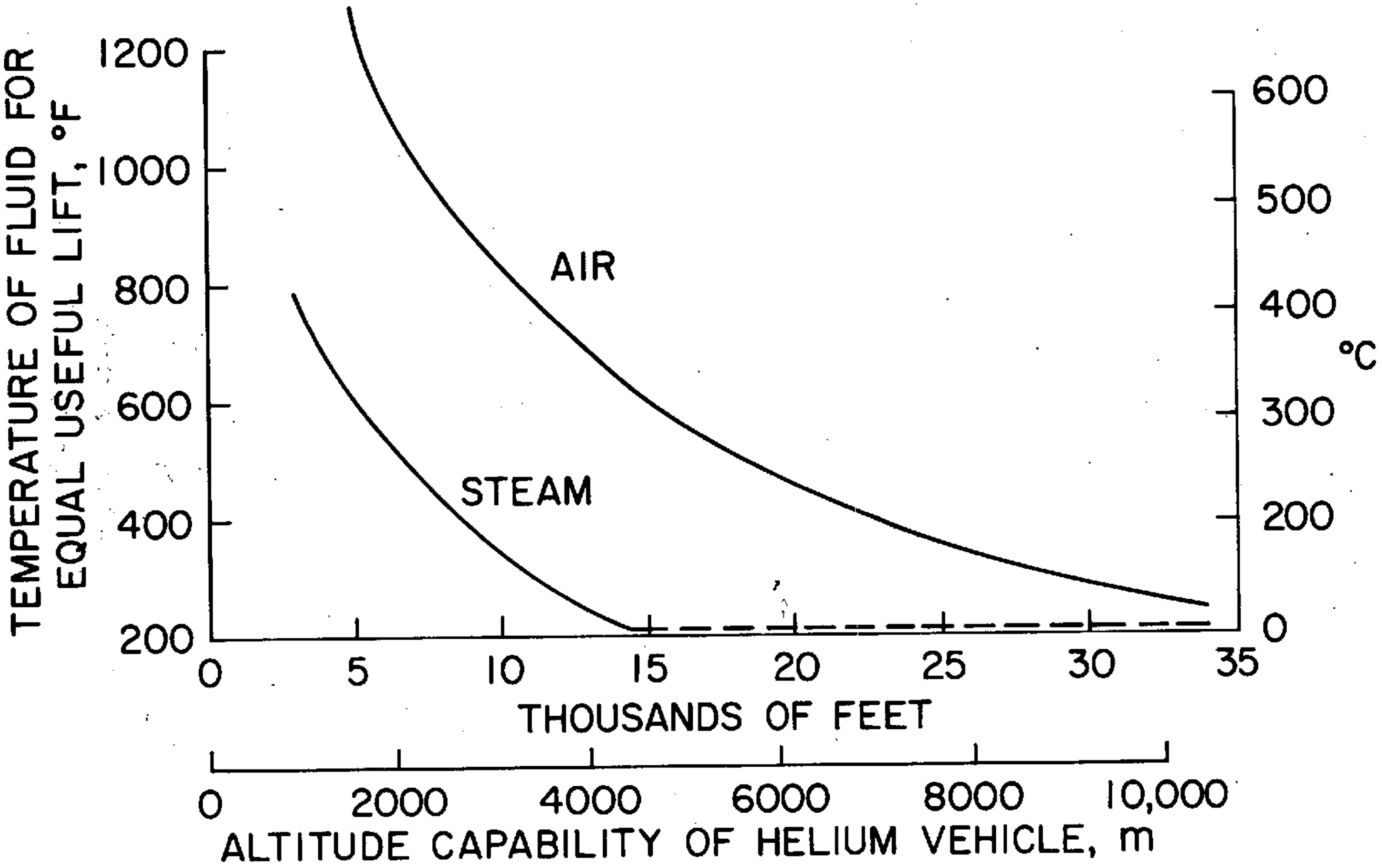

Figure 3.– Temperature of buoyant fluid for equal performance.

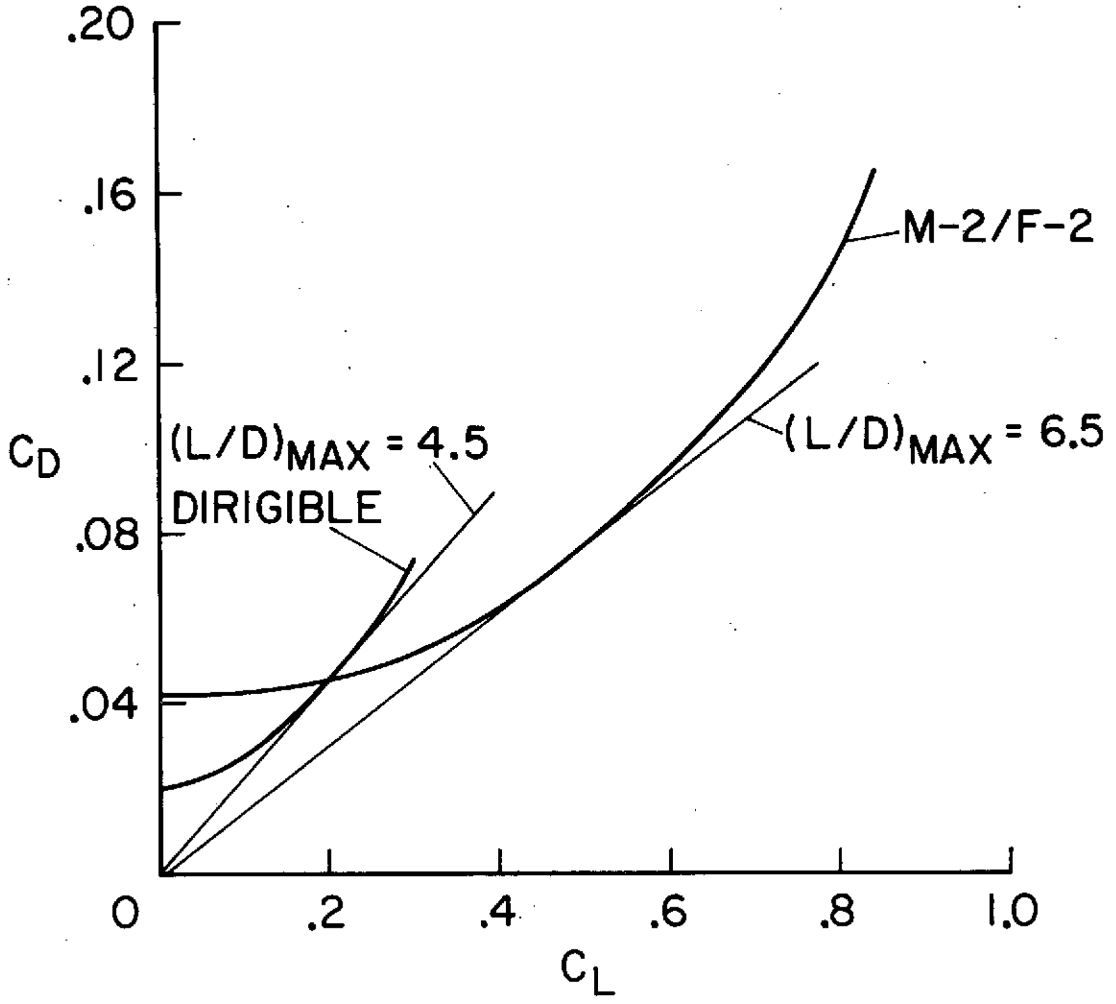

Figure 4.— Aerodynamic characteristics.

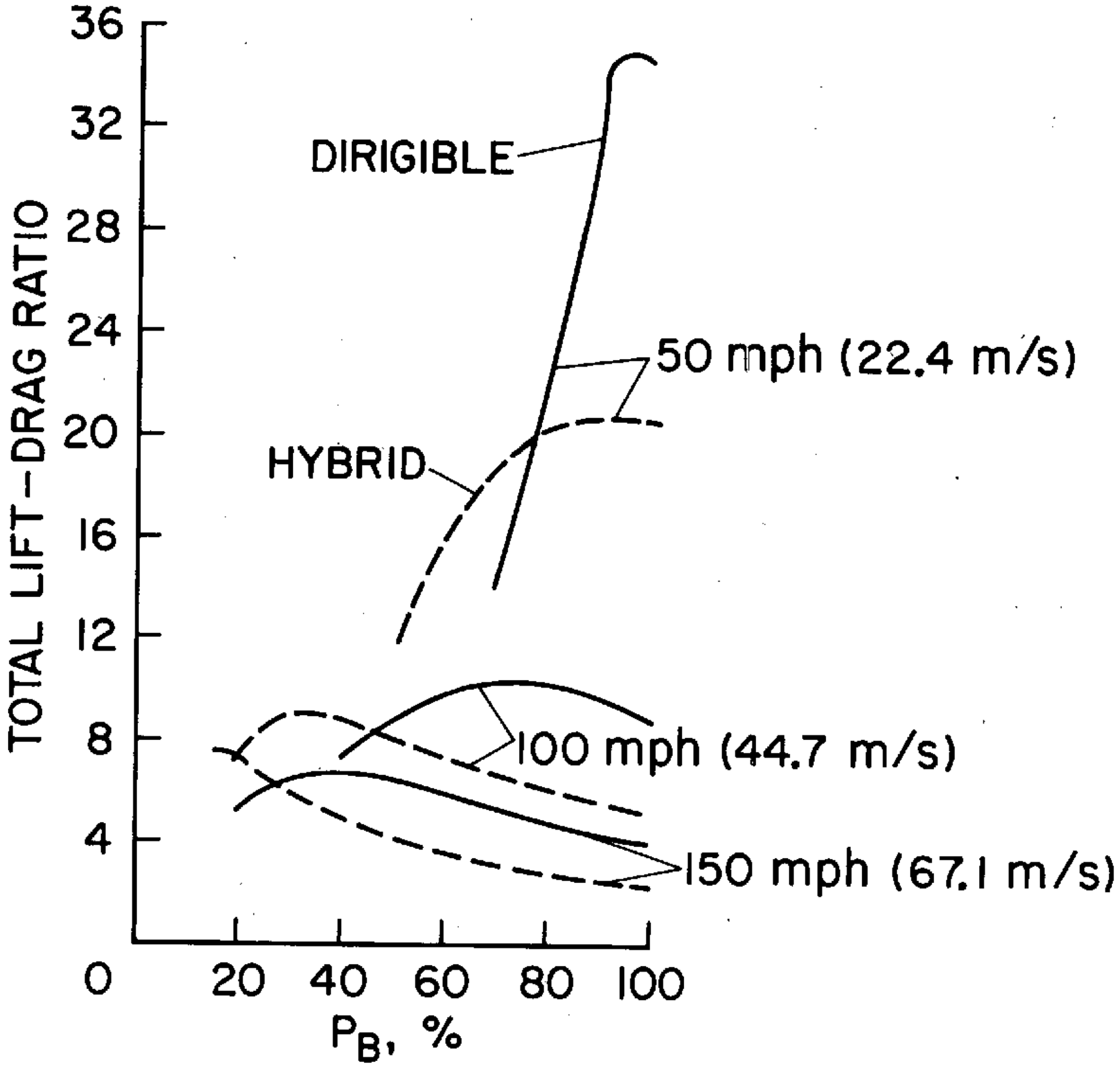

Figure 5.– Total lift-drag ratio.

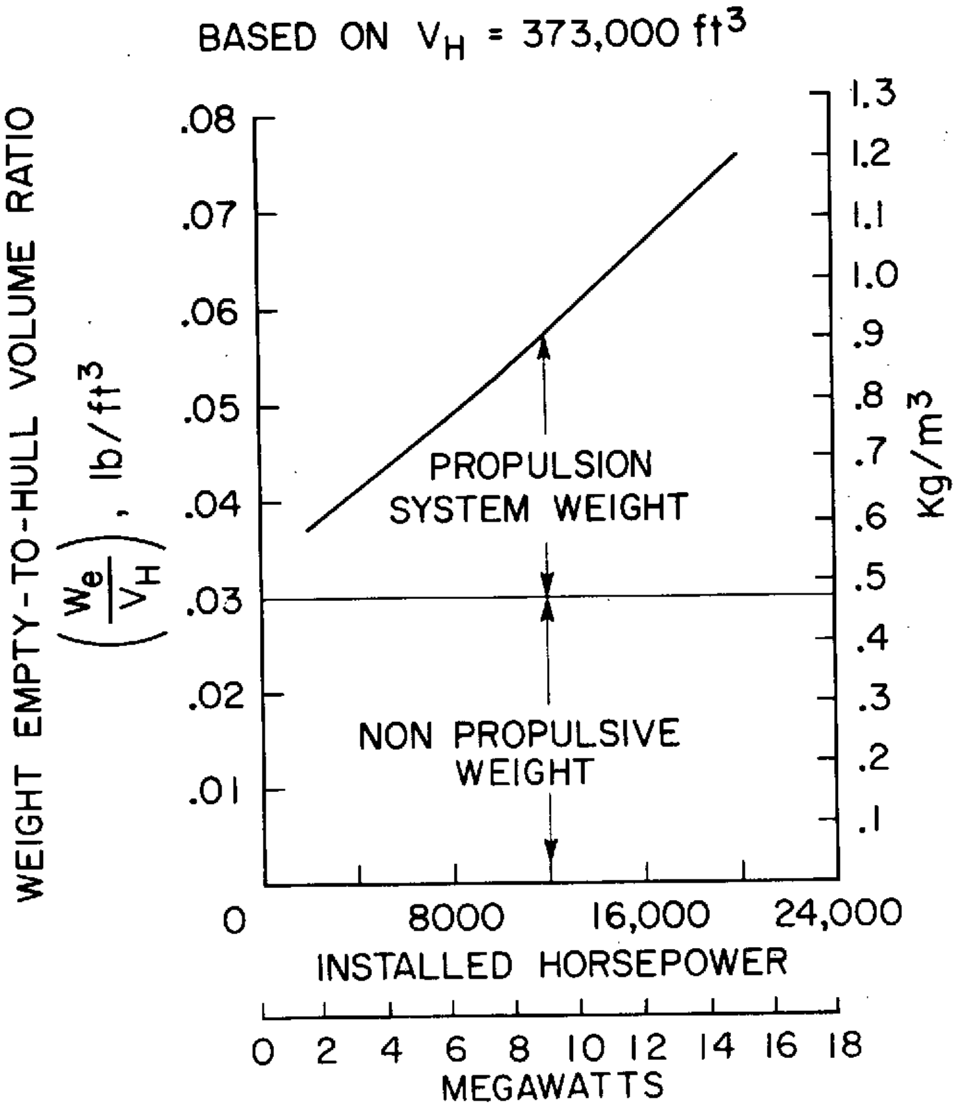

Figure 6.– Vehicle empty weight.

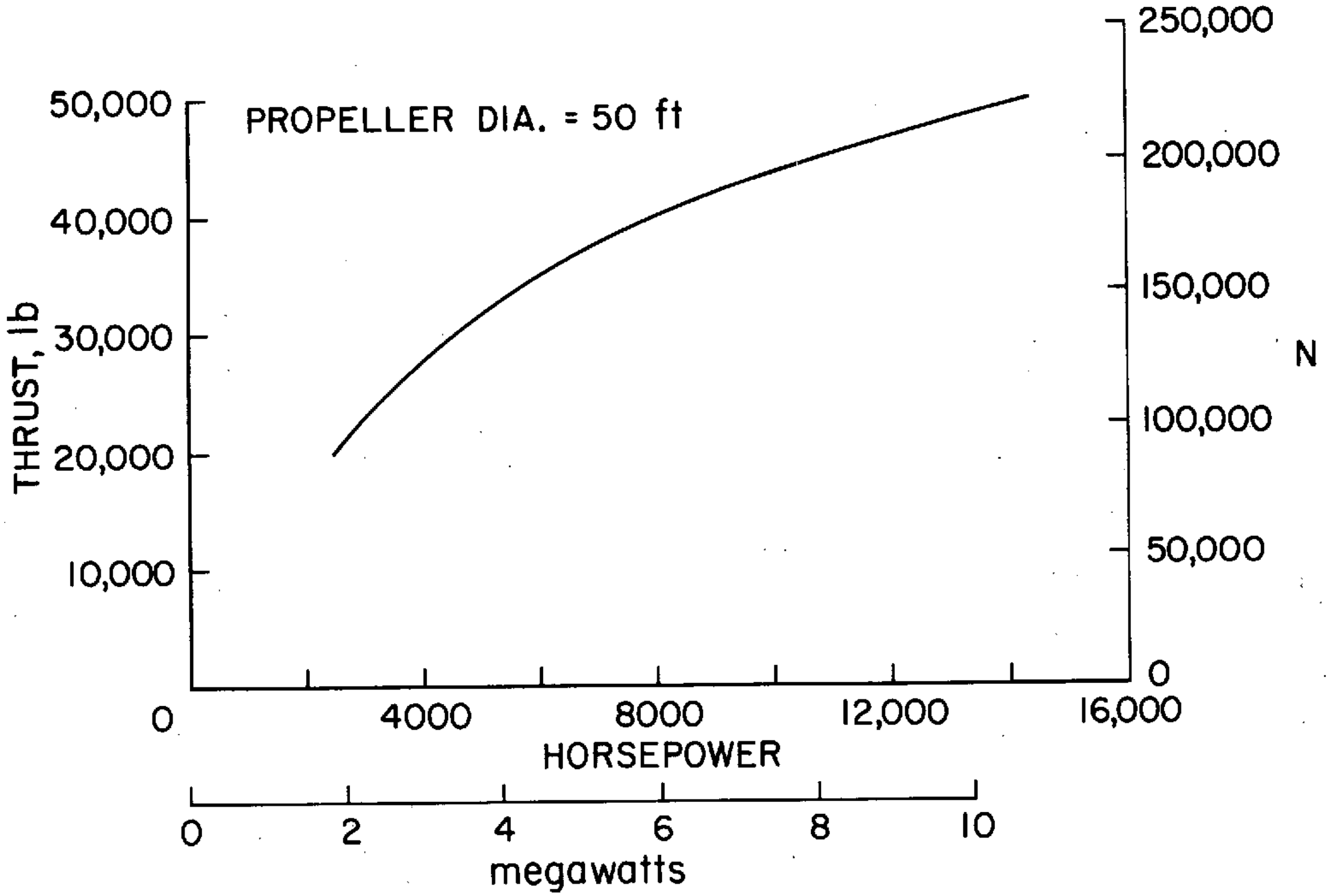

Figure 7.— Propulsive thrust.

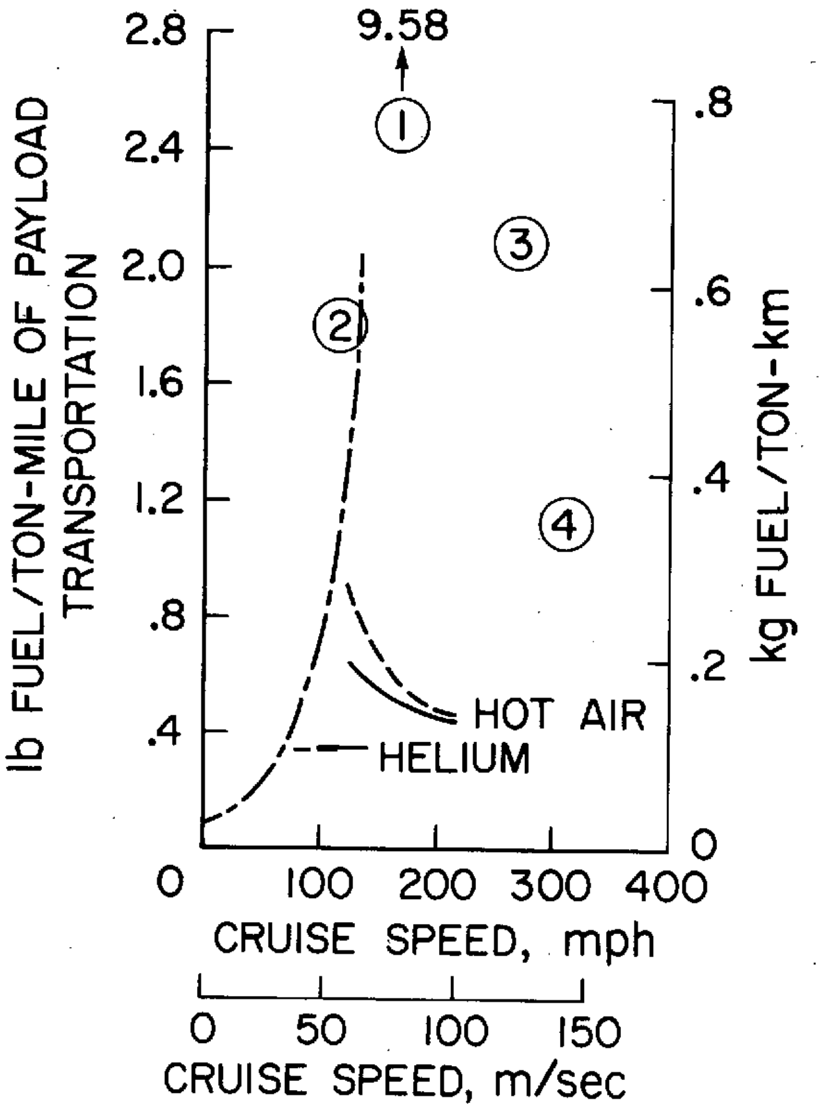

Figure 8.– Fuel consumption.

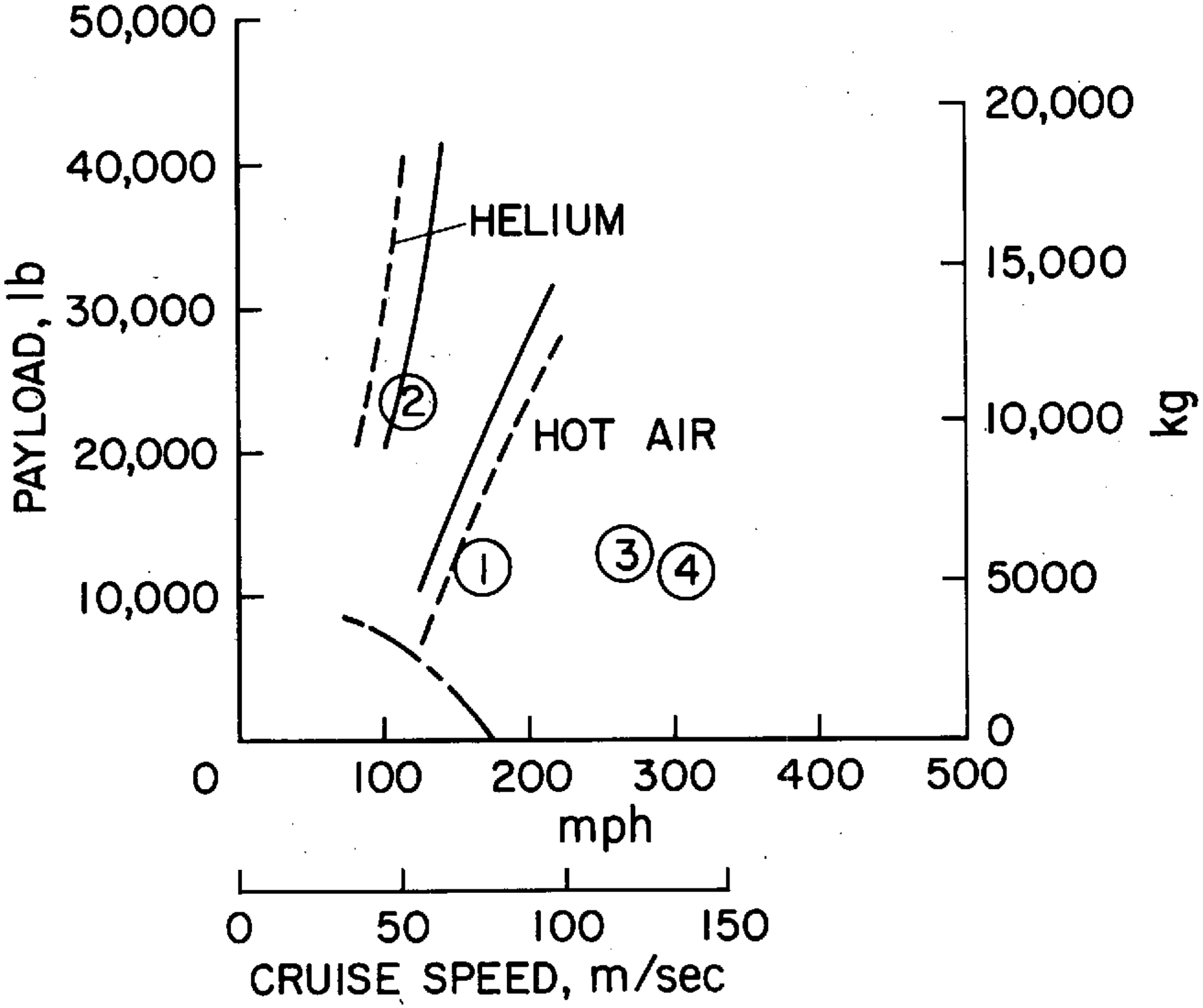

Figure 9.– Payload capability.

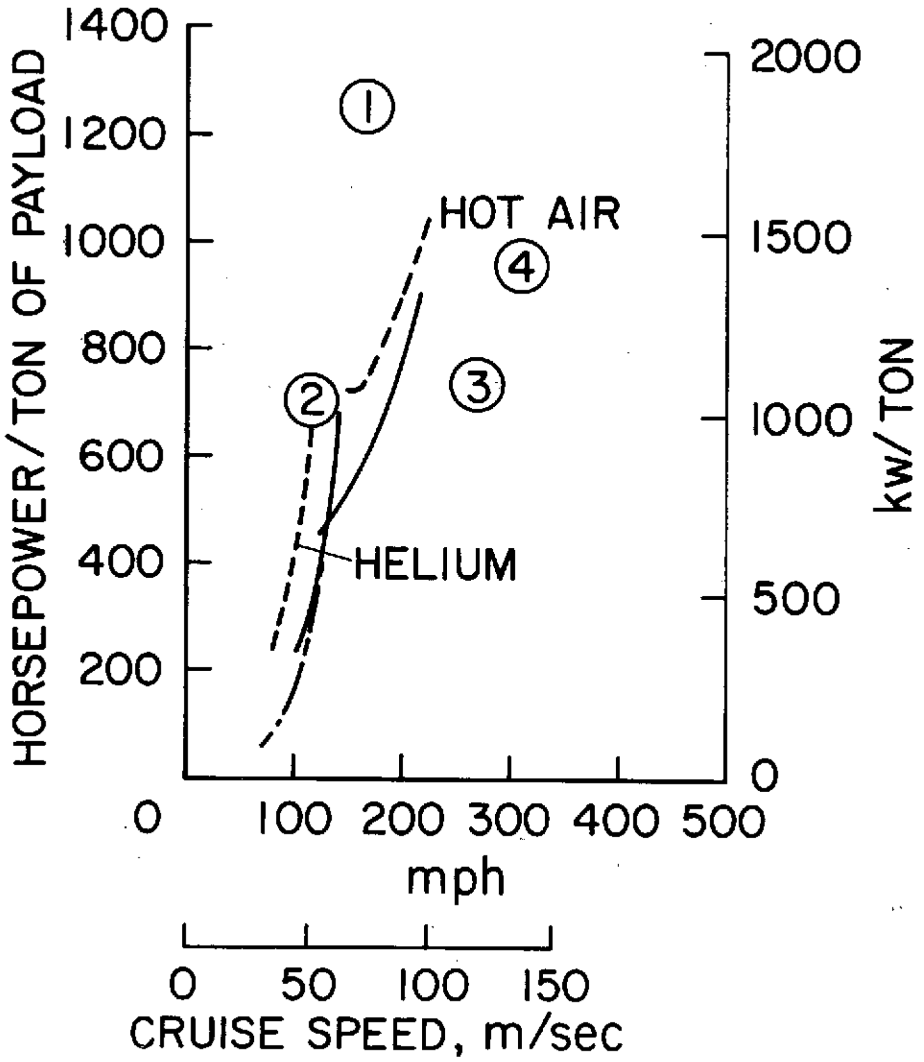

Figure 10.– Power requirements.

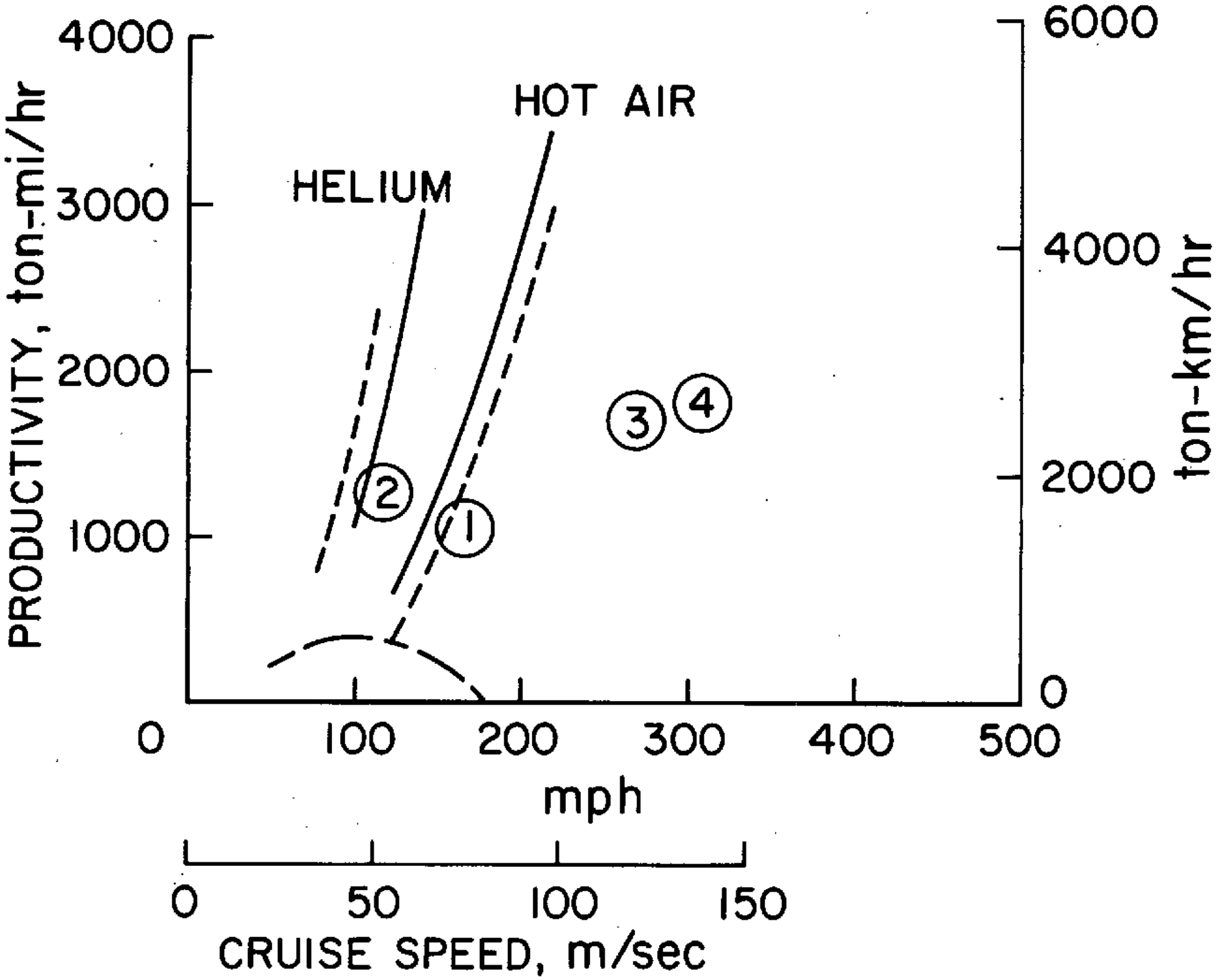

Figure 11.– Productivity.

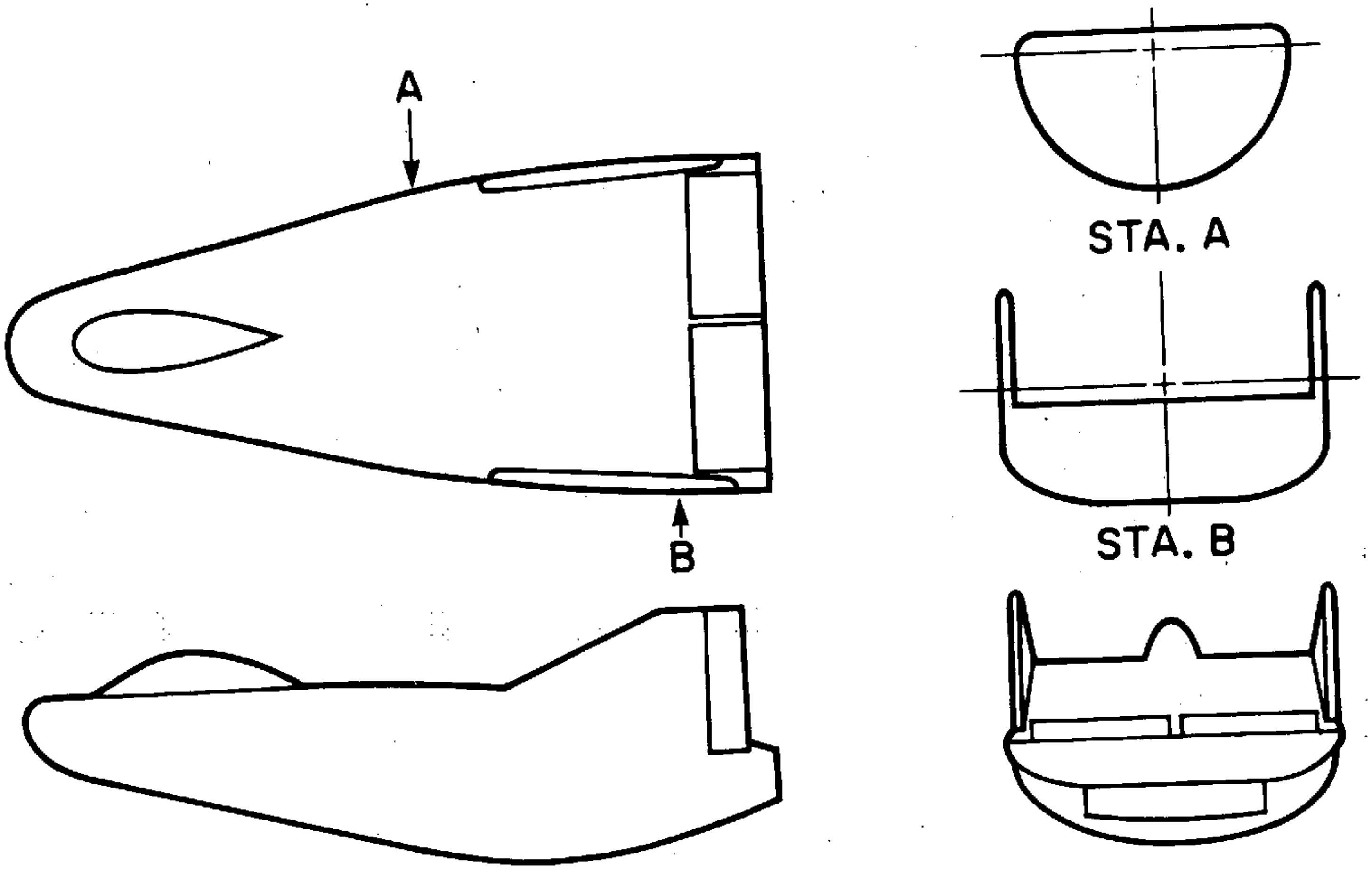

Figure 12.– M2/F2 lifting body