An Informal Report

AIRSHIP OPERATION IN ALASKA

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SUMMARY

An evaluation of the utility of lighter-than-air vehicles (airships) for Alaskan service suggests that very large vehicles operating at low speeds would transport heavy loads to remote areas with excellent fuel economy, but that the potential market for such vehicles would not justify the cost of their development in present circumstances.

Equations relating the effect of design parameters on the ratio of payload weight to fuel weight may be used to verify performance claims made for innovative designs.

INTRODUCTION

This is a quick and cheap review of the status of Lighter-Than-Air technology designed to help Alaska DOT employees review proposals for exotic transportation systems. It is not a scholarly paper, and sources are largely the writer's personal library, memory of books read long ago and experience in flying airplanes and balloons.

Ten minutes of research disclosed a major problem. The great age of airships ended before the University of Alaska had a library, and current LTA articles are, perhaps unfairly, relegated to obscure transactions that Alaskan libraries do not collect. Those collected are personal memoirs of historic voyages or popularized digests of technical papers. Some of the digesters did their homework though, and enough numbers can be gleaned to perform a rudimentary analysis of airship performance.

No one who has seen a Zeppelin filling the sky overhead can ever be completely objective about these magnificent machines, and proposals for their renewed application must be read with some sympathy for the hypnotic effect of airships on even the most serious author. The writer has seen a Zeppelin and this paper may appear unreasonably severe in weighing the potentialities of lighter-than-air vehicles in a deliberate attempt to resist the hypnosis.

AEROSTAT NOMENCLATURE

Vehicles deriving lift from buoyancy of the air are properly called aerostats. The commonly used term Lighter-Than-Air (LTA) is misleading because they often operate at a weight greater than that of the air they displace. Lift is obtained by inflating the vehicle with a gas, commonly hot air, hydrogen, or helium, having a lower density than the surrounding air. Balloons have no powered means of propulsion, but may be sailed by canting them to the wind if tethered to a tramway or powered by gravity as in balloon logging. Some control over the path of a free balloon may be exercised by seeking altitudes at which the wind blows in a favored direction, or by employing a sail and trailing friction rope in the manner of the Andre expedition.

The terms "airship" or "dirigible" apply to any aerostat with propulsion and steering. Blimps (non-rigid airships) have no rigid structure inside the gasbag, and rely on gas pressure to hold the bag in shape. They may, however, have quite sophisticated fabric and cable structures inside the bag to convey buoyant lift from the bag to the car, and usually incorporate an inner balloon or "balonet" inflated with air by a blower to maintain a fixed pressure as the temperature of the lifting gas changes. Most non-rigid airships operate as "superpressure" vehicles, meaning that the pressure inside the bag is significantly greater than atmospheric pressure, but at least one hot-air non-rigid airship has been flown in which the bottom of the bag is vented to the atmosphere.

Semirigid airships have a keel structure running the length of the craft to carry bending loads on the hull, but the gasbag is held in shape by internal pressure. Semirigids Norge, Italia, and America have attempted polar voyages, the Norge alone completing a flight from Svalbard to Alaska. Rigid airships, often called "Zeppelins" after their originator and most successful builder, have a complete structure and outer cover containing many independent partially inflated gas cells. These cells expand as the airship rises or the gas becomes warmer, becoming fully inflated when the "pressure height" is reached. Further increases in altitude or temperature require valving of the buoyant gas, for the gas cells are not designed to operate at superpressure.

A variety of hybrid vehicles combining aerostatic and aerodynamic lift have been proposed, some employing helicopter rotors and others a wing-shaped lifting hull. Nearly all airships of conventional form carry a portion of their load by aerodynamic lift, but the shape of a conventional airship hull makes it an inefficient wing and aerodynamic lift is usually limited to minor trim adjustments that avoid frequent release of gas or ballast.

AEROSTAT CONTROL

Control of even a simple hot air balloon presents a number of problems not apparent to the casual observer. While the balloon may be lighter than air, it is not weightless or massless, and it responds very slowly to changes in lift. The burner does not directly control the vertical speed or acceleration, but rather the rate of change of acceleration and considerable practice is required before the pilot can anticipate its motion far enough in advance to exercise smooth control. Since the difference in density between the air in the balloon and the surrounding atmosphere is relatively small, the balloon is extremely sensitive to changes in ambient air temperature. The rising currents of warm air called "thermals" so eagerly sought by glider pilots can be disastrous to balloonists because the loss of buoyancy in the warm air of a thermal is much larger than the dynamic lift caused by its upward motion.

Hydrogen or helium balloons are controlled by valving off gas to reduce lift or dropping ballast to reduce weight, and the history of the sport is replete with tales of wild fluctuation in altitude as inexperienced pilots attempt to regulate their height. Further complications are introduced as the buoyance of the lifting gas expands in the heat of the sun or decreases in the shadow of clouds or nightfall.

Airship operation under power permits aerodynamic lift to supplement the dropping of ballast and valving of gas. Present-day Goodyear non-rigids begin their flights heavier than air, making a short takeoff run to gain speed and then nosing the craft upward to develop lift. Using the short, stubby gasbag as a lifting wing permits extreme nose-up attitudes without risk of a stall, often unnerving fixed-wing pilots on board the airship as passengers.

Once airborne the airship becomes progressively lighter as fuel is consumed so that modern non-rigids land at nearly neutral buoyancy. Long flights, however, may consume more fuel than can be carried at takeoff by aerodynamic lift, and landing the lighter-than-air craft presents special problems if costly helium is not to be wasted. American rigid airships scheduled most of their long flights so that landings were made in the cool of evening, contracting the helium cells and reducing lift.

Engines of the Graf Zeppelin were fueled by a mixture of propane and other gases having nearly the same density as air, contained in cells similar to those holding the lifting hydrogen, so that consumption of fuel did not change the weight of the airship. Hindenburg collected water ballast to replace the weight of fuel by deliberately flying through rainstorms, and American helium-filled airships employed heavy and troublesome condensers to collect ballast water from engine exhaust.

Airships inflated with helium or hydrogen are less sensitive to small changes in ambient air temperature than hot air balloons, but the updrafts associated with thunderstorms create a special maneuvering difficulty - if the ship is lifted above its pressure height (the altitude at which gas cells are completely filled) lifting gas must be vented to prevent superpressure and the ship emerges from the updraft much heavier than air. Ballast must then be dropped to restore balance, often initiating the altitude fluctuations common to free balloons. An incident of this type appears to have caused the loss of the U.S.S. Akron and efforts to prevent valving helium in similar incidents may have resulted in a superpressure condition that initiated the structural disintegration of the U.S.S. Shenandoah. (1)

Another difficulty common to all airship operations in the Los Angeles area was the difficulty of descending through an inversion layer without valving gas, a problem that will be magnified during winter months in interior Alaska.

Perhaps the greatest hazard to airships is atmospheric turbulence. Nearly all the large rigids have been damaged by storm encounters, and the U.S.S. Macon appears to have been destroyed in this manner. Despite their imposing appearance, Zeppelins were extremely fragile machines. By contrast, the non-rigid airships of World War II were surprisingly sturdy, often carrying out patrol duty in weather that grounded fixed-wing airplanes.

LIFTING GASES

Helium, hot air and hydrogen have been used as lifting gases in aerostats with helium the choice of conventional wisdom for large vehicles because it is incombustible and has a lifting capacity only 7.3% less than that of hydrogen. Hot air at 250°F, having only one-third the lift of hydrogen in a 32°F atmosphere, is currently used in sport ballooning.

A closer look suggests that helium need not be the automatic choice. Zeppelins in commercial service carried thousands of passengers without injury in the years between 1909 and 1937. It is commonly forgotten that most of the occupants of the Hindenburg survived and that the hydrogen fire that consumed the badly designed R101 in the only other commercial airship accident was a result of the crash, not the cause of it. Even under the military extremities of World War I, most airship fires followed crashes attributable to the primitive navigation and weather forecasting techniques of the day. British fighter pilots found them surprisingly difficult to shoot down until special incendiary ammunition had been developed and many airships struggled home with their hydrogen gas cells riddled with bullet and shrapnel holes.

Zeppelin engineers were masters of their craft and had they continued to perfect it, passengers might feel safer beneath a cloud of hydrogen that burns upward with a nonradiating flame than surrounded by a sea of jet fuel that turns to instant napalm in an accident.

Apart from being the ultimate lifting gas, hydrogen has two other virtues that offset or capitalize on its combustibility. Hydrogen is cheap and can be produced in many ways from common materials. It is an an excellent engine fuel and the problems of using hydrogen as an alternate fuel in a gasoline engine have recently been solved (2).

Helium doesn't burn, but it is expensive and the supply is limited. These constraints have governed the design of airships that employ it, perhaps to their disadvantage. Commanders of helium airships could not casually valve gas to penetrate an inversion layer, and exceeding pressure height was a costly transgression of the rules.

Hot air aerostats have only recently been taken seriously by the professional community, but their virtues are twofold. Hot air doesn't burn, and it is cheap in the short run. It may be cheaper still if the solar balloon (3) concept can be applied.

AIRSHIP OPERATIONS IN ALASKA

The only instance of powered airship operation in Alaska known to the writer was the emergency landing of the Norge at Teller (4), terminating Amundsen's successful polar flight (parts of the dismantled Norge are on display in the University of Alaska museum). Proposed future operations must be weighed with consideration for the special problems and advantages presented by the Alaskan environment. Chief among the problems are high winds common to coastal areas, mountain ranges, inversion layers, and the remoteness of many potential operating sites. On the positive side may be listed the light winds found in the interior of the state, infrequent occurence of thunderstorms and low temperatures prevalent during much of the year.

Airships are sometimes promoted as ideal vehicles for transporting heavy loads to remote areas without prepared landing sites. Often overlooked is the fact that the airship must hover as a free balloon while lowering its cargo to the ground and that release of the cargo requires either valving gas or taking on an equivalent amount of ballast to maintain neutral buoyancy. Valving helium would be prohibitively costly, so the remote site must be prepared to supply ballast water or fuel of weight equal to the cargo offloaded.

Limited by engineering and economics to speeds of 100 knots or so, airships are much more sensitive to wind than are faster aircraft, and on round trips to an upwind destination, the higher speed on the return trip does not compensate for the reduced speed upwind.

Proposals to build aerostats shaped like airplanes in the hope of getting the best of both worlds should be viewed with suspicion. The best shape of a classical airship is the worst shape for an airplane wing and hybrids combine the worst of both worlds.

Unusual shapes are also proposed to reduce airship drag by active boundary layer control. At least one of these (5) shows promise for the hull of an extreme altitude blimp to serve as a communication relay at latitudes too high to be served by geosynchronous satellites, but the journey from wind tunnel to flight line is long and arduous.

AIRSHIP ECONOMICS

Fuel consumption is a matter of paramount concern for all forms of transportation at the present time. An elementary study of airship parameters in Appendix I yields an equation for the ratio of payload to fuel weight that may be used to evaluate proposed designs. Application to an airship constructed with modern materials gives

$$P/F = 674000\sqrt{A}\,/V^2L - \quad 4V/L - 1$$

A is the hull cross section area in square feet, V is the airspeed in miles per hour, and L is the length of the voyage in miles. On a voyage of 1000 miles at 100 miles per hour an airship with a hull diameter of 150 feet could carry 7.6 pounds of payload for each pound of fuel consumed. At a fuel cost of $1.00 per gallon, each pound of payload would consume 2.2¢ in fuel, or 4.4¢ per ton-mile. The equation also shows that the payload/fuel ratio increases as the airship size increases, and decreases rapidly with increase in speed. Efficient airships must, therefore, be large vehicles with low cruising speeds.

Other aspects of airship economics are not so easily evaluated. Vehicles of classical design will require at least one heated hangar for maintenance and repair in the Alaskan winter climate and for shelter from severe storms. Very large nuclear powered aircraft might conceivably remain aloft continuously, moving to avoid storms and migrating to warmer climates for periodic maintenance, but development costs of such innovative craft are certain to be high and costly mistakes will be made in the first attempts to advance the long-dormant technology of large airships. The writer's observation that the real cost of any innovative project ultimately proves to be three times the estimated cost is widely accepted as a fundamental of engineering.

Service life to be expected of a modern airship is difficult to estimate, but has in the past been surprisingly short, those not lost through mishap being removed from service after seven to ten years because of wear and fatigue beyond economical repair. Another significant cost is replacement of helium lost through diffusion or emergency valving.

It should be borne in mind that development of the great rigid airships was funded by the German military budget of World War I. At the end of the war, Zeppelin production facilities were largely intact, and an experienced labor force was eager to work for any wage in the depressed postwar economy. By contrast, surviving airship hangars are crumbling with age, the art of building rigid airships has been forgotten, and large airships are far too vulnerable to modern weapons to justify military support.

The ultimate economic criterion is, as always, the number of units that the market will support. A single large airship of innovative design for Alaskan service cannot succeed unless its cargo is gold from an otherwise inaccessible mother lode at $5,000 an ounce. At the other extreme, an order for 100 Mayflower class blimps slightly modified to serve the Alaska Department of Fish and Game would surely activate the production line at Goodyear at an attractive price.

CONCLUSIONS

A half century ago, large airships routinely transported heavy loads over long distances with minimal terminal facilities, and they could do so again today if an adequate market existed for the product. Fifty years of technological progress, however, will not significantly improve their performance. Zeppelins were the product of superb engineering, and the best that can be hoped for is improved reliability and economy.

There are in Alaska transportation problems for which a specially designed rigid airship might be the best solution, but the revenue generated could not, under present circumstances, justify the cost of producing airships for this service.

Many have attempted to design modern airships of monumental size or exotic configuration (7). Most have run the numbers and sadly consigned their dream ship to the circular file, but a few persist and submit proposals. Perhaps the test of Appendix I will serve as a quick check on performance claims.

One ray of hope penetrates the clouded future of airships. In Alaska we burn much fuel and wreck many Super Cubs counting caribou, hunting wolves, and watching pipelines. These functions might well be performed by a small nonrigid airship, whose technology is alive and well and hungry.

APPENDIX I

AIRSHIP PAYLOAD AND FUEL CONSUMPTION

Airship range and fuel consumption:

Aerodynamic drag is given by the equation

$$D = \tfrac{1}{2}\rho V^2 C_d A \qquad [1]$$

D = drag (lb.)
V = velocity, (ft/sec)
C_d = drag coefficient
A = area (ft^2)
ρ = air density ($slug/ft^3$)

Noting that thrust horsepower is obtained from the product of drag and velocity divided by 550,

$$HP = \rho V^3 C_d A/1100 \qquad [2]$$

which may be solved for the drag coefficient to yield

$$C_d = HP \times 1100/(\rho V^3 A) \qquad [3]$$

Fuel consumed during a voyage of length L is obtained by multiplying the engine fuel rate f by the horsepower and duration of the voyage.

$$F = f[\rho V^3 C_d A/1100][1.47L/V]$$

which may be simplified to:

$$F = V^2 A[\rho f C_d/748] \qquad [4]$$

F = fuel consumed (lb.)
L = voyage length (miles)
f = fuel rate (lb/HP-hr)

Considering the major weight components to be the lifting gas G, structural weight S, fuel weight F, engine weight E, and payload P, the gross buoyant force B is

$$B = G + S + F + E + P \qquad [5]$$

If gas cells are fully inflated at cruising altitude gross buoyancy will be the product of displacement volume and air density

$$B = \rho g A^{3/2} q \qquad [6]$$

g = acceleration of gravity (ft/sec^2)

$q = \frac{\text{Volume}}{A^{3/2}}$ (shape factor)

Weight of the lifting gas G is given by

$$G = \rho g A^{\frac{3}{2}} q \left(\frac{\rho_g}{\rho}\right)$$

or

$$G = Br \qquad [7]$$

ρ_g = lift gas density (slug/ft^3)

r = ratio of lifting gas density to air density, $\frac{\rho g}{\rho}$

Structural weight S may be expressed as a fraction of gross buoyancy s.

$$S = Bs \qquad [8]$$

Engine weight is the product of the weight per cruise horsepower e and the power required from equation [2].

$$E = e\rho V^3 C_d A/1100 \qquad [9]$$

Inserting expressions [6] - [9] into [5] and solving for the payload gives

$$P = \rho A^{\frac{3}{2}} gq(1-r-s) - \rho C_d V^2 A(1.47fL + Ve)/1100 \qquad [10]$$

and the ratio of payload to fuel weight is

$$P/F = 748gq\sqrt{A}\,(1-r-s)/V^2 LfC_d - Ve/(1.47fL) - 1 \qquad [11]$$

Shape factor q is constant for airship hulls of similar configuration but varying size. Gas density ratio r is a function of the lifting gas selected, and remains constant as long as the lifting gas and outside air have common temperatures and pressures. Structural weight ratio s depends on the method of construction and safety factor employed, and is only approximately independent of size. The ratio is large for small craft where manufacturing constraints govern minimum practical thicknesses of much of the structure, and increases again for very large airships. A common misconception relates structural weight to surface area, implying a structural weight ratio that decreases with size. Lift and payload increase as the cube of size and bending moments vary as the fourth power of size. Thus, purely geometric scaling (s = constant) would increase section modulii to the third power, leaving a structurally deficient vehicle.

Fuel rates f depend on the choice of engines. For reciprocating engines, typical values are .5 lb/HP-rh, and aviation gas turbines have a fuel rate in the order of 1.0 lb/HP-hr. Engine weight ratios e may be based on the 1 lb/HP achieved by large reciprocating engines, but the power on which this is based is maximum takeoff power. An e ratio based on cruise power would typically be 1.5 or 2.0 for reciprocating engines, and roughly .5 for gas turbines. Drag coefficients C_d are determined by the hull shape, cleanness, and the flight Reynolds number. Representative values may be obtained by applying equation (3) to performance data of past designs.

Data for the U.S.S. Macon, one of the last rigid airships constructed, are as follows (6)

Displacement volume	6,850,000 ft^3
Installed power	4,480 HP
Hull diameter	133 ft
Maximum speed	87.2 mph
Disposable load	173,000 lb

At sea level in standard atmosphere, gross buoyancy is 524,515 lb. Estimating weight of the rather heavy engines of the airship era as 3 lb/HP, total engine weight was approximately 13,440 lb. Subtracting engine weight and disposable load from gross buoyancy leaves a structural weight ratio $s = .64$. Although all the great airships were understrength, technological progress in the half century since they were designed could probably reduce this ratio to 0.5 or so in a modern version.

Drag coefficients may be based on any typical area as long as one is consistent, and the hull cross section is convenient*. Applying equation (3) with appropriate units gives $C_d = .071$. Fifty years of aerodynamic research (5) justify use of $C_d = .05$ for a modern airship.

Applying equation (6), the shape factor q for the U.S.S. Macon was 4.2.

Gas ratio r for helium is .14, and for hydrogen, .07. Engines constitute a surprisingly small fraction of the total weight of an airship, and reciprocating engines would be chosen over turbines to obtain a fuel rate $f = .5$ lb/HP-hr, accepting the weight penalty of $e = 2$ lb/HP.

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* Others (5) prefer a volumetric drag coefficient based on the 2/3 power of hull volume. Caution is indicated when comparing published drag coefficients.

Inserting these estimates into equation (11), gives a payload/fuel ratio for a modern helium airship

$$\frac{P}{F} = 1457000 \frac{\sqrt{A}}{V^2 L} - 2.72 \frac{V}{L} - 1 \qquad (12)$$

On a voyage of 1000 miles at 100 mph a modern airship of the Macon class with a diameter of 150 feet would have a payload/fuel ratio of 7.6 and a fuel cost of $1.00 per gallon translates to 2.2¢ per pound of payload, or 4.4 cents per ton-mile.

A similar flight of 100 miles would incur a fuel cost of 20¢ per pound or 4 cents per ton-mile.

At a range of 8,560 miles, the payload/fuel ratio approaches zero, signalling the maximum range of the unloaded airship at 100 miles per hour.

EPILOGUE

A document received after the bulk of this paper had been written (8) summarizes modern airship feasibility studies conducted by Boeing and Goodyear under a NASA contract. Central to their efforts were parametric studies similar to those of Appendix I, with a more detailed breakdown of weight components and slightly more optimistic engine and structural weight ratios. Both groups chose gas turbine power units, accepting their higher fuel rates in the interest of reduced gross weight. Recent trends in fuel cost and availablility argue against this choice.

Analyses of hybrid vehicles disclosed that optimum efficiencies for various missions tended toward the extreme ratios of buoyant/dynamic lift, i.e., build an airship or an airplane, but not a hybrid.

In an interesting comparison of airship and airplane construction costs it was found that during their years of coexistence costs per pound of airframe were nearly the same, and followed the same trend with time. It is inferred that, had rigid airship construction not been halted in the 1930's, the cost per pound of airframe would roughly equal that of modern jet transports after the initially high development expenses had been written off.

Both studies concluded that there are indeed missions for which a large airship might be the ideal vehicle, but doubt remains whether there are enough of them to justify the expense of re-inventing the airship at today's prices.

REFERENCES

1. Hook, T., Shenandoah Saga, 1973

2. Billings, R.E., Baker, N., Lynch, F., and MacKay, D., "Ignition Parameters of the Hydrogen Engine," Proceedings of the 9th Intersociety Energy Conversion Engineering Conference, 1974, pp 487-492.

3. Stefan, K., "Performance Theory for Hot Air Balloons," AIAA Journal of Aircraft, Vol. 16, No. 2, August 1979, pp 539-542.

4. Clarke, Basil. Polar Flight, 1964

5. Goldschmied, F.R., "Aerodynamic Hull Design for HASPA LTA Optimization," Journal of Aircraft, Vol. 15, No. 9, September 1978, pp 634-638.

6. Robinson, D. H., Giants in the Sky, 1973

7. McPhee, J., The Deltoid Pumpkin Seed, 1973

8. Ardema, M. D. , "Feasibility of Modern Airships: Preliminary Assessment," Journal of Aircraft, Vol. 14, No. 11, November 1977, pp. 1140-1148.