Feasibility of Modern Airships: Preliminary Assessment

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This paper gives a review of the Phase I portion of the NASA-sponsored "Feasibility Study of Modern Airships." Phase I consisted of a historical survey, a screening of potential civil missions, a parametric definition of vehicle concepts, and an identification of vehicle/mission combinations deserving further study.

Introduction

SEVERAL decades have passed since the days of the Hindenburg and other large rigid airships. Periodically, there has been nostalgic interest in a possible revival of these majestic vehicles. More recently, with national attention focused on energy conservation and environmental pollution reduction and with the recognition of several unique large-lift requirements for potential missions, the interest has become more intense. In addition, significant improvements have occurred in materials, structures, and aerospace technology in general since the 1930's. Hence, it appeared to be appropriate and timely that an up-to-date evaluation be made of the technical and economic feasibility of airships and their potential role in providing an alternative, fuel-conserving means of transportation compatible with a clean environment. To this end, NASA initiated the "Feasibility Study of Modern Airships." The primary objective of this ongoing study has been to improve the basis for decisions regarding possible new research and technology programs to address technical problems associated with airship developments.

Several individuals and organizations have proposed specific "hybrid" airship concepts. This term is used to describe a vehicle that generates only a fraction of its total lift from buoyancy, the remainder being generated aerodynamically and/or by the propulsion system. Although preliminary studies had indicated that hybrids may be superior to conventional, fully buoyant airships for many applications, no such vehicles have ever been produced and operated, and the validity of these initial indications was questionable. Therefore, both conventional and hybrid airships were considered in the feasibility study.

It will be useful in later discussions to have a clear understanding of the definitions of various types of airships and how they are related. A lighter-than-air craft (LTA) is an airborne vehicle that obtains all or part of its lift from the displacement of air by a lighter gas. LTA's are conveniently divided into airships (synonymous with dirigibles) and balloons, the former being distinguished by their capability for controlled flight. Only airships are considered here. The term "conventional" applies to the class of approximately ellipsoidal-shaped, fully buoyant airships developed in the past. It is traditional to classify conventional airships according to their structural concept (rigid, nonrigid, or semirigid). Hybrid airships are herein classified according to the means by which the aerodynamic or propulsive portion of the lift is generated.

The study tasks for the Feasibility Study of Modern Airships are shown in Fig. 1. Phase I was primarily a broad parametric evaluation of airship design concepts and potential civil applications. The two prime contractors, The Boeing-Vertöl Company and Goodyear Aerospace Corporation, each performed all of the Phase I tasks independently. Both employed subcontractors and consultants. This paper gives a review of the the Phase I portion of the Feasibility Study as reported in Refs. 1-11. Only the highlights of the study are given here, and the reader is referred to these references for the many important details of the study. Phase II results will be reported at a later date.

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Historical Survey

Task Description

The first task in Phase I of the Feasibility Study was to conduct a brief historical overview of airship vehicles and operations. Included were summaries of major missions, markets, vehicle performance and technical features, acquisition and operating costs, operating procedures, other system elements, and key subsystem characteristics. The goal was not to obtain a comprehensive catalog of data on past airships but to concentrate on data relevant for modern airship designs. Also, part of this task was a comparison between the technical and economic states of the art in 1930 and 1974 to assess the impact of modern technology.

Past Airship Concepts and Development History

Before considering the history of airship development, the distinguishing characteristics of the two major conventional airship concepts – rigid and nonrigid – will be discussed. The third type, semirigid, is essentially a variant of the nonrigid type, differing only in the addition of a rigid keel.

A typical nonrigid airship consists of a flexible envelope, usually fabric, filled with lifting gas and slightly pressurized. Internal air compartments (called ballonets) expand and contract to maintain the pressure in the envelope as atmospheric pressure and temperature vary. Ballonet volume is controlled by ducting air from the propwash or by electric blowers. The weights of the car structure, propulsion system, and other concentrated loads are supported by catenary systems attached to the envelope.

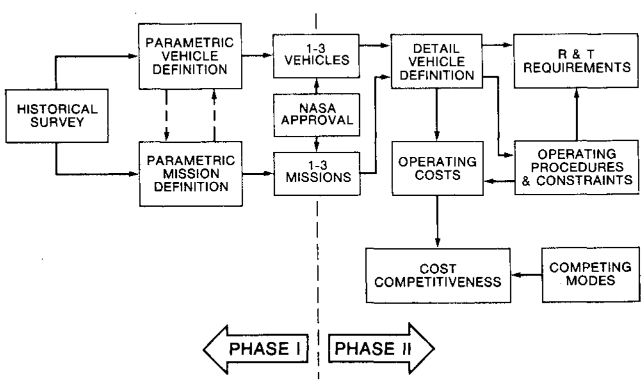

Fig. 1 Feasibility study of modern airships.

The other major type of airship was classified rigid because of its rigid structure. This structure was usually an aluminum ring-and-girder frame. An outer covering was attached to the frame to provide a suitable aerodynamic surface. Several gas cells were arrayed longitudinally within the frame. These cells were free to expand and contract, thereby allowing for pressure and temperature variations. Thus, despite their nearly identical outward appearance, rigid and nonrigid airships were significantly different in their construction and operation.

The principal development trends of the three types of conventional airships are depicted in Fig. 2. The nonrigid airships are historically significant for two reasons. First, a nonrigid airship was the first aircraft of any type to achieve controllable flight, nearly 125 years ago. Second, nonrigid airships were the last type to be used on an extensive operational basis; the U.S. Navy decommissioned the last of its nonrigid airship fleet in the early 1960's. During the many years the Navy operated them, a high degree of availability and reliability was achieved. Most of these nonrigid airships were built by Goodyear and a few, based on a modified Navy design, are used today for advertising by that company.

The rigid airship was developed primarily by the Zeppelin Company of Germany and, in fact, rigid airships became known as Zeppelins. Even the small percentage of rigid airships not built by this company were based, for the most part, on Zeppelin designs. The rigid airships of the Zeppelin Company recorded some historic "firsts" in air transportation, including inaugurating the first scheduled passenger air service. The culmination of Zeppelin development was the Graf Zeppelin and Hindenburg airships – unquestionably outstanding engineering achievements for their day. All of the rigid airships produced in the United States were for military purposes; none were in operation at the outbreak of World War II.

Aerodynamics and Design

All three types of conventional airships evolved into a common shape, the familiar "cigar shape" with circular cross sections and nearly elliptical profile. The fineness ratio of the later rigid airships was typically in the range 6-8. The fineness ratio of the nonrigid airships, which tended to be smaller and slower than the rigid ones, was typically in the range 4-5.

It is generally acknowledged today that past conventional, fully buoyant airship designs were very nearly optimum for this class of vehicle in terms of aerodynamic shape and fineness ratio. Thus a modern conventional airship could not be expected to show much improvement in this regard. It is estimated that a drag reduction of approximately 10% would be possible with adequate attention to surface smoothness and cleanliness. Use of boundary-layer control may give significantly greater drag reduction, but this technology is relatively undeveloped at present.

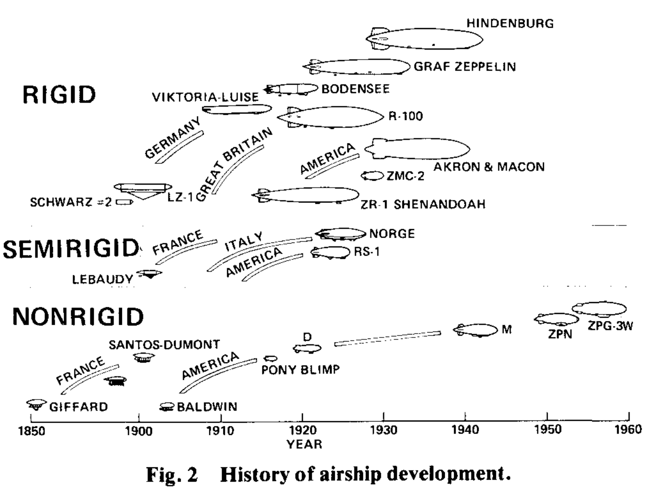

Fig. 2 History of airship development.

The early airships were designed primarily by empirical methods, and the only company to accumulate sufficient experience to design successful rigid airships was the Zeppelin Company. Two areas in which there was a serious lack of knowledge were aerodynamic loads and design criteria. Work in these areas was continued after the end of the last rigid airship in expectation of further rigid developments. Significant progress was made in both analytical and experimental techniques, but further work would need to be done in these areas for a modern airship.

Structures and Materials

The frames of most of the past rigid airships consisted of built-up rings and longitudinal girders stabilized with wire bracing. The rings and longitudinals were typically made of aluminum alloy and the bracing was steel. This structure was very light and efficient, even by present standards. However, this construction was highly complex and labor intensive and any modern airship of this type would have to have a much simpler construction. Possibilities include the use of metalclad monocoque, sandwich, or geodesic frame construction. Materials would be modern aluminum alloys or, further in the furture, filamentary composite materials. A good candidate for wire bracing, if required, is Kevlar rope. It is estimated that the use of modern construction and materials would result in a hull weight savings of approximately 25% compared with a past design such as the Macon.

There have been dramatic improvements in softgoods with applications for airships in the past two decades. Softgoods are used for gas cells and outer covering for rigid airships and for envelopes for nonrigid airships. The material most often used in past airships for these applications was neoprene-coated cotton, although the envelopes of the later nonrigid airships were of dacron. The dramatic improvement in strength of modern softgoods compared with cotton is shown in Fig. 3. Kevlar appears to be the best material, but it has not been fully developed for use in large airships. It is estimated that use of modern softgoods would result in component weight reductions of 40-70% compared with past designs. Coating films also have been improved greatly, which will result in a tenfold improvement in gas cell and envelope permeability.

With a few explainable exceptions, past airships have all had about the same structural efficiency (as measured by empty weight/gas-volume ratio) despite differences in size, design concept, year of development, and lifting gas. The insensitivity to size is a reflection of the airship "cube-cube law" (i.e., both the lifting capability and the structural weight increase in proportion to the cube of the length for a constant shape). Since fixed-wing heavier-than-air craft follow a "square-cube law," airships will compare more favorably with airplanes as size is increased. Smaller airships have tended to use nonrigid or semirigid construction, whereas the larger airships have been rigid.

Propulsion Systems

Either Otto- or Diesel-cycle engines were used on the large airships of the 1930's. Modern airships will most likely use

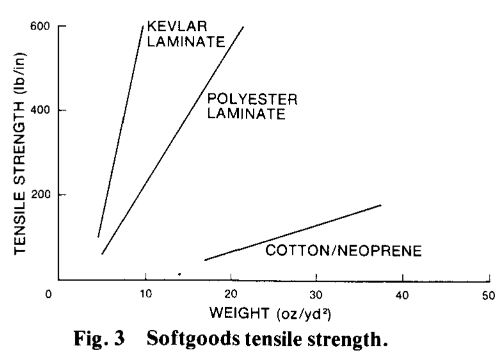

Fig. 3 Softgoods tensile strength.

turboshaft engines that are highly developed at present. Thrustors will be prop/rotors. As compared with engines of the 1930's, these modern engines have about 90% of the specific fuel consumption and as low as 10% of the specific weight and volume. Perhaps more important than these improvements is the greatly improved reliability and maintainability of the modern turboshaft engines.

There are also some longer-term alternative propulsion systems for airships. The Diesel engine is attractive because of its low fuel consumption. However, no Diesel currently available is suitable for airship use. Another possible propulsion system is a nuclear powerplant, particularly for long endurance missions and large airships. An extensive development program will be required to develop a nuclear-powered airship.

Engine controls of the rigid airships consisted of an engine telegraph that transmitted engine control commands from the helmsman to an engine mechanic, who would then manually make the required engine control changes. Modern electronic power management systems will eliminate this cumbersome system and greatly increase the responsiveness, accuracy, and reliability of engine controls. Control of the thrust vector orientation by tilting mechanisms will also be greatly enhanced with modern systems.

Controls, Avionics, and Instrumentation

Flight-control systems on past airships have been largely mechanical. Commands from the helm (one each for vertical and horizontal surfaces) were transmitted by cable and pulley systems to the control surfaces. In addition, there were manual controls for releasing ballast and valving lifting gas. For a large modern airship, a fly-by-wire control system has obvious advantages and would likely be employed. This system would use many airplane- and/or helicopter-type components. An autopilot would also be provided.

Between the 1930's and the present, there has been a vast improvement in avionics systems due largely to the dramatic changes in electronic communications devices. For example, as compared with 1930 components, modern aviation radio equipment is about one-tenth the size and weight and is much more versatile and reliable. Progress in the development of electronic components has also made possible the introduction of many navigation devices not available in the 1930's (e.g., VOR/DME/ILS, TACAN, radar, LORAN, OMEGA, and inertial systems).

The various improvements in controls, avionics, and instrumentation will only modestly reduce the empty weight of the airship, but will significantly improve its controllability and reliability. There will be, of course, a large increase in acquisition cost associated with these modern systems and components, but this will be offset by lower operating costs due to manpower reductions.

Flight Operations and Ground Handling

The operation of the 1930's airships was as labor intensive as their construction. In flight, large onboard crews were required to constantly monitor and adjust the trim of the ship and maintain nearly neutral buoyancy. Trim and neutral buoyancy were maintained by one or more of the following procedures: valving lifting gas, dropping ballast, transferring fuel or other materials within the airship, collecting water from the atmosphere and engine exhaust, and moving crew members within the airship. Also, it was not unusual to repair the structure and the engines in flight. It is obvious that modern structural concepts, engines, avionics, control systems, and instrumentaion will decrease the workload of the onboard crew considerably.

The experience of the U.S. Navy in the 1940's and 1950's with nonrigid airships indicates that modern airships can be designed to have all-weather capability at least equivalent to that of modern airplanes. High winds and other inclement weather need not endanger the safety of the airship and its crew either in flight or on the ground. However, high adverse winds will continue to have a negative impact on the operational capability of airships due to their low airspeeds.

Extremely large ground crews were needed to handle the early Zeppelins. These airships were walked in and out of their storage sheds by manpower. Up to 700 men were used to handle the Zeppelin military airships. The first significant change was the development of the high-mast mooring system by the British. The U.S. Navy then developed the low-mast system, which was more convenient, less expensive, and allowed the airship to be unattended while moored.

Important developments in ground handling subsequent to the 1930's were made by the Navy in connection with its nonrigid airship operations. By 1960, the largest nonrigid airships were routinely being handled on the ground by small crews that used mobile masts and mules. These mules were highly maneuverable tractors with constant-tension winches. Some further improvement in ground-handling procedures would be possible with a modern airship. Handling "heavy" or hybrid airships would be relatively easy.

Economics

As shown in Fig. 4, the flyaway costs per pound of empty weight of the rigid airships of the 1930's were comparable with those of transport airplanes of the same era. Since then, the costs of transport airplanes have steadily risen, even when inflationary effects are factored out, because the steady introduction of new technology has made succeeding generations of airplanes more sophisticated and expensive. This increased cost has paid off in increased safety, reliability, and productivity. As discussed above, a modern airship would have several systems and components that are highly advanced compared with 1930's technology. Thus it seems likely that rigid-airship flyaway costs would follow the trend of fixed-wing aircraft (Fig. 4), and therefore a modern rigid airship should cost about the same as an equivalent size modern airplane.

The only significant past commercial airship operations were those of the Zeppelin Company and its subsidiary DELAG. The highlights of these operations are listed on Table 1. None of these commercial operations can be considered a financial success and most were heavily subsidized by the German government. For example, the transatlantic service with the Graf Zeppelin in 1933-1937 required a break-even load factor of 93-98%, a value seldom achieved, despite carrying postage at rates over ten times higher than 1975 airmail rates.

Throughout most of these commerical operations, there was little or no competition from heavier-than-air craft. However, airplane technology was making rapid strides and airplane speed, range, and productivity were rising steadily. Airships and airplanes are difficult to compare because of the remoteness of the time period and the limited operational experience. Nevertheless, by the time of the Hindenburg disaster in 1937, it seems clear that the most advanced airplane, the DC-3, had lower operating costs as well as higher cruising speeds than the most advanced airship, the Hin-

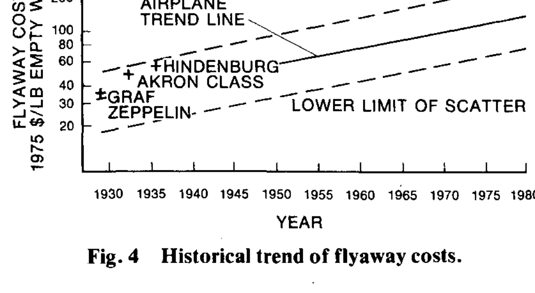

Fig. 4 Historical trend of flyaway costs.

Table 1 Past commercial operations

AIRSHIP	YEAR	MAIN ROUTE	NUMBER OF FLIGHTS	FLIGHT HOURS	TOTAL DISTANCE,nm	NUMBER OF PASSENGERS	MAIL lb	FREIGHT lb
7 AIRSHIPS (DELAG)	1910—1914	PLEASURE FLYING	1,588	3,176	93,000	35,028	——	——
LZ-120 BODENSEE & NORDSTERN	1919	FRIEDRICHSHAFEN — BERLIN	103	532	27,650	2,253	11,000	6,600
LZ-127 GRAF ZEPPELIN	1933—1937	FRIEDRICHSHAFEN — RIO DE JANEIRO	590	17,177	914,000	13,110	86,200	67,000
LZ-129 HINDENBURG	1936—1937	FRIEDRICHSHAFEN — LAKEHURST	63	3,088	182,000	3,059	19,550	21,450
TOTAL			2,617	23,973	1,220,964	56,040	116,750	95,050

denburg. Of course, this tended to be offset by the Hindenburg's greater luxury and range.

Mission Analysis

Task Description

In this task, the two feasibility study contractors were required to survey potential missions for airship applications. Emphasis was on civil transportation missions, although other types of missions were also considered. Included were unique LTA applications, as well as conventional missions currently performed by other transporation modes. Because the operating characteristics and economics of most of the potential modern airship concepts have not been established at present and because of the broad scope of the study, the mission analysis was primarily qualitative in nature.

Passenger Transportation

Past commercial airship operations have consisted primarily of long-haul transportation of passengers along with freight and mail. Because of the airship's low speed and productivity, neither contractor concluded that this is a viable mission for a modern airship.

Because of an airship's natural attributes and drawbacks compared with other transportation modes, attention is drawn to short-haul applications. For short stage lengths, the speed disadvantage of airships as compared with airplanes is relatively unimportant and the V/STOL capability and relatively low noise and fuel consumption (due to lower power levels) of the airship become important advantages. These advantages may in fact allow an airship to penetrate short-haul markets which have to date been largely unavailable to heavier-than-air craft.

Boeing performed a preliminary analysis comparing an airship system with a ground-based system for commuter traffic. The airship was a lifting-body hybrid carrying 200 passengers, with a station spacing that varied from 0.5 to 1.8 miles. The conclusion was that the airship was not competitive with the ground mode for this application, perhaps not surprising in view of the short stage lengths. Boeing felt, however, that there may be some passenger application of the 50-ton payload cargo airship discussed later.

The Goodyear study focused on markets not presently serviced by the trunk or local airlines due to uneconomically short stage lengths, noise restrictions, or other factors. Specific missions identified were between city centers, between minor airports, and airport feeder service. Vehicles in the 30- to 150-passenger range would be required and stage lengths would be between 20 and 200 miles. Air modes have been able to capture a small segment of short-haul passenger travel despite their higher costs relative to ground modes, because in some cases they allow savings in door-to-door trip times. An airship has a good chance to be competitive in this market due to the relatively high operating costs of the competing heavier-than-air craft. An airship system may also have other advantages such as being quieter, cleaner, and more comfortable in terms of accommodations and ride.

Cargo Transportation

Because of the many factors involved in cargo transportation, a definitive analysis of this market could not be attempted in the feasibility study. For example, among the items of interest when a shipper selects a transporation mode are door-to-door capability, door-to-door trip time, price, schedule, frequency, reliability of service, security of shipment, and environment for the cargo. These items all affect the shipper's transportation costs, his responsiveness to his customers, his inventory and warehousing requirements, the quality of his product, and his packaging requirements.

Speed is not as significant for shippers as for passengers as evidenced by the relatively low percentage of cargo that travels by air. For example, the air mode carries only 0.5% of the total cargo by weight in the U.S.-Europe market and less than 0.2% of the U.S. domestic freight. Because of the higher availability of trucks and their more numerous terminals, trucks generally give faster door-to-door service than airplanes at stage lengths less than 500 miles. Goodyear concentrated on stage lengths up to 500 miles for their cargo analysis. In this market, they would compete with trucks for high-value cargo by offering door-to-door service at shorter trip times, although generally at high costs. Airships are not likely to compete with rail because of the low cost of rail transportation and the typically low value of the cargo carried by this mode. Goodyear felt that, beyond stage lengths of 500 miles, airships are probably not competitive with airplanes on established routes because of their low block speeds and consequently likely higher costs. (Reference 12 discusses in more detail the prospects for airships in the long-haul cargo market.)

Boeing considered the entire U.S. freight commodity market, irrespective of range, for airship application. As compared with other modes, it was postulated that an airship would offer a unique capability and therefore find a role in this market. As opposed to airplanes, it would offer door-to-door service and would be faster than trucks. Thus an airship would not necessarily have to have equivalent or lower costs to capture a portion of the market. What makes this application attractive is the size of the domestic freight market; if an airship operation could capture only 1% of it, approximately 100 vehicles of a 50-ton payload size would be required. Boeing estimated that this would be possible if direct operating costs (DOC) in the range of 10-16¢/available ton-mile could be achieved.

In addition to the conventional cargo transportation missions just discussed, there may be special cargo missions for which the airship is uniquely suited. An example is transportation in less developed regions where ground mode infrastructure and air terminals do not exist. Argicultural commodities are a particularly attractive application since their transportation is one-time-only or seasonal in nature, and crop locations are often in remote regions with difficult terrain. Closely related to this application is timber harvesting and transportation in remote areas. The problem with this class of application is that the market size is not well defined at present and may be too small to warrant a vehicle development. There may be the same problem with long-haul transport of heavy and/or outsized cargo, another potential airship mission.

Heavy-Lift Short-Haul Applications

The heavy-lift short-haul (HL/SH) applications are, strictly speaking, not true transportation missions because they encompass aerial crane missions. Prime vehicle requirements are VTOL capability, low-speed controllability, and station-keeping capability. Speed is not an important factor and ranges are usually nominal. Two situations are of interest: first, the payload is either outsized or overweight for ground modes; second, either the origin or the destination is a site inaccessible by ground modes. In many applications, both situations will be present. Many of the shipments will be one time only. The airship's only competition for these HL/SH applications is the helicopter.

Several specific civil applications have been proposed for an HL/SH airship. Among these are siting of nuclear and conventional powerplants, loading/unloading of container ships, delivery of modularized structures such as factory-built houses, and use as an aerial crane in the construction industry. In addition, there are several military applications. In many applications, the payloads are too large for existing helicopters and an airship offers the only viable alternative. However, since these are new missions for air vehicles, the market size is not established with any certainty at present.

The Boeing study concluded that there was a market for only one airship nationally in the 800-ton payload class, which would be needed for the large nuclear powerplant components. Furthermore, it was felt that additional uses for such an airship would add little to its utilization. Instead of developing a new airship concept for the HL/SH application, Boeing recommended using a towed-balloon system in which the balloon would support the weight and helicopters would supply the propulsive force and steering. In time, such a concept might then generate a sufficient market demand to warrant development of a more sophisticated system.

The Goodyear study, on the other hand, concluded that the aggregate of civil and military HL/SH missions constituted an "immediately required market" for HL/SH airships. This conclusion is based on such an airship's greatly improved payload capability and presumed lower operating costs per pound of payload compared with existing helicopters.

Surveillance Missions

Although surveillance and platform missions were not emphasized in the study, both contractors considered them briefly. This class of missions seems attractive for airship applications because of the airship's high-endurance capabilities compared with heavier-than-air craft. Goodyear listed many civil and military surveillance and platform missions which, when considered together, constitute a good prospect for airship application. Boeing on the other hand felt that there might be military and Coast Guard applications for high-endurance airships but civil applications were unlikely.

Transportation of Natural Gas

An airship application frequently mentioned and under detailed study elsewhere is for transporting natural gas. This application is unique in the sense that the cargo itself would serve as the lifting gas and possibly even as the fuel. Significant advantages of an airship over pipeline and liquid natural-gas tanker ships are increased route flexibility and decreased capital investment in facilities in countries that are potentially politically unstable.

Boeing conducted a preliminary economic analysis of the transportation of natural gas by airships compared with existing systems. They found that, due to the extremely low costs of transportation by pipelines and tankers, airship costs would be several times higher than transportation costs of existing systems. Goodyear, too, did not rate the natural gas mission among the most promising ones for further study. Therefore, despite some obvious advantages, transporting natural gas does not seem to be a viable mission for airships.

Vehicle Parametric Analysis

Task Description

The vehicle parametric analysis was regarded as the most important task in Phase I of the feasibility study. In this task, the entire spectrum of airship concepts, encompassing both conventional airships and hybrids, was examined. The contractors were required to include conventional ellipsoidal-shaped concepts and delta planform hybrids in their parametric analysis, but were also encouraged to study additional shapes. Vehicles with gross lifting capabilities ranging from 3000 to 6 million lb were investigated. The parametric studies included the effects of important design factors such as vehicle geometry, ratio of buoyant lift/total lift (β), and cruise speed (V_c).

Since the emphasis of Phase I was on transportation missions, the principal figure of merit was productivity, which may be defined as either payload (PL) times V_c or useful load (UL) times V_c. Useful load is the sum of payload and fuel weight. If the first definition is adopted, range must be treated as a parameter. The second definition is frequently used in airship analysis, but neglects the effect of range and is therefore occasionally misleading. Another similar figure of merit used by the contractors was specific productivity, defined as productivity divided by empty weight (EW). Productivity is a good indicator of the economic worth of a transportation system and, in particular, specific productivity has historically been closely correlated with vehicle direct operating costs.

In addition to the parametric studies, several design options were investigated. These included choice of structural concept, use of vectored thrust, choice of structural materials, use of boundary-layer control, and choice of lifting gas.

Lifting-Gas Selection

A primary consideration for an airship is the selection of the lifting gas. Many factors are to be evaluated in this selection, but the principal one is lifting capability. The lift per unit volume of several potential gases is shown in Fig. 5. Other lighter-than-air gases, such as methane, ammonia, and

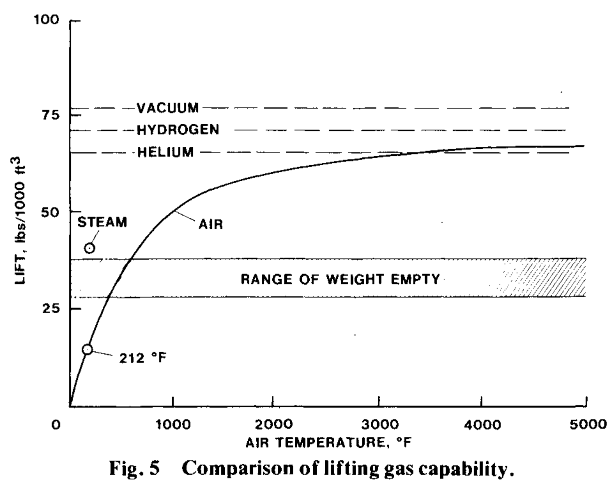

Fig. 5 Comparison of lifting gas capability.

natural gas, have less lifting capability than steam and could probably lift only the empty weight of an airship. Within the temperature limitations of conventional airship structural materials (about 300°F), hot air also has insufficient lift for most conventional airship designs. Thus it seems clear that the only possible lifting gases are hydrogen, helium, and steam.

Hydrogen has the greatest lifting capability and is relatively inexpensive with an inexhaustible supply. However its flammability precludes its use, at least at present. Because of its attributes, development of a fail-safe hydrogen containment system is a worthwhile goal, particularly if helium becomes scarce.

The lifting capability of helium is not dramatically less than that of hydrogen, and helium has the great advantage that it is not flammable. The disadvantage with helium is that it is a limited resource, which leads to relatively high prices and possible problems of availability in the future. Although the supply appears adequate for the foreseeable future, large-scale use of airships may create a serious shortage. All factors considered, helium seems to be the clear choice for lifting gas for airships in the near future and both contractors assumed the use of this gas in their parametric analyses.

The other possibility, steam, has a lifting capability significantly less than hydrogen or helium. The advantages of steam are low cost, unlimited availability, and nonflammability. However, the elevated temperature of the gas requires a containment and temperature-control system that is undeveloped at present. The elevated temperature also places new demands on structural materials. Because of its relatively poor lifting capability, steam will be restricted to airships with low ratios of EW to gross weight (GW).

Methods of Analysis

Both contractors developed and used vehicle synthesis (integrated conceptual design) computer programs in the vehicle parametric study. The Boeing program is called the Comprehensive Airship Sizing and Performance Computer Program (CASCOMP) and the Goodyear program is the Goodyear Airship Synthesis Program (GASP). These programs compute mission performance for a specified vehicle concept, shape, and mission definition. Included are subroutines for calculating geometrical characteristics, aerodynamic performance, control surface sizes, power requirements, and component weights. The GASP and CASCOMP programs can be used to conduct parametric studies of a wide variety of both conventional and hybrid airships.

The methods of analysis used in the synthesis programs are, for the most part, standard methods used in preliminary design of aircraft. They use a mixture of analytical and empirical techniques. One major difference between the two contractors was in the manner of estimating the structural weight of the basic hull. Boeing used conventional regression analysis to obtain an empirical weight-estimating relationship (WER) based on past airship hull weights. A factor was then applied to this equation to account for modern design concepts and materials. The resulting equation was applied to all the conventional and hybrid concepts considered in their parametric study.

Goodyear devoted a significant effort toward developing WER's for conventional and hybrid airships. In their analysis, the hull weight was broken down into approximately six elements. For conventional airships, the WER for each element was based on past studies updated to current technology. Lifting-body hybrids were treated separately. Because no large vehicles of this type have ever been built, there is no reliable data base for developing empirical WER's. Goodyear therefore used an analytical approach based on airload shear and moment distributions and simplified structural analysis in developing WER's for lifting-body hybrids.

Conventional Airships

Both contractors analyzed and compared several conventional airship concepts. The rigid design considered by Goodyear was essentially the classical Zeppelin structural concept updated with modern materials. Metal components were assumed to be made of aluminum alloy and fabric components were of coated dacron. Thus this design is well within the current state-of-the-art. The Goodyear nonrigid concept was also of traditional design. Both dacron and Kevlar envelopes were considered. Several types of pressurized metalclad designs were analyzed. The selected design was similar to a nonrigid airship in that it used ballonets and was not compartmented.

Boeing approached the vehicle parametric task by first making an exhaustive survey of recent proposed airship concepts. It was decided to select a representative rigid and a nonrigid design for the parametric analysis of conventional airships. Analysis of structural and material tradeoffs resulted in the selection of triaxial-weave Kevlar 29 laminate coated with polyurethane and Tedlar films for the primary envelope material of the nonrigid airship. Several rigid airship structural concepts and materials were evaluated by considering the design of a typical bay. The selected concept consisted of a geodetic construction made of Kevlar composite materials. The Boeing conventional airship designs are somewhat beyond the current state-of-the-art, but should be capable of development in the near future.

Both contractors investigated the effects of type of construction, size, and V_c on performance in their parametric analysis of conventional airships. The effects of type of construction and size, as determined by Goodyear, are shown in Fig. 6. The dashed lines for the nonrigid concepts at the higher gross weights indicate a requirement for improved seaming technology in this region. This figure shows that nonrigid concepts tend to be favored for small sizes, metalclad for midsized, and rigid for large sizes, but that generally there is not a great deal of difference between the concepts. In fact, all concepts had a structural-weight/gross-weight ratio of about 0.4 over a wide range of gross weights.

Figure 6 also shows that if Kevlar is developed as an envelope material for a nonrigid airship, then the nonrigid concept is superior for almost all sizes. Boeing, which considered only a Kevlar nonrigid concept, reached the same conclusion. The optimum cruise speed of fully buoyant conventional airships (based on specific productivity) was found to vary from 60 to 120 knots, depending on size and concept, but was usually in the 80- to 90-knot range.

The effect of fineness ratio was investigated by Goodyear. They found that the optimum (based on specific productivity) fineness ratio for nonrigid airships is approximately 3.25, regardless of size. For rigid airships, the optimum fineness ratio varies from 4 for a 10,000-lb GW vehicle to 8 for a 1,000,000-lb GW vehicle.

Goodyear considered the effects of "heavy flight" of conventionally shaped airships, i.e., flying these vehicles at an angle of attack to obtain a portion of the lift aerodynamically.

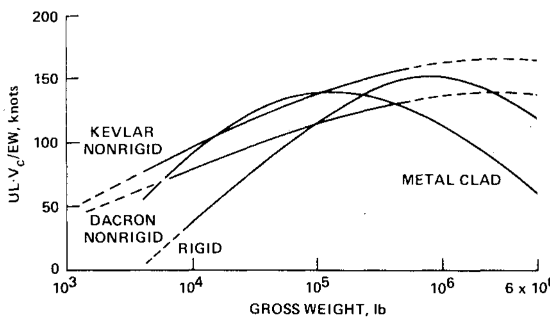

Fig. 6 Specific productivity of fully buoyant airships.

For small airships (i.e., less than about 50,000 lb GW) it was found that, for ranges at least up to 1500 n.mi., the optimum β tends to zero, i.e., a vehicle with all propulsive lift for takeoff and landing and all aerodynamic lift for cruise is the most desirable. This is because aerostatic lift is relatively inefficient at low GW. For large airships (i.e., those with GW greater than about 2×10^6 lb) the highest productivity is obtained with fully buoyant airships, regardless of range. For intermediate sizes of airships, the value of optimum β depends on range, e.g., for a 400,000-lb GW airship (Fig. 7), no buoyant lift is optimum at short ranges and all buoyant lift is optimum at long ranges. At intermediate ranges, intermediate values of β are optimum.

Hybrid Airships

In the past few years, various individuals and organizations have proposed a great variety of hybrid airship concepts. The concepts include airships with wings, lifting-body shapes, multiple conventional hulls, and combinations of buoyant hulls with rotors or rotor systems. These concepts may have either VTOL or STOL capability.

Because of the large number of potential hybrid concepts, the feasibility study contractors conducted a brief qualitative survey to select a few promising, representative concepts for parametric evaluation. Both contractors quickly eliminated the more radical concepts due to design uncertainty and the multiple hull concepts due to their relatively high surface-area/volume ratios.

The concepts selected for study by Boeing are shown in Fig. 8, which includes the conventional concepts discussed earlier. The Aereon Dynairship was selected as representative of the lifting-body concepts because of the background of information available on the delta planform lifting-body shape. The Megalifter concept is a typical example of the winged airships. The Helipsoid, introduced by Boeing in this study, is a compromise between the cylindrical and delta shapes. It will have a better surface-area/volume ratio than the Dynairship, possibly at the expense of degraded stability and control characteristics. The Heli-Stat, selected to represent the rotary-wing hybrids, combines an airship hull with helicopters or helicopter rotor systems.

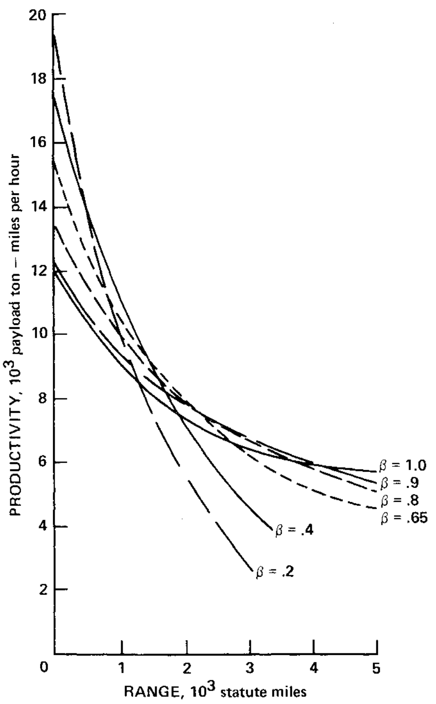

Fig. 7 Effect of heaviness and range on productivity of 400,000-lb gross weight rigid airships.

The productivity of the four selected hybrid concepts was assessed as a function of range, V_c, β, and PL. An example of these results is shown in Fig. 9. For a given β, specific productivity is maximized at a specific value of V_c. These optimum cruise speeds are significantly higher than those for conventional airships. The maximum productivity for $\beta=0.35$ is greater than that for $\beta=0.75$. However, results for additional β values would be needed to determine an optimum. One possibility is a trend to $\beta=0$ for maximum productivity. This conclusion would agree with the Goodyear results for heavy conventional airships of this payload size and range (discussed earlier).

Goodyear selected two hybrid concepts for parametric evaluation. The first of these was a lifting-body shape that had a parabolic planform with elliptical cross sections. This shape was chosen because of structural weight considerations and the proximity of the centers of buoyancy and pressure (which should lead to good stability and control characteristics). An interesting feature of the shape is that the longitudinal sections closely resemble standard airfoil profiles. The hull structure was assumed to be conventional Zeppelin-type rigid construction.

The parametric analysis of the Goodyear lifting-body hybrid focused on determining the values of aspect ratio, thickness/chord ratio, and V_c which maximized productivity at various values of GW, β, and range. The results show that V_c tends to decrease with increasing β, to increase with increasing size, and to decrease with increasing range. Aspect ratios range from 0.5 to 1.5. The effects of variations in β on the productivity are discussed later.

The second hybrid investigated by Goodyear was the Heli-Stat. This concept was not assessed with a productivity figure of merit and was not compared to the other concepts, but

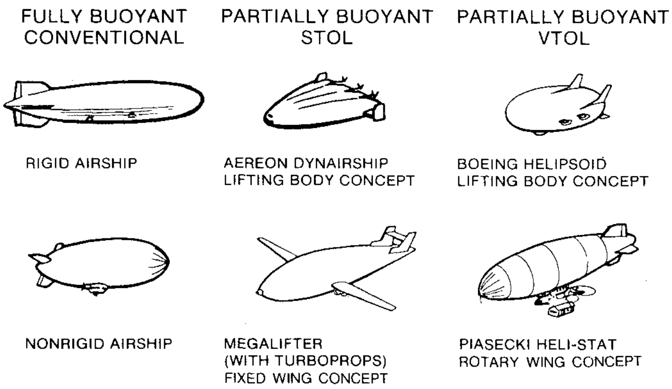

Fig. 8 Concepts selected for parametric evaluation.

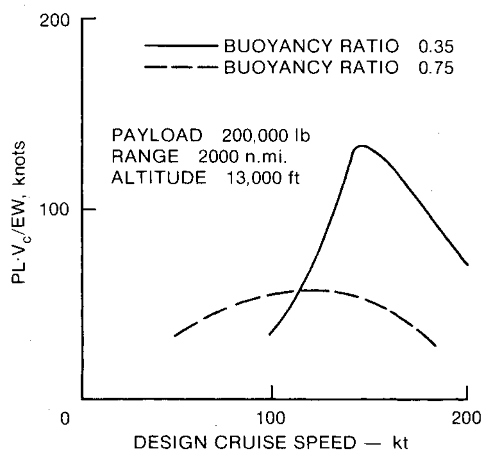

Fig. 9 Effect of buoyancy ratio and cruise speed on specific productivity, Helipsoid configuration.

rather was considered as a specialized vehicle for HL/SH application. The Heli-Stat configuration was selected because it utilizes proven and existing components and systems and thus is presumably a relatively near-term, cost-effective, and low-risk concept. The advantages of the concept over conventional airships are greater controllability and station-keeping capability and elimination of the need for ballast. The advantages over helicopters are increased payload capability and decreased operating costs per pound of payload. Goodyear concluded that this concept can be sized to meet a large range of payloads while maintaining a UL/EW ratio of approximately 1.0.

Comparison of Concepts

Goodyear compared their lifting body hybrid concept with their conventional rigid concept at various values of GW, β, and range. Figure 10 presents an example that shows the results for 400,000-lb GW vehicles. The conventional rigid is required to have VTOL capability, whereas the hybrid is not. The break in the curve for the zero range rigid occurs because, below $\beta = 0.65$, the power requirements are determined by takeoff and above this value by cruise. The figure shows that at short ranges the productivity increases continually as β is decreased, indicating that a vehicle with no buoyant lift (an airplane) would be optimum. For a 1500-n.mi. range, the conventional airship has an optimum β between 0.5 to 0.6. The hybrid, however, exhibits a minimum productivity at intermediate values of β and productivity is best at either very low or very high β. Finally, note that, at nearly every value of range and β, the conventional airship has higher productivity than the hybrid.

Based on their comparative analysis of conventional rigid airships and lifting-body hybrids for productivity missions, Goodyear concluded the following: 1) for short ranges or low gross weights or both, the optimum airship, regardless of type, tends to zero buoyancy, i.e., an airplane; 2) for intermediate to long ranges and intermediate to large gross weights, the optimum hybrid tends either to zero or full buoyancy; 3) for intermediate ranges and intermediate to large gross weights, heavy flight is optimum for the conventional rigid; 4) for long ranges and large vehicles, the conventional rigid tends toward full buoyancy; 5) only at extremely large sizes (on the order of 6×10^6 lb GW) does the hybrid seem to have an advantage over the conventional airship. (It may also be superior to airplanes in this size; however, there is the question of the utility of these large vehicles.)

Boeing compared its six study concepts on three different missions in 50- and 100-ton payload sizes. The missions consisted of a short-range profile (300-n. mi. range and 2000-ft altitude), a transcontinental profile (2000 n.mi. and 13,000 ft), and an intercontinental profile (5000 n.mi. and 2000 ft). The results showed that on a specific productivity basis the Helipsoid concept was best for the short-range and transcontinental missions, whereas the conventional nonrigid concept was best for the long-range intercontinental mission.

For the transcontinental mission and a 50-ton payload, the Helipsoid was found to have the highest productivity by a

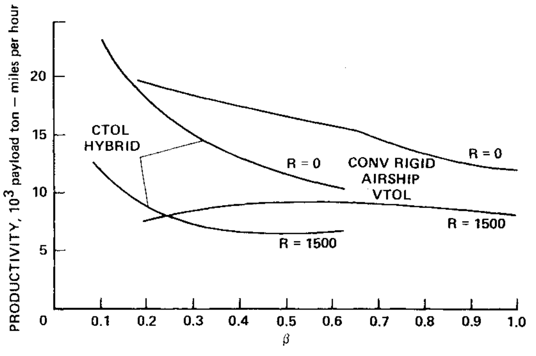

Fig. 10 Effect of buoyancy ratio and range on productivity of 400,000-lb gross weight conventional rigid and lifting body hybrid airships.

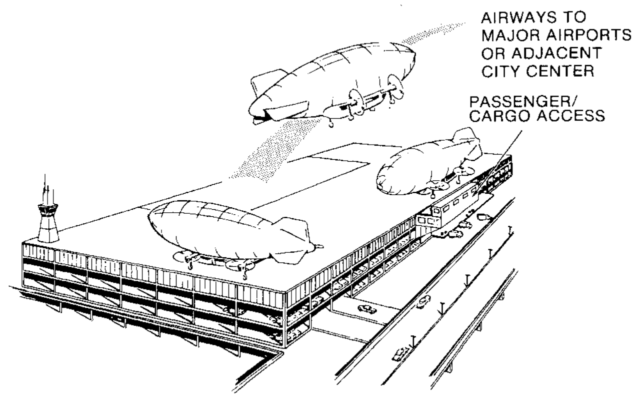

Fig. 11 Airport feeder concept.

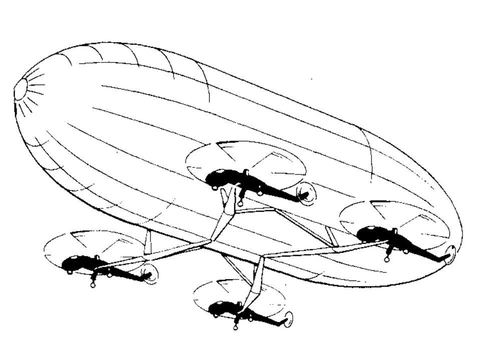

Fig. 12 Heavy lift concept.

Table 2 Proposed civil vehicle/mission combinations for Phase II study

	LIFTING VOLUME SHAPE	BUOYANT LIFT / GROSS LIFT	LANDING/ TAKEOFF MODE	PROPULSION	GROSS LIFT, 1000 lb	PAYLOAD, 1000 lb	MISSION
GOODYEAR	CONVENTIONAL ELLIPSOID	0.20	VTOL	TILTING TURBOPROP	40	~18	AIRPORT FEEDER & SHORT-HAUL CARGO
GOODYEAR	CONVENTIONAL ELLIPSOID	0.55	VTOL	HELICOPTER	1500	500	SHORT-RANGE, HEAVY LIFTER
BOEING	HYBRID HELIPSOID	0.35?	VTOL OR STOL	TURBOPROP	300	100	TRANS-CONTINENTAL FREIGHT

significant margin, followed by the other three hybrid concepts. The conventional concepts have the lowest productivity with the rigid design being the worst of all. Significantly, the optimum speed of the hybrids (150 knots) is almost double that of the conventional airships. For the hybrids, $\beta = 0.35$, but as discussed earlier, insufficient data were generated to establish this as the optimum value.

Conclusions and Recommendations

The civil vehicles and their missions proposed for detailed study in Phase II by the two feasibility study contractors are shown in Table 2. Both Goodyear vehicles essentially use conventionally shaped envelopes, i.e., circular cross sections and approximately elliptic profiles. The Boeing vehicle concept is the Helipsoid with elliptic cross sections and profile.

Boeing selected the transcontinental freight mission. Essentially, they postulated that, if airship operating costs proved to be sufficiently low, then a small segment of the domestic freight market might be captured. Even a small segment of this large market would be sufficient to generate development incentive. A payload size of 50 tons was felt to offer a good compromise between the efficiency of larger vehicles and the utility of smaller vehicles.

The selection of a small, short-haul concept by Goodyear (Fig. 11) deserves some explanation in view of their finding that airships probably cannot compete on a productivity basis with airplanes for this class of missions. Many of these missions are in heavily populated areas where noise and pollution requirements, especially the former, are of critical importance. Since an airship can achieve VTOL capability with lower power requirements than a heavier-than-air craft, an airship can achieve low noise levels more easily and may be the preferred system for many of these short-haul missions when all factors are considered.

The other concept recommended by Goodyear would provide airborne lifting capabilities far in excess of anything in existence today (Fig. 12). There are several potential military as well as civil applications for such a vehicle, although the extent of the market is not well defined at present. It should be noted that several vehicle concepts appear promising for this application. Goodyear selected the Heli-Stat based on their judgment that it would need relatively little development effort.

The rather dramatic differences in the selected vehicle/mission combinations of the two contractors are easily explained when the differences in their Phase I analyses are examined. For example, the difference in vehicle concepts selected results from the following: 1) Goodyear considered heavy flight of conventional airships, whereas Boeing did not. 2) The structural weight-estimating techniques for lifting-body hybrids were different for the two contractors. 3) The extent of the analysis of the effects of partial buoyancy for lifting-body hybrids was different.

The Feasibility Study of Modern Airships represents the most comprehensive technical evaluation of airships in several decades. The final results of this study should establish the worth of future airship research and development and indicate the directions this research and development should take.

Acknowledgment

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