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VEHICLE CONCEPTS AND TECHNOLOGY REQUIREMENTS FOR BUOYANT HEAVY-LIFT SYSTEMS

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Several buoyant-vehicle (airship) concepts proposed for short hauls of heavy payloads are described. Numerous studies have identified operating cost and payload capacity advantages relative to existing or proposed heavy-lift helicopters for such vehicles. Applications involving payloads of from 15 tons up to 800 tons have been identified. The buoyant quad-rotor concept is discussed in detail, including the history of its development, current estimates of performance and economics, currently perceived technology requirements, and recent research and technology development. It is concluded that the buoyant quad-rotor, and possibly other buoyant vehicle concepts, has the potential of satisfying the market for very heavy vertical lift but that additional research and technology development are necessary. Because of uncertainties in analytical prediction methods and small-scale experimental measurements, there is a strong need for large or full-scale experiments in ground test facilities and, ultimately, with a flight research vehicle.

INTRODUCTION

Feasibility studies of modern airships (refs. 1-18) and other studies (refs. 19-27) have determined that modern air-buoyant vehicles (airships) could satisfy the need for air transport of heavy or outsized payloads over short distances.

There are two reasons that such aircraft, called heavy-lift airships (HLAs), appear attractive for both civil and military heavy-lift applications. First, buoyant lift does not lead to inherent limitations on payload capacity as does dynamic lift. Large conventional dynamic-lift vehicles, including rotorcraft, tend to follow a "square-cube law" in that lift increases with the square of the vehicle's principal dimension, while empty weight increases with the cube, notwithstanding the effect of fixed-weight items. This means that the vehicle's structural weight increases faster than the gross weight as size is increased; thus, as the size is increased, the percentage of the total weight available for useful load decreases. On the other hand, buoyant-lift aircraft tend to follow a "cube-cube law" and thus have approximately the same efficiency at all sizes.

Figure 1 shows the history of rotorcraft vertical-lift capability. Current maximum payload of free world vehicles is about 18 tons. Listed in the figure are several payload candidates for airborne vertical lift that are beyond this 18-ton payload weight limit, indicating a market for increased lift capability. Extension of rotorcraft lift to a 35-ton payload is possible with existing technology (refs. 28, 29), and future development of conventional rotorcraft up to a 75-ton payload appears feasible (ref. 29). With HLA concepts, however, payload capability of up to

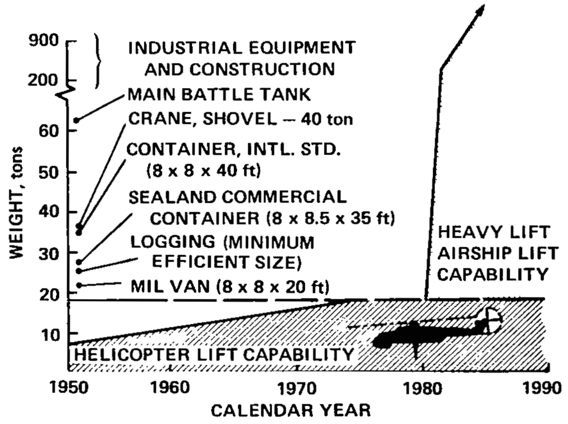


Figure 1.– Potential heavy-lift payloads.

200 tons is possible using existing propulsion-system technology or even, if desired, existing rotorcraft propulsion-system hardware.

The second reason airships appear attractive for heavy lift is cost. Most HLA concepts are projected to offer lower development, manufacturing, maintenance, and fuel costs than large rotorcraft with the same payloads; thus total operating and life-cycle costs may be lower. The lower development cost arises from extensive use of existing propulsion-system technology or hardware or both, making major new propulsion-system development unnecessary. Low manufacturing and maintenance costs accrue because buoyant-lift components are less expensive to produce and maintain than dynamic-lift components. Lower fuel costs follow directly from lower fuel consumption. As fuel prices increase, the high fuel efficiency of HLAs will become increasingly important. HLA costs and fuel efficiency will be discussed in more detail later.

Because the market for vertical lift of payloads in excess of 20 tons is a new one for aerial vehicles, the size and characteristics of the market are somewhat uncertain. As a result, several studies have been undertaken. Many of these studies have been privately funded and their results are proprietary, but the results of some have been published (refs. 26, 27, 30-33). HLA market-study conclusions have been generally favorable. Table 1 summarizes the results of one of these, the recently completed NASA-sponsored study of civil markets for HLAs (refs. 30, 31).

The HLA civil market tends to fall into two categories. The first consists of services that are now or could be performed by helicopters, but perhaps only on a very limited basis. Payloads are low to moderate, ranging from about 15 to 80 tons. Specific markets include logging, containership offloading (of interest also to the military), transmission-tower erection, and support of remote drill rigs. HLAs would be able to capture greater shares of these markets than helicopters because of their projected lower operating costs. Most of these applications are relatively sensitive to cost. The largest market in terms of the potential number of vehicles required is logging.

The second HLA market category involves heavy payloads of 180 to 800 tons – a totally new application of vertical aerial lift. This market is concerned primarily with support of heavy construction projects, especially power-generating plant construction. The availability of vertical aerial lift in this payload range will make the expensive infrastructure associated with surface movements of heavy or bulky items largely unnecessary. It would also allow more freedom in the selection of plant sites by eliminating the restrictions imposed by the necessity for readily accessible heavy suface transportation. Further, it could substantially reduce construction costs of complex assemblies by allowing more extensive preassembly at manufacturing areas. This application is relatively insenstitive to cost of service.

TABLE 1.– PRINCIPAL HEAVY-LIFT AIRSHIP MARKETS [From refs. 30, 31]

Market area	Useful load, tons	Number of vehicles required
Heavy lift		
Logging	25-75	>1000
Unloading cargo in congested ports	16-80	200
High-voltage transmission tower erection	13-25	10
Support of remote drill-rig installations	25-150	15
Ultraheavy lift		
Support of power-generating plant construction	180-900	30
Support of oil-gas offshore platform construction	500	3
Other transportation	25-800	10

In the remainder of this paper, HLA concepts will be reviewed. The buoyant quad-rotor (BQR), or helistat, will be emphasized because it has been the principal subject of technology development efforts to date. As a result, there is more technical information available about the BQR than other HLA concepts.

The next section briefly describes free-flying HLA concepts other than the BQR. The following section discusses the BQR in terms of: (1) development history, (2) description of the concept, (3) technology needs as currently perceived, and (4) the current NASA research and development program.

HEAVY-LIFT AIRSHIP CONCEPTS OTHER THAN BUOYANT QUAD-ROTOR

The classical fully buoyant airship is unsuitable for most heavy-lift applications because of poor low-speed control and ground-handling characteristics. Therefore, almost all HLA concepts that have been proposed are "hybrid" aircraft, that is, vehicles that obtain part of their total lift from the displacement of air by a lighter gas (buoyant lift) and the remainder by dynamic or propulsive forces. Because buoyant lift can be scaled up to large sizes at low cost per pound of lift (as previously described), it is advantageous from a cost standpoint in hybrid aircraft to provide as much of the total lift as possible by buoyancy. The fraction of total lift derived by dynamic or propulsive forces is determined primarily by the amount of control power required. The dynamic forces therefore provide propulsion and control as well as a portion of the total lift.

The characteristics of hybrid aircraft and their potential for the heavy-lift mission were clearly recognized (by the mid-1970s) by Piasecki (refs. 12, 21), by Nichols (ref. 20), and by Nichols and Doolittle (ref. 24). References 20 and 24, in particular, describe a wide variety of possible hybrid HLA concepts.

Perhaps the simplest and least expensive of the HLA concepts are those which combine the buoyant and dynamic-lift elements in discrete fashion without major modification. Examples, taken from references 7 and 24, are shown in figure 2. Although such systems will obviously require minimal development of new hardware, there may be serious operational problems associated with them. Safety and controllability considerations would likely restrict operation to fair weather. Further, cruise speeds would be extremely low. The concept from reference 24 that is shown in figure 2 was rejected by the authors of reference 24 because of the catastrophic failure which would result from an inadvertent balloon deflation.

An early hybrid HLA concept, which has subsequently received a significant amount of study and some initial development, is a rotor-and-balloon configuration (called Aerocrane by its inventors, the All American Engineering Company). Early discussions of this concept appear in references 19, 20,

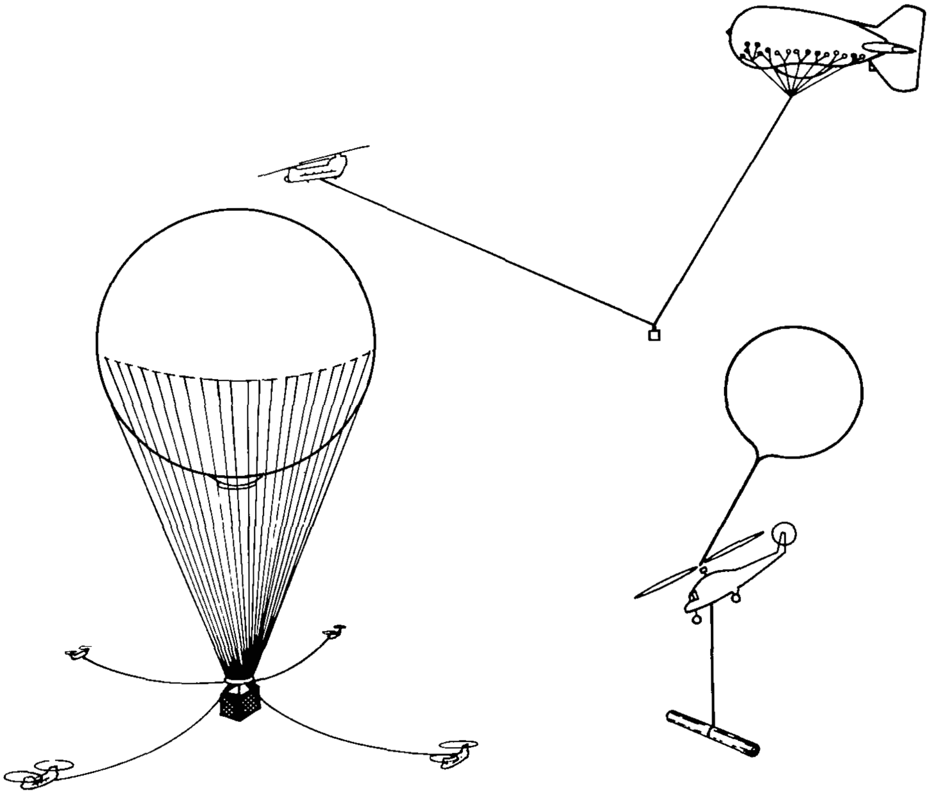
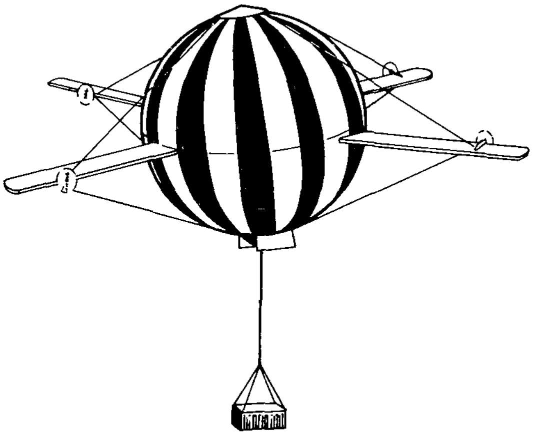


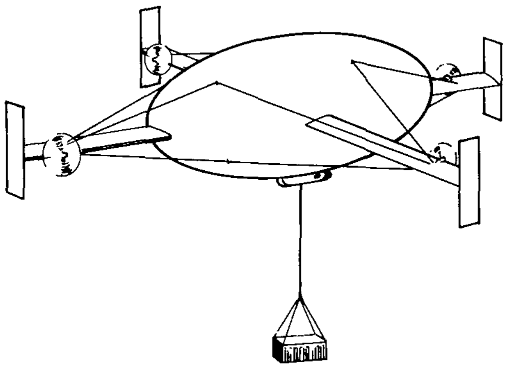
Figure 2.– Combined discrete concepts (refs. 7, 24).

23-25, 34; two versions of the Aerocrane are depicted in figure 3. The original configuration consisted of a spherical helium-inflated balloon with four rotors (airfoils) mounted at the equator. Propulsors and aerodynamic control surfaces are mounted on the rotors. The entire structure (except the crew cabin and payload support, which are kept stationary by a retrograde drive system) rotates (typically at a rate of 10 rpm) to provide dynamic rotor lift and control. Principal applications envisioned for the rotor-balloon are logging and containership offloading.

Study and technology development of the rotor-balloon concept have been pursued by All American Engineering and others, partly under U.S. Navy sponsorship. Emphasis of the program has been on devising a suitable control system. A remotely controlled flying model was built to investigate stability, control, and flying qualities (fig. 4). Results (refs. 35-37) have shown that the rotor-balloon is controllable and that it promises to be a vehicle with a relatively low empty-to-gross weight ratio and low acquisition cost across a wide range of vehicle sizes. Technical issues that emerged were (1) the magnitude and effect of the Magnus force on a large rotating sphere and (2) the high acceleration environment (about 6 g in most designs) of the propulsors.



ORIGINAL



ADVANCED

Figure 3.– Aerocrane concept.

Although the rotor-balloon technical issues are thought to be solvable, two characteristics emerged as being operationally limiting. First, large vehicle tilt angles would be required to obtain the necessary control forces in some operating conditions. Second, the high drag associated with the spherical shape results in very low cruise speeds, typically 25 mph for a 16-ton payload vehicle. This low speed means that operation in winds of over 20 mph probably is not possible and that the efficiency of operation in even light winds is significantly degraded. Even with no wind, the low speed will result in low productivity. Thus, the original rotor-balloon concept was limited to very short-range applications in very light winds.

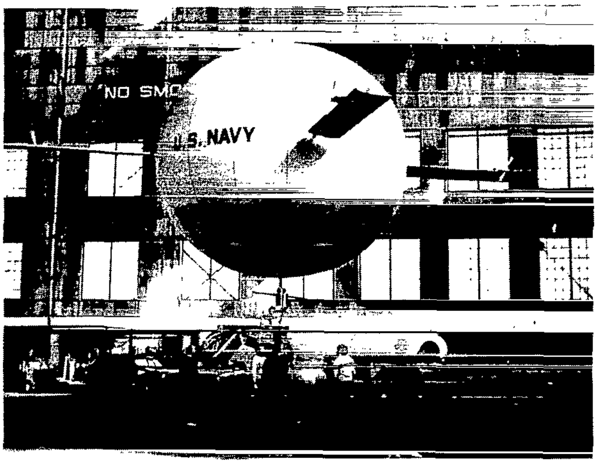


Figure 4.– Aerocrane remotely controlled flying model.

The advanced configuration rotor-balloon depicted in figure 3 (ref. 38) is designed to overcome the operational shortcomings of the original concept. Winglets with aerodynamic control systems are fitted to allow generation of large lateral-control forces, thereby alleviating the need to tilt the vehicle. A lenticular shape is used for the lifting gas envelope to decrease the aerodynamic drag. The increase in cruise speed of the advanced concept is, however, accompanied by some increase in design complexity and structural weight.

A more substantial departure from the original Aerocrane concept has been proposed recently. The Cyclo-Crane of Aerocranes of Canada (refs. 39, 40) is essentially a new HLA configuration concept (fig. 5). It consists of an ellipsoidal lifting gas envelope with four strut-mounted airfoils at the midsection. The propulsors are also located on these struts. This entire structure rotates about the longitudinal axis of the envelope to provide control forces during hover. Isolated from the rotating structure by bearings are the control cabin at the nose and the aerodynamic surfaces at the tail. The payload is supported by a sling attached to the nose and tail. The rotation speed and yaw angles of the wings on their struts are controlled to keep the airspeed over the wings at a constant value, namely, a value equal to the vehicle cruise speed. Thus, for hover in still air, the wingspan axes are aligned with the envelope longitudinal axis. As forward speed is increased, the vehicle rotational speed decreases and the wings are yawed until, at cruise speed, the rotation is stopped and the wingspan axes are perpendicular to the forward velocity. Hence, in cruising flight the Cyclo-Crane acts as a winged airship.

Preliminary analysis of the Cyclo-Crane has indicated that a cruising speed of 50 mph would be possible with a 10-ton payload vehicle and that the economic performance would be favorable. However, there are obvious questions of structural weight and

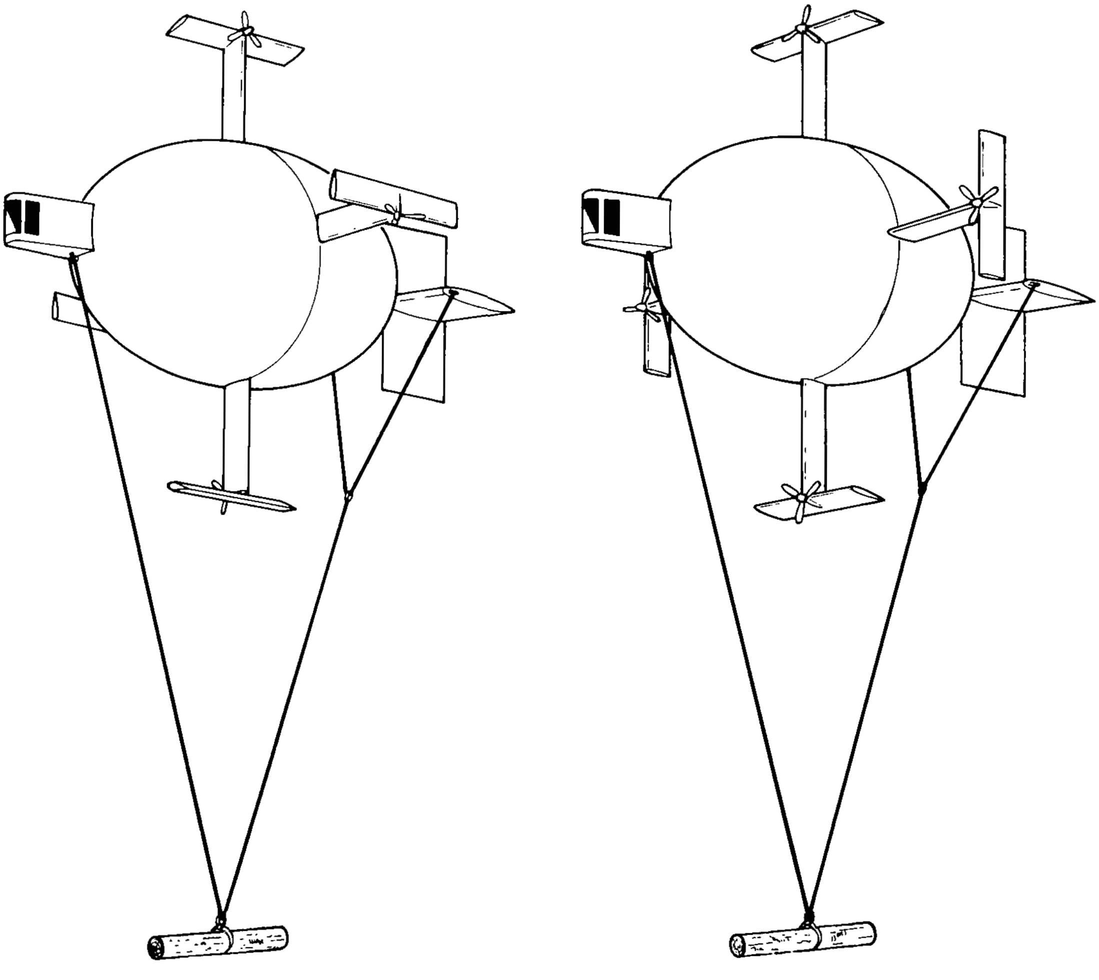
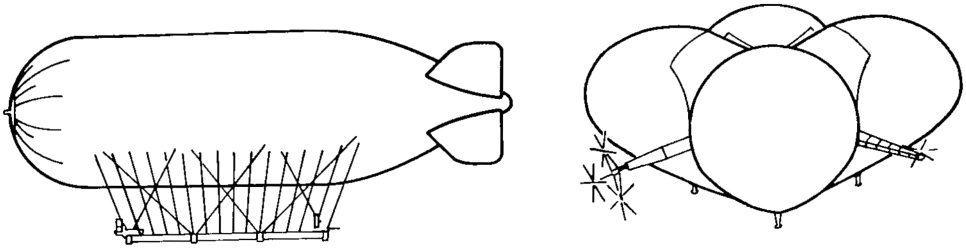

HOVER CRUISE

Figure 5.– Cyclo-Crane concept (refs. 39,40).

aerodynamic interference between the various vehicle components, and more detailed investigation is required to resolve them.

Another approach to heavy lift with buoyant forces is the clustering of several small buoyant elements. Examples of this are the ONERA concept and the Grumman concept (ref. 41) shown in figure 6. In the Grumman idea, three airships of approximately conventional design such as the one shown are used to lift moderate payloads. When heavy lift is needed, the three vehicles are lashed together temporarily while in the air. The technique for joining the vehicles and the controllability of the combined system need further study.

Finally, another HLA concept that has received some attention is the "ducted-fan hybrid" shown in figure 7 (ref. 24). In this vehicle, a toroidal-shaped lifting gas envelope provides a duct or shroud for a centrally located fan or rotor. There has been too little study of the ducted fan hybrid, however, to permit an assessment of its potential.



GRUMMAN

ONERA

Figure 6.– Multielement concepts (refs. 7, 41).

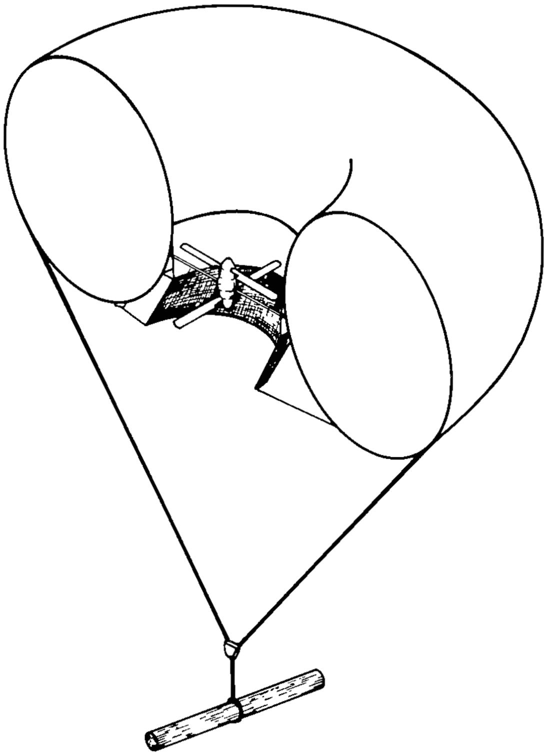


Figure 7.– Ducted-fan concept (ref. 24).

BUOYANT QUAD-ROTOR CONCEPT

History and Description

The idea of combining helicopter engine/rotor systems with airship hulls is not new. In the 1920s and 1930s, a French engineer, E. Oehmichen, not only conceived this idea but successfully built and flight-tested such aircraft, which he called the Helicostat (ref. 26). One of his first designs (top photograph in fig. 8) had two rotors driven by a single engine mounted beneath a cylindrical buoyant hull. According to reference 26, Oehmichen's purpose in adding the buoyant hull to the rotor system was threefold – "to provide the helicopter with perfect stability, to reduce the load on the lift-rotors, and to slow down descent with optimum efficiency."

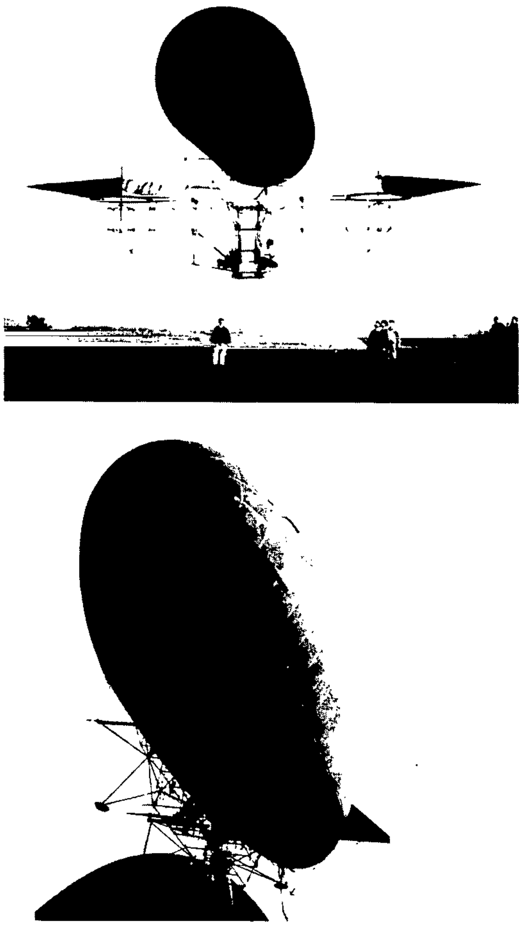


Figure 8.– Oehmichen's Helicostat flight vehicles.

Oehmichen's later effort was a quad-rotor design with two rotors mounted in the vertical plane and two in the horizontal (bottom photograph in fig. 8). The hull was changed to an aerodynamic shape more characteristic of classical airships. Existing motion pictures of successful flights of the Helicostat demonstrate that the buoyant quad-rotor (BQR) concept was proven feasible in the 1930s.

The modern form of the concept was first proposed by Piasecki (refs. 12, 21). Piasecki's idea is to combine existing, somewhat modified helicopters with a buoyant hull, as exemplified in figure 9. The configuration shown in figure 9 will be called the "original" BQR concept in this report. The attraction of the idea lies in its minimal development cost. In particular, no new major propulsion-system components would be needed (propulsion systems are historically the most expensive part of an all-new aircraft development). A fly-by-wire master control system would command the conventional controls within each helicopter to provide for lift augmentation, propulsive thrust, and control power.

Other variants of the BQR idea are currently under study. A design by Goodyear Aerospace (ref. 42) is shown in figure 10. As compared with original concept (fig. 9), this design (called the "advanced" concept) has a new propulsion system, auxiliary horizontal-thrusting propellers, and aerodynamic tail surfaces and controls. The four propulsion system modules would make extensive use of existing rotorcraft components and technology but be designed

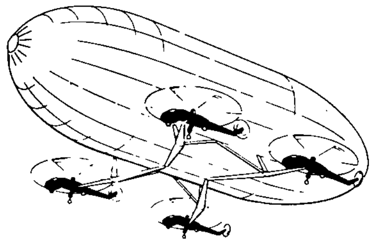


Figure 9.– Buoyant quad-rotor, original concept (Helistat).

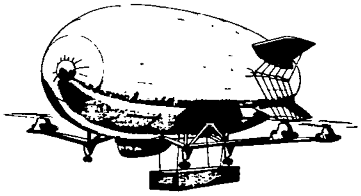


Figure 10.– Buoyant quad-rotor, advanced concept.

specifically for the BQR. The horizontal-thrusting propellers would be shaft-driven from the main rotor engines. These propulsion modules would be designed more for high reliability and low maintenance costs and less for low empty weight than are typical helicopter propulsion systems. They would be "de-rated" relative to current systems, leading to further reductions in maintenance costs.

In a revival of the Helicostat concept, a buoyant dual-rotor HLA is currently under study by Aerospatiale (ref. 26). It would use the engines and rotors from a small helicopter, but propellers would be fitted for forward propulsion and yaw control (fig. 11). Payload would be about 4 tons; the principal application is envisioned to be logging.

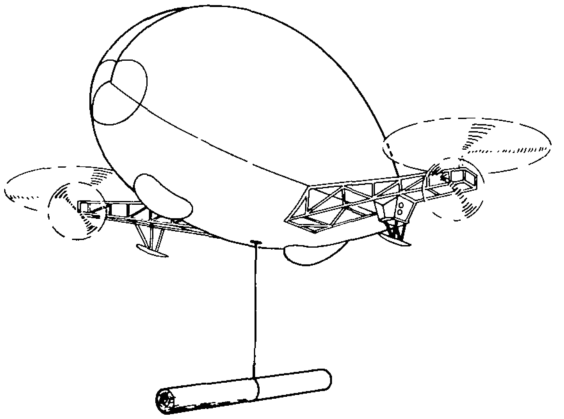


Figure 11.– Modern Helicostat (ref. 26).

Performance and Economics

The performance capability of the BQR design (fig. 9) examined in the feasibility studies of references 12-14 and 16 is listed in table 2. This design employs four CH-54B helicopters, somewhat modified, and a nonrigid envelope of 2.5×10^6 ft^3. Total gross weight with one engine inoperative is about 325,000 lb, of which 150,000 lb is payload. Empty-to-gross weight fraction is 0.455 and design cruise speed is 60 knots. Station-keeping is estimated to be possible in crosswinds up to 30 knots. Range with maximum payload is estimated to be 100 n. mi.; with the payload replaced by auxiliary fuel, the unrefueled ferry range would be over 1,000 n. mi. Performance of the advanced concept (fig. 10) should be much better than that of the design shown in figure 9.

In references 12, 16, and 21, the ratio of buoyant-to-total lift (β) is chosen so that the vehicle is slightly "heavy" when completely unloaded. In effect, the buoyant lift supports the vehicle empty weight, leaving the rotor lift to support the useful load (payload and fuel). A different approach has been suggested and studied by Bell et al. (ref. 43). Bell et al. proposed that β be selected so that the buoyancy supports the empty weight plus half the useful load. It is then necessary for the rotors to thrust downward when the vehicle is empty with the same magnitude that they must thrust upward when fully loaded. This same principle has been used in the studies of the rotor-balloon. Use of the approach suggested by Bell et al. (high β), as opposed to the approach assumed in table 2 (low β), has the potential of offering lower operating costs (since buoyant lift is less expensive than rotor lift) and better control when lightly loaded (because higher rotor forces are available). In comparison, the low β approach may result in a vehicle that is easier to handle on the ground (since it is heavy when empty) and one that is more efficient in cruise or ferry when lightly loaded or with no payload (because of low rotor forces). Selection of the best value of β depends on these and many other factors and will require a better technical knowledge of the concept.

TABLE 2.– WEIGHT STATEMENT AND PERFORMANCE OF 75-TON BUOYANT QUAD-ROTOR, ORIGINAL CONCEPT
[From refs. 12, 16]

Gross weight,[a] lb	324,950
Rotor lift, lb	180,800
Buoyant lift, lb	144,150
Empty weight, lb	148,070
Useful load,[a] lb	176,800
Payload, lb	150,000
Static heaviness,[a] lb	3,920
Envelope volume, ft^3	2.5×10^6
Ballonet volume, ft^3	5.75×10^5
Ballonet ceiling, ft	8,500
Hull fineness ratio	3.2
Design speed (TAS), knots	60
Design range	
With maximum payload, n. mi.	100
No payload, n. mi.	196
Ferry, n. mi.	1,150

[a] Sea level, standard day, 93% inflation, one engine out, reserves for 100 ft/min climb.

The BQR vehicle will be efficient in both cruise and hover compared with conventional-design heavy-lift helicopters (HLH). This arises primarily from the cost advantages of buoyant lift when compared with rotor lift on a per-unit-of-lift basis, as discussed earlier. Fuel consumption of the BQR vehicle in hover will be approximately half that of an equivalent HLH. Relative fuel consumption of the BQR in cruise may be even less because of the possibility of generating dynamic lift on the hull, thereby reducing or eliminating the need for rotor lift in cruising flight.

When cruising with a slung payload, the cruising speeds of HLHs and BQR vehicles will be approximately the same since external load is generally the limiting factor on maximum speed. When cruising without a payload, as in a ferry mission, the speed of the BQR will be lower than that of an HLH. The many HLA studies have shown, however, that the higher efficiency of the BQR more than offsets this speed disadvantage. Therefore, the BQR should have appreciably lower operating costs per ton-mile in either the loaded or unloaded condition.

Total operating costs per ton of payload per mile in cruise flight are compared in figure 12 (based on data provided by Goodyear). The figure shows that the advanced BQR concept offers a decrease in operating costs by as much as a factor of 3 compared with existing helicopters. Of course, much of this cost advantage results from the larger payload of the BQR (approximately eight times larger). The low operating costs in cruise flight of the advanced concept compared with those of the original arise from the use of propellers instead of rotor cyclic pitch for forward propulsion and from lower assumed propulsion maintenance costs. The advanced concept would be particularly efficient when cruising lightly loaded (as in ferry), since it would operate essentially as a classical fully buoyant airship.

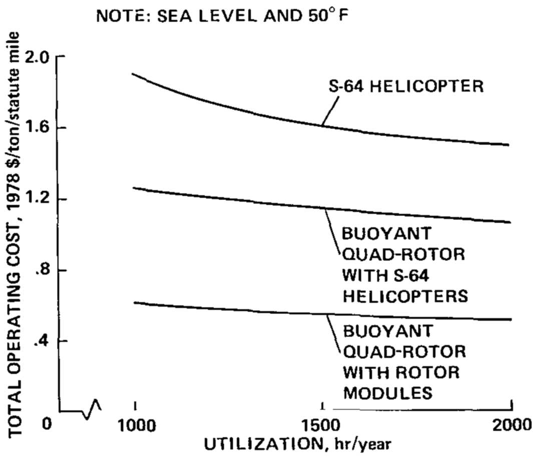


Figure 12.– Relative heavy-lift operating costs.

Studies have shown that precision hover and station-keeping abilities approaching those of proposed HLHs are possible with BQR designs (refs. 12, 21, 44-46). Automated precision hover systems recently developed for an HLH (ref. 28) can be adapted for BQR use.

Ultimate selection of the original (fig. 9), the advanced (fig. 10), or some other variant of the BQR concept will depend on the relative importance of development cost, performance, and efficiency. This choice will obviously depend on the uses to which the vehicle is to be put as well as on the total number of vehicles to be built.

Technology Needs

The many recent studies of the BQR concept have all concluded that the concept is basically technically feasible, as was in fact verified by Oehmichen's limited flight tests more than 40 years ago. However, to realize the best economic performance and most suitable operational characteristics from the concept, as well as to minimize development risk and cost, a significant amount of research and technology development will be required. There are technology needs in the areas of aerodynamics, propulsion, controls, structures and materials, and operations.

In *aerodynamics*, the most important requirement is to develop an accurate analytical characterization of the flow field around the vehicle. This characterization must account for aerodynamic interference between all elements of the vehicle and must be verified by experimental data. Many of the other technology needs depend on an accurate aerodynamic description of the vehicle. Specific aerodynamic items of interest are (1) effect of the hull on the aerodynamic environment of the rotors, particularly for rotors in the hull wake; (2) effect of the rotor wake on the hull flow field; (3) interactions between the vehicle and the ground, such as rotor fountain effects and suckdown on the hull caused by crossflow; and (4) accurate estimation of cruise and hover performance in all flight conditions, including oblique crosswinds and atmospheric turbulence.

Propulsion needs include better definition of the design of BQR propulsion modules based on existing helicopter systems technology. The effect of rotor/hull aerodynamic interference on rotor loads must be determined. Rotor/rotor and rotor/ground interactions, such as ground resonance, must also be investigated.

In flight controls, the most important task is to define suitable and optimal control-systems concepts. This will be a formidable task because of the many flight-control inputs that are available. A BQR design may employ many or all of the following controls: rotor collective pitch (used in unison or differentially); rotor cyclic pitch; tilting or gimballed rotors in one or two axes (free or forced); aerodynamic surfaces; buoyancy distribution (e.g., ballonets); auxiliary thrustors; deflected slipstream; and cold jets. Also of importance is characterization of handling qualities, which are likely to be quite different from those of helicopters and other VTOL aircraft. A new subset of handling-qualities criteria will probably need to be developed. Automatic precision hover systems need to be developed or adapted, possibly including active control systems for payload support. Preliminary work in BQR flight dynamics and controls is reported in references 12, 21, and 44-46.

New technology in structures and materials could be quite crucial to successful HLA production vehicles. Perhaps the most important item in this category is analysis of the propulsion-system/flexible-structure/aerodynamic interactions, which may lead to critical design conditions for many vehicle components. Design and manufacture of nonrigid envelopes and interconnecting structure in the sizes being contemplated is state of the art, provided state-of-the-art materials are used. Modern filimentary composite materials have the potential for reducing empty weight and permeability and therefore increasing vehicle performance. They would, however, need further development for this application. If large-sized BQR vehicles are contemplated, rigid-structure envelopes will have to be considered. Preliminary work in BQR structures and materials is reported in references 47-49.

As for any lighter-than-air (LTA) vehicle, operational factors will be important. Mooring systems need to be defined and analyzed. The mooring concept will influence operating suitability and economics and may affect vehicle design. Flight procedures need definition, taking into account the fact that the vehicle will typically be operating in turbulent air near ground level. Finally, procedures and operating systems must be developed to handle all foreseeable inclement weather.

BQR technology needs have commonality with needs of other vehicles of current interest. Nonbuoyant quad-rotor aircraft also are being considered for the heavy-lift mission. Such aircraft have many technical similarities to the BQR (e.g., both will need development of fly-by-wire control systems for multiple rotors). Modern conventional airships are being proposed for coastal patrol and related applications (refs. 50-53); these aircraft will be required to station-keep and hover and therefore will require development of control systems for hover-capable buoyant vehicles.

Research and Technology Development Activity at Ames Research Center

Over the last seven years, many organizations and individuals, both foreign and domestic, private and public, have studied HLA concepts in general and the BQR concept in particular. Foreign countries that have conducted or funded published studies include Canada (the Province of Alberta (ref. 27); the National Research Council, Canadair (ref. 25); the Forest Engineering Research Institute of Canada (ref. 32); Aerocranes of Canada (ref. 39); and others); Japan (Japanese Buoyant Flight Association (refs. 54, 55), and others); France (Aerospatiale (ref. 26), and others); and the U.S.S.R. In the United States, government agencies with HLA interest and programs include NASA, the Navy, and the Forest Service. Many private U.S. companies have pursued HLA work, some under government sponsorship and some with private funds. In this report, only the BQR research and technology program at Ames Research Center are reviewed. A comprehensive review of all HLA work under way would require a much more lengthy report.

Figure 13 is an overview of Ames Research Center's LTA activity from the Monterey Workshop in 1974 through the end of 1979. Using the LTA vehicle concepts and potential missions collected at the workshop as a data base, the feasibility study of modern airships provided a preliminary evaluation of the LTA field. There were two principal feasibility study contractors, Boeing Vertol and Goodyear Aerospace, and funding was provided both by NASA and the Navy. The most important conclusion of the studies was the identification of the potential of LTA vehicles for heavy vertical lift.

Subsequent to the feasibility studies, NASA has focused on technology development of HLA, specifically on the BQR concept. Thus far, the work has been confined to the areas of aerodynamics and controls, in the belief that these are the most critical

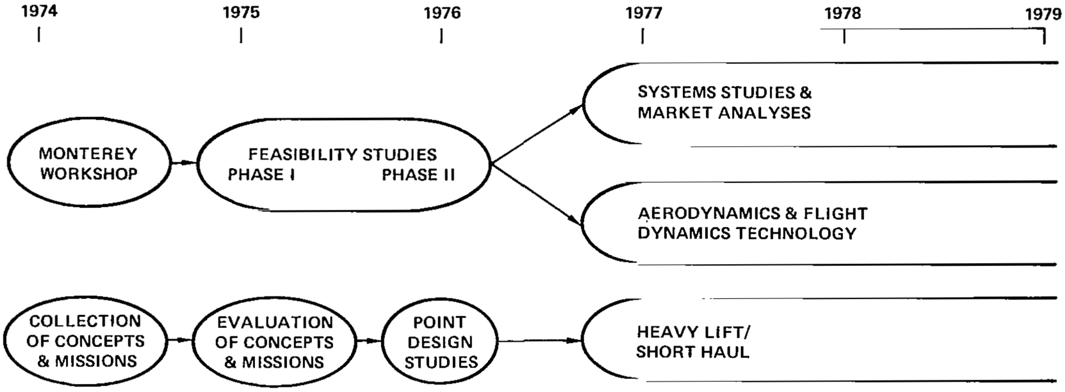


Figure 13.– History of lighter-than-air program at Ames Research Center.

technical areas. The program consists of theoretical analyses, wind-tunnel experiments, moving-base piloted simulation experiments, and studies.

A theoretical study of BQR aerodynamic interference has been completed by Nielsen Engineering and Research (NEAR) (refs. 56, 57). In that study, a preliminary computer program to compute BQR flow fields was developed. Figure 14 shows the velocities induced on the surface of the hull and the circumferential pressure distributions as predicted by the NEAR program for a specific case.

A small-scale, wind-tunnel test program is currently in the planning stage (refs. 58, 59). Tests will be done in the 12-Foot Pressure Wind Tunnel at Ames Research Center. The purposes of the wind-tunnel tests are (1) validation of theoretical analyses, (2) establishment of the influence of Reynolds number, (3) determination of aerodynamic loads, (4) determination of pressure distributions, (5) flow visualization, (6) determination of the effect of configurational changes on aerodynamic characteristics, and (7) provision of experimental data for a flight-dynamics analysis and simulation effort. Figure 15

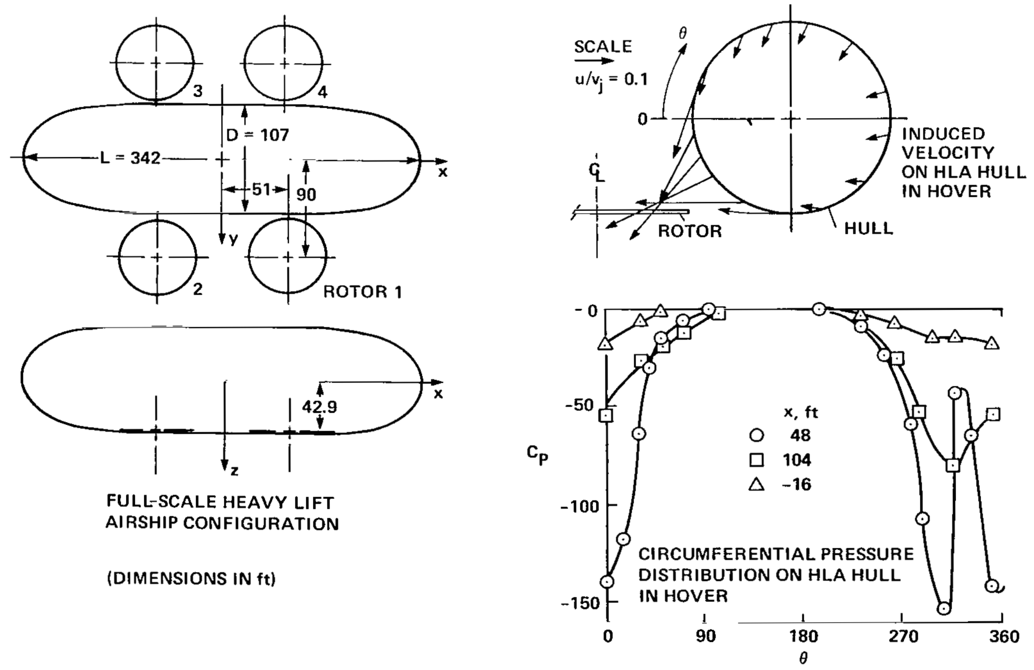


Figure 14.– Interference analysis results (refs. 56,57).

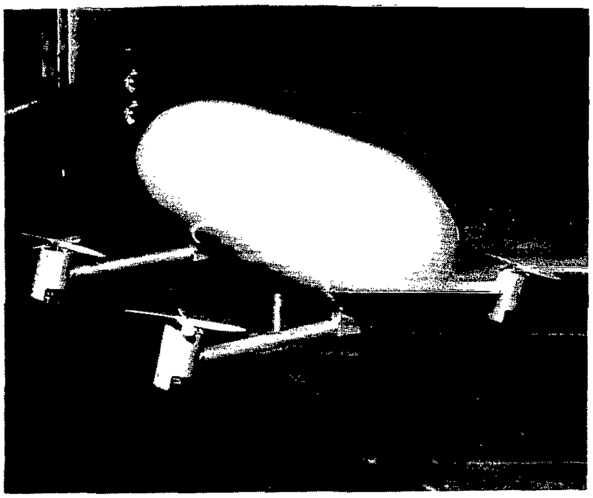


Figure 15.– 7- by 10-Foot Wind Tunnel buoyant quad-rotor model (ref. 14).

shows the model used in an earlier test of the BQR. This model was built by NEAR (funded by Goodyear) and tested in the 7- by 10-Foot Wind Tunnel at Ames. Results of this early test were somewhat inconclusive because of insufficiently high Reynolds numbers (ref. 14).

A major effort that is under way is flight-dynamics simulation and analysis of the BQR concept. The primary goal of this contracted effort is to develop an accurate, nonlinear, off-line simulation of the generic BQR, including all aerodynamic interference effects. The contractor, Systems Technology, Inc., will also develop linearized and real-time simulations for use in piloted moving-base simulators. Development of suitable turbulence models and correlation with experimental data are important parts of this effort.

In future work, the flight-dynamics simulation will be used in control-system research for the BQR. Included will be defintiion of suitable control-system logic and investigations of handling qualities. Moving-base simulators will be used extensively in this work.

Studies will continue to be made primarily in support of the research and technology projects. Currently under way are design studies of BQR research aircraft and studies of ground handling systems and procedures.

Because the BQR is a new aircraft concept, large-scale testing, and, ultimately, a flight research vehicle (FRV) are essential parts of any comprehensive research and technology program. An FRV is necessary to validate the results of analytical and small- and large-scale model experimental research, particularly in the areas of aerodynamics and flight controls. Further, flight vehicles will be needed eventually to verify the operational feasibility of the concept. Many of the remaining uncertainties are connected with operational aspects, such as ground handling, adverse weather effects, and manpower and ground facility requirements; these can be adequately investigated only by flight test of sufficiently large vehicles. Finally, an FRV will be a valuable aid in establishing the certification and airworthiness criteria for this new and unique class of vehicles.

As currently envisioned, the buoyant quad-rotor research aircraft (BQRRA) would use the propulsion system components of an existing small helicopter type. The vehicle would be capable of incorporating a large variety of flight-control schemes and have a certain amount of variable-geometry capability (e.g., changeable location of rotors relative to the hull). Two envelope sizes would be desirable for use in investigating two different regimes of buoyant-to-total-lift ratio. The smaller envelope would be sized to allow testing of the BQRRA in the future 80- by 120-foot section of the Ames Large-Scale Wind Tunnel. This would allow safe and systematic exploration of the flight envelope and collection of data before manned flight.

CONCLUDING REMARKS

The history and current state of knowledge of several buoyant heavy-lift vehicle concepts have been reviewed. Many of these concepts appear to have promise, and the technical feasibility of a few has been largely established. The buoyant quad-rotor vehicle, in particular, has been studied by many organizations, and results to date have been generally positive. Research and technical development of this concept is under way at Ames Research Center and at several other government and private organizations.

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Moffett Field, California 94035, April 10, 1981

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15. Supplementary Notes

16. Abstract

Several buoyant-vehicle (airship) concepts proposed for short hauls of heavy payloads are described. Numerous studies have identified operating cost and payload capacity advantages relative to existing or proposed heavy-lift helicopters for such vehicles. Applications involving payloads of from 15 tons up to 800 tons have been identified. The buoyant quad-rotor concept is discussed in detail, including the history of its development, current estimates of performance and economics, currently perceived technology requirements, and recent research and technology development. It is concluded that the buoyant quad-rotor, and possibly other buoyant vehicle concepts, has the potential of satisfying the market for very heavy vertical lift but that additional research and technology development are necessary. Because of uncertainties in analytical prediction methods and small-scale experimental measurements, there is a strong need for large or full-scale experiments in ground test facilities and, ultimately, with a flight research vehicle.

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