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AN INVESTIGATION OF THE APPLICABILITY OF HIGH ALTITUDE, LIGHTER-THAN-AIR (LTA) VEHICLES TO THE TACTICAL COMMUNICATIONS RELAY PROBLEM

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13. ABSTRACT

The various types of large balloon systems in use today, or under development, are examined with regard to potential use in the SEEK STAR multi-mode transmission system, being developed by the 478T System Program Office of the Electronics Systems Division, AFSC. Tethered balloons are shown to satisfy many communications applications, but to lack the altitude capability needed by SEEK STAR. The powered free balloon is seen to offer the best potential. the AFCRL powered balloon system, POBAL, is described and test results are presented. Its successor system, POBAL-S, is also described and evaluated. The demise of the POBAL-S development at AFCRL and the reappearance of the concept under the Navy's HASPA program is discussed and the applicability of HASPA to the SEEK STAR mission is evaluated. It is shown that, although the HASPA can theoretically satisfy or exceed all SEEK STAR needs, a delay of about three years must be endured before definitive results are available. Free-flying (that is, unpowered) balloon systems, both zero-pressure and superpressure, are evaluated and the advantages of the ground-launched and air-launched systems are pointed out. A status report on the Air-Launched Balloon System (ALBS) development is given. A recommendation is made to maintain surveillance over the HASPA program, to continue the ALBS program currently in being, and to exploit the advantages of ground-launched zero-pressure balloons.

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Preface

It is never easy to assess the status of an on-going development program where changes are the order of the day. This report has attempted to stop the action for a brief instant and to portray the Lighter-than-Air (LTA) communications relay platform scene as of July 1974. Further developments are in the offing and will change the picture presented here. Nevertheless, it is hoped that the data contained in this report will be informative, especially to planners of combat theater communications systems.

The author is indebted to his colleagues in the Aerospace Instrumentation Laboratory of AFCRL for their technical assistance in the writing and review of this report. Special thanks are due to Messrs. Arthur Korn, James Dwyer, Lewis Grass, James Payne, George Nolan, and Francis Doherty. Appreciation is expressed also to Miss Ann Leone and AlC Patrick Keeley for their help in preparing the various drafts leading up to this printed version.

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1. INTRODUCTION

In a previous report under In-House Work Unit 66651101, Air-Launched Balloon Techniques, there was a comprehensive discussion of methods for inflating large, free-flying balloon systems in mid-air subsequent to their deployment from a cargo aircraft or from a high-altitude rocket.[1] In that report it was concluded that systems employing such methods are capable of being developed and that they have the potential of satisfying a number of important military needs. The report emphasized the technical aspects of the deployment and inflation processes, however, with only passing reference to military operations.

This report is a sequel to AFCRL-TR-73-0633. It is more user-oriented and has been written to assist personnel responsible for upgrading tactical communication systems to understand the characteristics, applicability, and operational limitations of Lighter-than-Air (LTA) vehicles, that is, balloons, as platforms for airborne relay units. Particular emphasis will be given to high-altitude platforms, flown at heights of 50,000 ft (15.24 km) or greater. The LTA vehicles to be considered will include both free-flying balloon systems (surface- and air-launched)

(Received for publication 16 August 1974)

1. Carten, Andrew S., Jr. (1973) An Investigation of Techniques for Launching Large Balloon Systems From Aircraft or Rockets in Flight, AFCRL-TR-73-0633.

and powered balloon (POBAL) systems. The scope of this report will, therefore, exceed that of the previous report and will include information generated under In-House Work Unit 66651001, Powered Balloons.

As will be seen shortly, the LTA relay platform concept has special relevance to the communication demands of modern tactical warfare. Those demands have forced the development of high-capacity, multi-mode transmission systems to replace the inadequate ground-netted systems currently in use. The SEEK STAR system, which is being developed by the 478T Combat Theater Communications Program Office of the Electronic Systems Division, USAF, is a multi-mode system of this type and will serve as the basic reference system in this report.

These new communications systems rely heavily on airborne relay units to achieve instantaneous point-to-point message or data transmittal. The "primary" airborne relays employed in these applications are carried aloft on spacecraft placed in synchronous earth orbit, such as those used in the Defense Satellite Communications System. "Secondary" or "backup" airborne relays are carried aboard aircraft, which, in this case, serve as gap-filler satellites. With respect to the latter category, the trend in recent years has been toward unmanned airborne relay aircraft for reasons of cost effectiveness, reduced crew vulnerability, increased station-keeping time, etc. The HALE RPV (High-Altitude, Long Endurance, Remotely Piloted Vehicle) development has been undertaken by the Aeronautical Systems Division to satisfy that trend. Aircraft built under the HALE program are expected to fly at altitudes as high as 50,000 ft (15.24 km) for up to 24 hours.

Although the RPV's are considered backup relay platforms, their inherent flexibility gives them advantages in their own right. Unlike conventional satellites, which require months of preparation and planning prior to being placed on station, RPV's generally can be on location within minutes or hours of the decision to launch. There are other advantages also: lower costs, less sophistication in design since the equipment does not have to be space-qualified, reduced vulnerability to jamming, and the ability to implement relay equipment changes quickly if battle requirements so dictate.

Two different classes of RPV have been evaluated for the HALE RPV role. One, the XQM-93A model, manufactured by E-Systems, Incorporated, has been identified by the 478T Program Office as the aircraft to be used in the TRI-TAC Service Test Bed at Fort Huachuca, Arizona in 1977, when a system operational test and evaluation program will be carried out. The other class of RPV consists of the YQM-94A and YQM-98A models developed by Boeing and Teledyne Ryan under the Compass Cope program.

The XQM-93A is quite a bit smaller than the Compass Cope aircraft: 4600-lb (2087 kg) launch wt, 29-ft (8.84 m) length, 57-ft (17.37 m) span vs 14,400 lb (6532 kg), 41 ft (12.5 m) and 90 ft (27.43 m) respectively. Its design service ceiling is also less: 45,000 - 52,000 ft (13.72-15.85 km) vs 50 - 70,000 ft (15.24-21.34 km) for the Compass Cope aircraft. The XQM-93A does have the advantage of having flown at its design altitude, however, for the required 24 hours.

The "roadmap" for the 478T system development shows that LTA platforms, if available, will also be evaluated in the 1977 tests. This inclusion of balloon systems implies, correctly, that the RPV platforms are not without disadvantages.

Perhaps the major disadvantage to a high-altitude RPV (Compass Cope) is its limited TRI-TAC (or tri-service tactical) utility because of its long wing span (≈90 ft, 27.43 m). The physical problems associated with handling an aircraft of that size, plus the need for a 2000-ft (610 m) take-off run, create obvious difficulties for Navy personnel trying to launch from a ship at sea or for Army personnel operating in rough field locations. The smaller XQM-93A RPV, which appears to be an interim selection, is easier to handle, of course, but if the stated goals of the multi-mode system are realistic, that is, relay operations at an altitude of 60 - 80,000 ft (18.29-24.38 km), operational planning should be in terms of the larger aircraft.

NOTE: The long wing span results from the need to fly in high altitude regions of sharply reduced dynamic pressure, q. Since $q = 1/2 \rho V^2$, it is seen to be a function of atmospheric density, ρ, and, hence, of altitude. (It is also a function of the square of velocity, of course, but V is considered constant here.) Through the relationship $L = C_L q S$, which is the formula for aerodynamic lift, q is seen also to be a determinant of such lift. If the other factors (V and the coefficient of lift, C_L) stay unchanged, the wing surface area, S, must increase, as ρ (and q) decrease, to maintain the same lift. We shall have more to say about dynamic pressure later.

Another major disadvantage of the HALE RPV is its fairly short flight endurance time, approximately 24 hours. This characteristic demands daily launching and recovery operations to insure continuous availability of a relay on station. In a battle situation, or under prolonged bad weather conditions, such a frequency might prove to be operationally impossible. Even in the best of circumstances, the daily operation would be less desirable and less cost effective than one carried out less frequently. Other constraints associated with the HALE RPV include its payload weight, ≈750 lb (340.2 kg) and payload volume, 44 ft^3 (1.25 m^3). Although those figures appear to be quite reasonable for the intended mission, they leave very little room for growth or for outsized payload configurations. Also, the service ceiling of the XQM-93A RPV, 52,000 ft (15.85 km) is comparatively low (by balloon standards) and, thus, inhibits line-of-sight transmission possibilities during the planned tests in 1977.

LTA or balloon platforms have been included in the 478T system roadmap principally for backup purposes. There is a strong possibility, however, that balloon relay platforms could actually increase the capabilities of the system. That is, by virtue of higher altitude capabilities, longer duration potential, and fewer constraints with respect to payload configuration, the balloon platform might actually be preferred in cases where either platform could be used. In the course of this report we shall examine this possibility.

The following objectives have been established under the SEEK STAR Program for LTA platform capabilities:

(1) Altitude: 60,000 - 80,000 ft (18.29-24.38 km).

(2) Remote control from ground (Powered Balloon, POBAL).

(3) Duration on station: Up to 30 days (POBAL), up to 48 hrs (Free).

(4) Launch: Rough fields, shipboard (POBAL); rough fields, shipboard, aircraft (Free).

(5) Payload wt: 50 lb (22.68 kg).

(6) Payload power: 50 W (Joules/second) continuously.

(7) Suitable for routine operational use, with high confidence of success.

(8) Prime payload attrition rates comparable to the HALE RPV rate ($\approx$1%).

In evaluating various LTA systems, the above-listed objectives will serve as essential criteria, even though they are not mentioned continuously.

Much of this report will be historical in nature with occasional discussions (sometimes detailed) of theory. This approach is believed necessary to develop a rationale with respect to the suitability and applicability of today's concepts and plans, particularly in the powered balloon area. It should be made clear that this is not a case of matching a fully developed capability against a military requirement. Station-keeping LTA platforms are still in the developmental stage. Thus, any judgment with respect to potential applicability of these platforms has to be formed both on a knowledge of accomplishments to date and on the technology base which has emerged from numerous experiments and test programs. The seemingly unrelated work of many investigators also must be examined and correlated to arrive at a composite, but plausible, picture of the present state of the art. The reader is forewarned that there will be some excursions from the main theme, but they will be limited to those believed relevant and essential.

As a final introductory note, the author would like to mention that there are several related investigations in process, the results of which are not yet available. Since new data that could alter portions of this report are likely over the next year, it should be considered interim in nature. (The Proceedings of the 8th AFCRL Scientific Balloon Symposium, to be held September-October 1974, will contain a number of relevant papers.)

2. BALLOON SYSTEMS: AN OVERVIEW

Because this report is intended for persons who may not be too familiar with balloon systems, it seems appropriate now to review the general classes of LTA vehicles, eliminating at the start those which do not appear suitable for the high-altitude, multi-mode communications application.

2.1 Tethered Balloon Systems

The first major class of balloon systems, namely tethered balloons, will be ruled out immediately, insofar as the SEEK STAR application is concerned, on the basis of altitude limitations. Nevertheless, a few comments are in order here to do justice to these workhorses of the balloon family, and to stress their great value to communications generally.

Tethered balloons come in many sizes, ranging from about 3000 ft^3 (84.96 m^3) to over 500,000 ft^3 (14,160 m^3). Figure 1 is a photograph of a 250,000 ft^3 (7080 m^3) tethered balloon developed by the Sheldahl Company for the TCOM program.[2] They are usually aerodynamically shaped (for example, class "C" shape) for reasons of lower drag and increased flight stability. (The aerodynamic shape also provides dynamic lift, over and above the buoyant or static lift caused by the displacement of air by the inflation gas.) Several major items of ground support equipment (winches, mooring mast, adjustable-height platforms, etc) are needed for successful launching and recovery of tethered balloons, but their costs are amortized over a large number of usages.

Many useful purposes are served by tethered balloons, especially in the communications field, as exemplified by the recent Family II Balloon System development for ARPA and the TCOM system developed by the Westinghouse Corporation.[2,3,4] The tethered balloon-borne radio relay system, operated by the State

2. Tethered balloon used for signal relay (1974) Aviation Week and Space Technology **100**(No. 17):52.

3. Klass, Philip J. (1973) Balloons provide stable platforms, Aviation Week and Space Technology **98**(No. 2):36.

4. Ibid. Balloon design advances spurred, **98**(No. 3):60.

Figure 1. Tethered Balloon—CV250 Class

of Israel, is another example. However, tethered balloons are employed at relatively low altitudes, usually below 20,000 ft (6.1 km). Although France recently flew a stratospheric tethered balloon at 55,000 ft (16.76 km) for 11 hrs,[5] such a flight is considered highly experimental at the present time and not yet ready for operational employment. Even so, this development bears watching and may, indeed, prove operationally useful to SEEK STAR at a later date.

Tethered balloons have the virtue of being recoverable and reusable—a feature seldom experienced in free (that is, untethered) balloons. (It should be noted that free balloon payloads are recoverable.) Tethered balloon payloads are easily serviced, and, typically, enjoy long periods of use. The basic concept of flying a balloon on a tether line derives both from the need for recoverability and the desire for maximum control over the balloon's flight path. With tethering, the operator can be assured that that path will constitute a small ellipse around a

5. Ibid. (1974) French launch balloons for atmospheric studies, 100(No. 1):37.

fixed point. Radio propagation distances and angles are virtually constant in such circumstances.

Because they are flown repeatedly, tethered balloons obtain maximum utilization of the helium gas used to provide lift, an important economic consideration. They are rugged—one stayed aloft during a hurricane[4]—and, with proper system design, can be highly mobile. That is, the balloon and its ground support equipment can be moved around from one operating location to another, with about the same amount of effort as is required for relocating a small carnival road show. The HUGO II tethered balloon system, 30,000 ft^3 (850 m^3), recently developed by AFCRL is an example of such mobility.[6] It is a self-contained trailer-mounted system, which, with two to three supporting trucks and personnel carriers, can readily move from location to location.

One very useful attribute of large tethered balloons is their ability to carry small gasoline-engine generators aloft to provide power for their electronic payloads. These power sources provide up to a week of continuous power, and thus, allow the balloon to stay on station all the while. Conductive tether cables and fuel transport systems, which may permit longer flight durations, are now being investigated.[4]

In short, tethered balloons deserve serious consideration in any communications relay system where flight operations above 20,000 - 30,000 ft (6.10-9.14 km) are not required. For the time being, however, they appear to be inapplicable to the SEEK STAR program.

2.2 Free Balloon Systems

The second major class of balloon systems encompasses all free balloons. The term "free balloon" refers to any balloon that is not tethered. Free balloon systems are subdivided into powered balloon systems and free-flying or unpowered balloon systems. (Other breakdowns can be made on the basis of shape, construction, method of inflation, method of launch, and so on, but will not be attempted here.) Having eliminated tethered balloons from further consideration in this report, we shall now discuss in detail the various classes of free balloon systems and their applicability to the high altitude communications relay problem.

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6. Corbin, C.D. (1974) Portable Tethered Balloon Wind Data System (HUGO II), AFCRL-TR-74-0034.

3. POWERED BALLOON SYSTEMS (POBAL)

3.1 General Considerations

Powered balloon systems are systems that rely on buoyant lift to stay aloft and on attached propulsion units for thrust for forward motion and directional control. Because they can be steered, or directed, these balloons are classified as dirigibles. (Dirigible is derived from the Latin verb dirigere: to direct.) Powered balloons (dirigibles) have been in use for many years. The best known examples were the rigid airships of the Zeppelin class, which date back to the year 1900, and the non-rigid blimps used in great numbers by the U.S. Navy in World War II. Although the rigid dirigible era effectively came to an end with the Hindenburg disaster in 1937, the use of blimps has continued to this day, albeit on a limited scale, such as the sightseeing and promotional activities of the Goodyear Corporation.[7] Zeppelins and blimps are both low-altitude (≈10,000 ft, 3.05 km) systems, in any event, and do not directly apply to the SEEK STAR situation. The word "directly" has some significance here in that the more relevant high-altitude powered balloon system, POBAL-S, which we will discuss in section 3.3, bears an outward resemblance to and relies on some of the technology of the earlier dirigibles. For example, the stern-mounted propulsion unit of the POBAL-S (see section 3.3.7.2) was tried out on a Goodyear Aircraft Corporation blimp during the Silent Joe II Program.[7]

NOTE: It has probably not escaped the reader's attention that there has been, lately, a surge of interest in large low-altitude dirigibles as evidenced by a number of recent articles.[8,9,10,11] This rekindled interest has been inspired in part by the energy crisis of the 1970's and represents an effort to develop powerful lifting devices or aerial transportation systems which are more conservative of energy than present-day aircraft and helicopters. Some of the proposals may be based more on nostalgia, however, than on lessons of the past.[12] Even before the

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7. Fisher, R.R. and Ross, R.S. (1970) Recent Airship Developments and Applications. Proc. 6th AFCRL Scientific Balloon Symposium, AFCRL-TR-70-0543.
8. Morse, Francis, et.al. (1972) Dirigibles: Aerospace opportunities for the '70's and '80's, Astronautics and Aeronautics 10(No. 11):32-40.
9. Hunt, J.R., et.al. (1973) The many uses of the dirigible, Astronautics and Aeronautics 11(No. 10):58-65.
10. Vaeth, J. Gordon (1974) The airship can meet the energy challenge, Astronautics and Aeronautics 12(No. 2):25-27.
11. Alexander, T. (1973) A new outbreak of Zeppelin fever, Fortune 87(No. 6):110.
12. Maiersperger, W.P. (1974) Zeppelins, not again!, Astronautics and Aeronautics 12(No. 2):28-30.

Hindenburg catastrophe, the safety record of the rigid dirigibles had been poor. Their inability to cope with turbulence was the major factor in this regard, and was inherent in the use of buoyant lift to control vertical motion. The ballasting and gas valving procedures were too slow to compensate for updrafts and downdrafts encountered in severe weather. This was complicated by the slow storm cell penetration speeds of the dirigible, plus its long cylindrical shape, and resultant destructive bending moments. In general, it was found that these dirigibles performed best in fair weather, non-scheduled operations. Thus, the reader is cautioned against non-critical acceptance of the claims of latter-day Zeppelin protagonists in considering large dirigibles for possible military applications.

3.2 Early High-Altitude Powered Balloon Systems

3.2.1 MINIMUM WIND FIELD STUDIES

Although rigid and non-rigid low-altitude dirigibles have been with us for many years, the concept of a high-altitude, 60,000 ft (18.29 km) or higher, dirigible or powered balloon (POBAL) is fairly recent. It resulted from studies and experiments at AFCRL to identify seasonal occurrences of minimum wind fields in the lower stratosphere.[13,14,15] Those studies were undertaken to examine the feasibility of controlling the trajectory of free-flying (unpowered) balloons by keeping them in wind fields where the speed was at or near zero, and thus, effectively causing these balloons to hover over a fixed location.

The flight of free balloons in minimum wind fields will be covered in depth subsequently. Before starting that discussion, brief mention will be made of the second objective of the minimum wind field studies: to locate regions of minimum dynamic pressure in the interest of carrying out stratospheric tethered balloon flights. In a note in the Introduction to this report, the dynamic pressure, q, was shown to be a function of the square of wind speed. (Also, q is a function of atmospheric density, but density will be assumed constant for the chosen flight level.) Minimum wind fields drastically lessen dynamic pressure values, therefore, and greatly reduce loading both on tethered balloons flown in those fields and on their tether cables. With reduced loading, lighter tethers are permissible, thus allowing higher float altitudes to be achieved. The French experiment (2.1) undoubtedly is aided by minimum wind fields.

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13. Nolan, G.F. (1964) High-Altitude Minimum Wind Fields and Balloon Applications, AFCRL 64-843.

14. Nolan, G.F. (1967) A Study of Mesoscale Features of Summertime Minimum Wind Fields in the Lower Stratosphere, AFCRL 67-0601.

15. Nolan, G.F. (1969) Meteorological Considerations for Tethered and Hovering Free Balloons, Symposium Proceedings, Earth Observations from Balloons, Am. Soc. for Photogrammetry.

The minimum wind field studies were inspired primarily by repeated inquiries from weapons system developers for a means of suspending a relay or surveillance sensor in the air, for an extended period, over an area of tactical or strategic interest. Balloons were seen as a natural candidate for this application because of their demonstrated capability to carry large payloads to very high altitudes. Since free-flying balloons are captives of the wind fields in which they are immersed, serious doubts arose regarding their ability to remain over the area of interest long enough to justify putting them on station.

The minimum wind field phenomenon offered a possible part-time solution to this dilemma. At certain times of the year and at certain latitudes a stratification of the atmosphere occurs in which a rising balloon will encounter successive layers where substantial differences in wind speed and direction will be found. In some of the layers, particularly in the lower stratosphere, 50 - 70,000 ft (15.24-21.34 km), the wind speed is at or near zero. This layering is caused by the annual reversal in direction of upper stratospheric winds from predominantly westerly to predominantly easterly. Figure 2 is a simplified diagram of the summertime wind pattern in the Northern Hemisphere. Note the layer of easterlies above the tropospheric westerlies, with a minimum wind field in between.

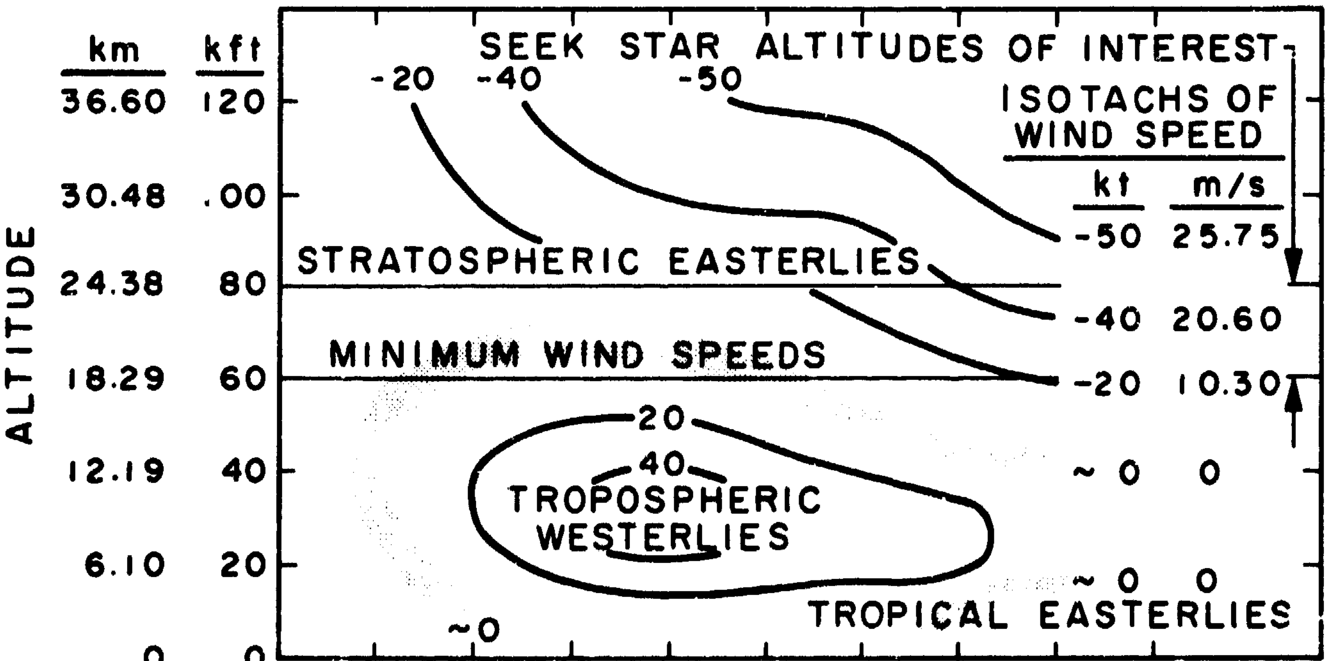

Figure 2. Summertime Minimum Wind Fields, Northern Hemisphere

Thus, if free-flying balloons can be commanded to ascend or descend (by ballasting or valving) and if the balloon controller has a good knowledge of the time and spatial variations of the wind at or near desired float levels, it should be possible, according to the minimum wind field theory, to keep the balloons in very light winds and, essentially, in a hovering condition for extended periods. This theory was verified in field tests at Chico, California during 1966-1968. In one flight, an unpowered balloon was kept within a radius of 100 miles (160.9 km) for a period of over 100 hours. It should be pointed out that this relatively long period of limited-range flight required the expenditure of 3000 lb (1361 kg) of ballast, a situation which may have cast additional doubt on the suitability of free-flying balloons to the station-keeping task, even when flown at the correct latitudes and times of the year. There has been only limited follow-up to the 1966-1968 experiments insofar as free-flying balloons are concerned. Most of the subsequent emphasis has been on the powered balloon (POBAL). Nevertheless, the concept of a free-flying balloon platform as a backup communications relay should not be dismissed out of hand. Later on in this report, particularly in the discussion of the Air Launched Balloon System (ALBS), we will see the true potential of free-flying platforms.

3.2.2 THE POBAL CONCEPT

Mr. Arthur Korn of AFCRL originated the POBAL concept when he proposed adding a propulsion unit to the free-flying balloon to make it independent of moderate departures from zero wind conditions. With such independence, the need for constant valving and ballasting would be eliminated and, thus, long-duration flights would be feasible without having to carry aloft inordinate amounts of ballast.

It was reasoned that an amount of forward thrust, equal to the drag force on the balloon, would negate the motion normally imparted to the balloon by the wind and would, thereby, permit station-keeping. If the thrust exceeded the drag force, the balloon could actually move against the wind; if the thrust turned out to be less than the drag force, it would at least reduce the travel of the balloon compared to the trajectory of an unpowered balloon in a similar situation.

Drag on a balloon in flight is determined by the formula $D = C_D q S$. C_D, or the coefficient of drag, has been determined for a number of balloon shapes, and is available from the literature. As already discussed, dynamic pressure, q, is a function of the square of the wind speed and of atmospheric density. S, the surface area is, by convention, taken as the airship hull volume to the 2/3 power. Thus, at a given density level, the only variable in determining the drag force for a particular size and shape of balloon is the wind speed. It remains then, simply, to specify the departures from zero, that is the maximum wind speed against which one might wish to design, in order to calculate the opposing thrust force to be provided by the on-board propulsion unit. Ideally, this thrust force will be variable to achieve a proper match between power required and power delivered.

Although it eliminated the requirement for large amounts of ballast, the POBAL concept introduced a new requirement: a sizeable energy source to power the propulsion unit. That requirement has been a pacing factor in the POBAL development and has been responsible for a major portion of the research and development effort expended to date on the program.

3.2.3 THE POBAL DEMONSTRATION MODEL

In 1966 and 1967, even while the free-flying balloon experiments in minimum wind fields were still in process, parametric design studies of the proposed high-altitude powered balloon system (POBAL) were undertaken. They began as an in-house effort but were augmented by the contractual assistance of the Goodyear Aerospace Corporation. The studies[16] indicated that high-altitude powered balloons could be developed with flight capabilities of up to 96 hours, depending on the power source chosen. They also recommended the construction of a demonstration model POBAL system. A follow-up contract to Goodyear led to the fabrication of such a model.

The parametric design studies had shown that an aerodynamically shaped balloon was preferable from the standpoint of reducing drag and, concomitantly, the system's power requirements. Such streamlined balloons introduced serious launching and recovery problems, however. This fact, plus monetary constraints, led to the selection of a natural shape (round) balloon for the initial demonstration model of the POBAL concept. The decision in favor of the higher drag shape meant, therefore, that a fairly powerful propulsion unit would be necessary.

Reciprocating engines, turbines, and electric motors had been evaluated during the studies as possible power sources. An electric motor operating from a battery power supply and recharged by solar cells emerged as the most promising candidate. (Microwave power transmission to the balloon from a ground station was also studied and found impractical.) Thrust was to be provided by a large diameter propeller driven by the electric motor since propellers of this type, when driven at low speeds (low disk loading), minimize the amount of power needed for a given level of thrust.[17] Monetary constraints imposed a limitation in this area also, and it was decided to employ only batteries as the power source. Solar cells were left for a later time.

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16. Vorachek, J.J. (1968) Investigation of Powered Lighter-than-Air Vehicles, AFCRL-68-0626.

17. Vorachek, J.J. (1970) A Comparison of Several Very High-Altitude Station-Keeping Balloon Concepts, Proc. 6th AFCRL Scientific Balloon Symposium, AFCRL 70-0543.

The demonstration POBAL system was designed to fly at 60,000 ft (18.29 km) with a useful payload of 200 lb (90.72 kg) for a period of 24 hours, 12 of which would be hours of powered flight. Thrust levels had to be sufficient to overcome the drag of 15-kt (7.7 m/s) winds, that is, the system would have a 15-kt airspeed. From the combined weights of the payload, the ballast (10% of system gross weight), the engine, batteries, propeller, gondola, parachute, etc, it was determined that the size of the balloon would have to be 711,000 ft^3 (20,135 m^3). The drag on a natural shape balloon of this size at 60,000 ft (18.29 km) and in a 15-kt (7.7 m/s) wind was calculated at 108 lb (480 N). This led to the selection of a two-bladed helicopter rotor with a diameter of 35.4 ft (10.79 m) which, at a speed of 196 rpm (3.27 rps) was calculated to deliver the required thrust.

NOTE: Propulsion power needs were initially computed on the basis that the coefficient of drag, C_D, for the round balloon was 0.19 (vs 0.07 for the streamlined, class C balloon). It is now believed[18] that the true value of C_D for the round balloon may be as high as 0.39, based on POBAL flight results.

The motor, batteries, payload and other components were mounted on a rectangular frame (gondola) as shown in Figure 3. A rudder was placed in the propeller's slipstream to control the azimuth heading of the gondola and, therefore, the direction in which the thrust was applied to the balloon being towed. Rudder settings were governed by an autopilot (with a radio command override) which, in conjunction with the rudder servo system, was designed to maintain the thrust axis within 3° of the desired heading. Several sensors were provided on the demonstration model to monitor system functions (motor rpm, rudder position, motor current, etc).

Although the amount of ballast carried on the demonstration unit, 600 lb (272.2 kg), was considerably less than that carried on the free-floating balloons, it was sufficient to allow the flight controller to seek ideal flight levels by the customary ballast/valve technique. The total weight of the gondola, with batteries and ballast aboard, turned out to be 3854 lb (1748 kg). Almost 400 silver-zinc rechargeable batteries were used: 368 Electric Storage Battery type 2-1000 for propulsion and 30 Yardney BB405 cells for other requirements. Not surprisingly, battery temperature control was one of the more critical features of the experiment.

The coupling between the balloon being towed and the powered gondola in the demonstration unit was very flexible. The gondola was suspended at a distance of about 300 ft (91.44 m) below the bottom of the balloon. The connecting link, a deployed in-line 100-ft (30.48 m) diameter parachute, plus a 200-ft (60.96 m)

18. Korn, Arthur O. (July 1974) Personal communication.

Figure 3. Demonstration Prototype, POBAL Propulsion System

extension load line, offered minimum resistance to twisting. Figure 4 shows the flight train used. For a more complete description of the demonstration design, see the final report on the Goodyear contract.[19]

NOTE: The 200-ft extension line was used to simulate the presence of much longer balloon gore lengths than were actually used. This was initially considered necessary to compensate for a possible system design problem. A balloon with the relatively short gore lengths of the POBAL balloon had never previously been launched carrying such a heavy gross load. Catastrophic failure upon release from the launch arm appeared possible without effectively lengthening the gores. However, two successful launches showed that the extension line was not really needed.

The demonstration model described above was actually flown in 1972. That test will be described in the next section. Prior to the 1972 flight test, 1/6 scale model tests of the propulsion system were conducted at AFCRL and full-scale

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19. Vorachek, J.J., McGraw, E.W., and Bezbatchenko, J.W. (1973) Development of a Free Balloon System, Final Report, Contract F19628-72-C-0072, AFCRL-TR-73-0128.

airdock tests were performed at the Goodyear plant. The airdock tests led to an increase in the size of the rudder to enhance its control characteristics. These tests were followed by another preliminary test, at Holloman AFB, in which an unpowered full-scale mockup was launched and flown to verify launch procedures and establish the suitability of the selected polyethylene balloon.

3.2.4 FIRST FLIGHT TEST OF THE POBAL DEMONSTRATION UNIT

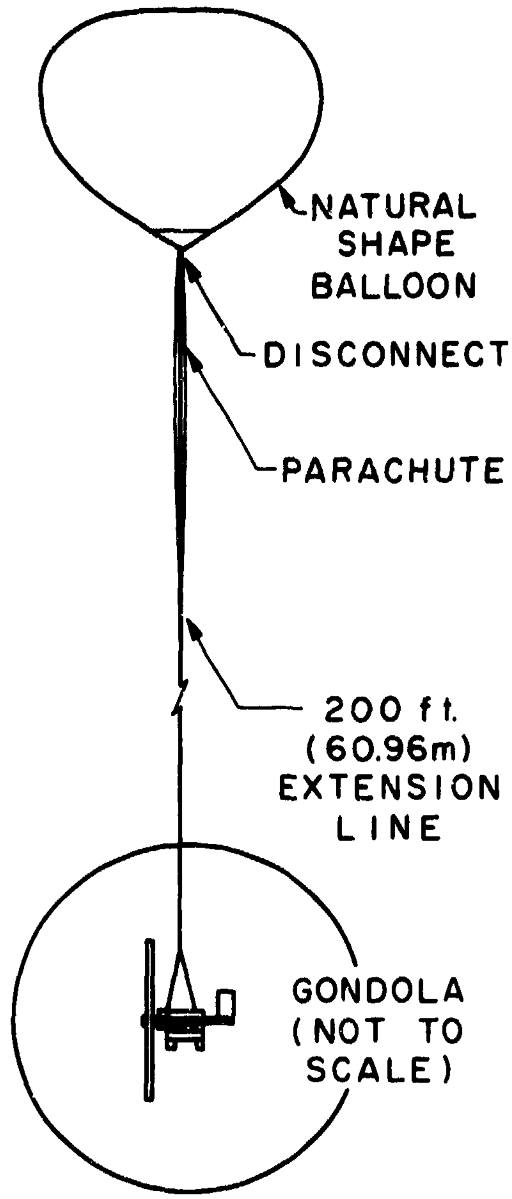

Figure 4. General Arrangement of Natural Shape Powered Balloon

On September 16, 1972, the demonstration model POBAL was successfully launched from Holloman AFB and ascended to the 60,000-ft (18.29 km) float level. Minimum wind field conditions were in effect at the time. The goals of the flight were to determine if the autopilot could successfully steer the system in a fixed course, the propulsion system could move the balloon at an airspeed of 15 kts (7.7 m/s), and the rudder-motor combination would effect turns in the balloon's trajectory. Unfortunately, the experiment had to be terminated after only three hours of powered flight, because the rudder separated from the gondola and fell to earth. Despite the brevity of the flight, it was possible to analyze the system's performance under power and to reach a number of conclusions.[20]

(1) Airspeed. Airspeed, that is, the speed of the POBAL system relative to the local wind, was considered to be the most important criterion in grading

20. Korn, Arthur O., LeClaire, R.C., and Rice, C.B. (1973) LDF Powered Balloon Program, AFCRL-TR-73-0424.

system performance during this first test. Unfortunately it turned out to be a difficult item to quantify. Because no reliable direct airspeed measurements were obtained from the on-board anemometer, the experimenters had to resort to vector subtraction to obtain computed airspeeds. The principal inputs to these computations—the system ground speed and direction, and the local wind speed and direction—were obtained from the balloon trajectory analysis, as established by radar "skin tracking." (Weight constraints precluded the use of the more accurate radar beacon.) To obtain values of the local winds, tracking was carried out when the balloon was unpowered; the wind values thus obtained were extrapolated to the time of powered flight. This practice, plus the assumption that the airspeed direction was the same as the gondola heading, introduced some uncertainties. (Gondola twisting was a problem, as will be noted.) Nevertheless, three independent analyses of the data yielded airspeeds in the range of 5 - 14 kts (2.58-7.21 m/s). The fact that the desired airspeed, 15 kts (7.7 m/s) was approached but not achieved indicated either the system was somewhat underpowered or the propulsion components had not performed to specifications. Since the on-board monitoring system showed that motor current and propeller rpm values had stayed within the expected operational ranges throughout the flight, sub-par component performance was ruled out.

(2) Thrust. Working from velocity, acceleration, and drag force data, maximum thrust attained during the test flight was calculated at 70 - 85 lb (311-378 N) as compared to the system design value of 108 lb[20] (480 N). The experimenters reasoned that the propeller must have been absorbing full design power from the motor, based on the steadiness of motor current and propeller rpm data. They concluded, therefore, that either full thrust was being achieved and simultaneously degraded by greater-than-anticipated drag forces (for example, the drag on the box-shaped gondola: unexpectedly high coefficient of drag for the balloon—see Note, section 3.2.3) or the effective propeller blade angle was incorrect for the conditions. A third possibility for the degraded thrust was the tendency of the gondola to rotate at the end of the long suspension line, thus reducing thrust in the direction of the balloon airspeed.

(3) Gondola Rotation. Referring back to Figure 4, it is obvious that the gondola is towing the balloon through a long flexible line. There is no torsional rigidity to the attachment to permit instantaneous translation of torque at the gondola into a steering effect on the balloon. In fact, the initial effect of rudder deflection was a rotating of the gondola about the suspension line.

Winding and unwinding of the gondola on the long load line had been observed during the ascent to float altitude—a phenomenon typical of large balloon ascents. Some of this rotation apparently carried over into the first powered run, but was dampened out when the power was removed. This was not the end of yaw instability however. Not only was it observed as a transient gyroscopic reaction every time the motor was started or stopped, it was found to be present in all powered flight when wind speeds were 6 kts (3.1 m/s) or less. One of the reasons advanced for this instability[20] is that the propeller thrust axis and the point of application of the POBAL drag force on the gondola are not colinear, thus creating a couple favoring clockwise yaw. Interaction between the propeller slip stream and the gondola contours was also suspected.

(4) Steering. Analysis of the autopilot-rudder system performance showed that the autopilot performed as expected but the rudder effectiveness was poor. At less than full rudder deflection, the rudder torque was found to be too low for dependable steering. By holding full rudder deflection for longer than 2 min, the system could be steered in a curved trajectory.

(5) Changes Needed. Three conclusions were reached: A larger rudder must be provided for succeeding test flights so that a given gondola heading can be maintained for longer periods; increased propeller pitch should be employed, in the interest of improving thrust effectiveness; radar beacons should be used for better tracking accuracy. Elimination of the 200-ft (60.96 m) gore-extending load line (see Note, section 3.2.3) was deemed necessary, along with streamlining the propeller hub and possibly the gondola. Lastly, the addition of improved on-board sensors (airspeed, suspension-line torsion) was recommended.

3.2.5 SECOND POBAL TEST FLIGHT

On 6 June 1973 the POBAL demonstration unit was flown again from Holloman AFB. It had been modified to incorporate the recommendations made after the initial flight. Misfortune struck this second flight, also, and it had to be terminated prematurely because a rudder malfunction, later identified as a poor socket-to-pin connection in the rudder servo loop, prevented proper steering control. To complicate matters, analysis of the powered flight runs was made virtually impossible through an administrative mixup which resulted in the loss of digital radar tracking data. Since very little in the way of useful information came out of this second test, a third try was scheduled for November 1973. That test was subsequently rescheduled to October 1974 to allow extensive rework of the rudder drive system and some of the electronic components.

3.3 The POBAL-S System

3.3.1 NEED FOR A MORE SOPHISTICATED DESIGN

The POBAL system which has been described thus far is a demonstration model intended to prove the general concept of high-altitude powered flight. The system has not proven to be an operationally useful configuration, despite its utility as a test bed for verifying certain system and component performance characteristics. This situation was anticipated before the first test of the demonstrator in September 1972. Even as preparations were being made for that initial test, negotiations were underway to let a study contract for the design of a more operationally suitable POBAL, one capable not only of remaining on station in higher winds and for many more days than was possible with the demonstration unit, but also of providing 500 W of power continuously to the payload. There will be no further consideration of the original POBAL demonstration unit in this report, therefore.

3.3.2 A STREAMLINED BALLOON CONFIGURATION

The goal of the new contract, on which Raven Industries began work November 1972 (contract F19628-73-C-0076), was to design a streamlined powered balloon system capable of keeping a 200-lb (90.72 kg) payload on station for seven days in a 20 kt (10.3 m/s) wind at approximately 70,000 ft. An aerodynamically shaped balloon was specified to meet the wind speed requirement, on the basis of drag coefficient differences between the round and the streamlined balloon shapes. When the design airspeed was 15 kts (7.7 m/s), as was the case with the demonstration model, the differences in drag characteristics of the two shapes were not critical. However, the drag force due to a 20-kt wind is significantly greater than that of a 15-kt wind, since, as previously stated, drag force is a function of the square of the wind speed. Studies of comparative power requirements of round and streamlined powered balloons, in winds of that magnitude, showed that the higher coefficient of drag of the round balloon results in unacceptably high power requirements, especially for long duration missions. Hence the decision was made to employ the streamlined aerodynamic shape. This, of course, represents a major design departure, relative to the configuration of the original POBAL demonstration model. Later on, as the contract was in progress, the wind speed requirement was reduced to 15.9 kt (8.2 m/s), but the streamlined configuration chosen to meet the 20-kt figure was retained.

Figure 5 shows the POBAL-S outline configuration developed on the Raven contract. This configuration is discussed in detail in section 3.3.7. Unfortunately, the final report on the Raven contract was unavailable at the time of this report. For that reason, the R&D Design Evaluation Report, Part II, 6 July 1973, has been the main source used in chronicling the POBAL-S development.[21] Anticipated discrepancies between that document and the final report will be pointed out, however.

21. Raven Industries, Inc. (6 July 1973) POBAL-S R&D Design Evaluation Report, Part II, under contract F19628-73-C-0076 (Raven Report No. R-0673006).

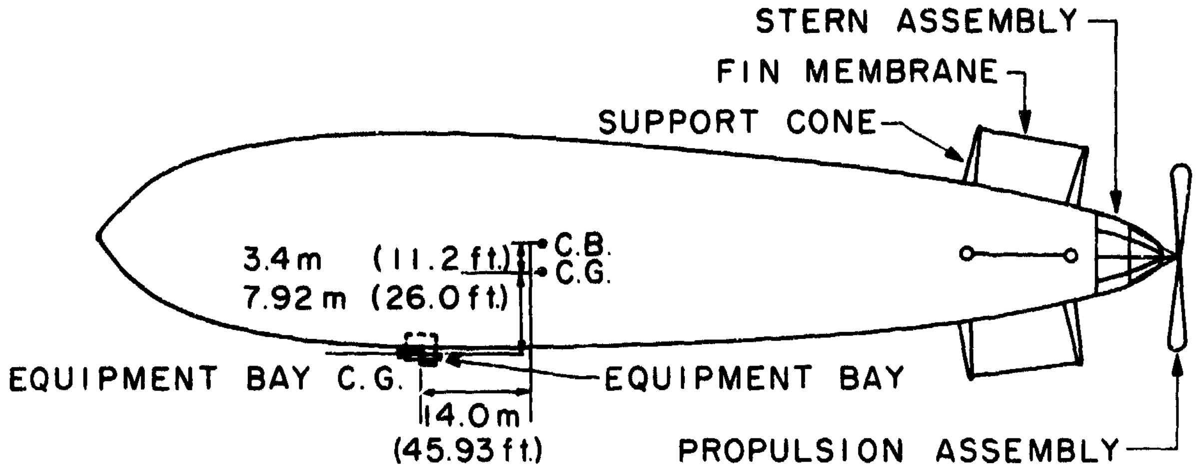

Figure 5. POBAL-S Airship

3.3.3 BALLOON PRESSURIZATION

A second major design departure was in the area of balloon internal pressure. The original demonstration unit employed a zero-pressure balloon as its vehicle. The new design specified a superpressure balloon. There is a big difference between the two pressurization systems, and the decision to adopt the superpressure mode has many ramifications. To appreciate them, it is necessary to take a closer look at the balloon internal pressure problem. This will require a digression from POBAL-S, so that we may examine superpressure theory.

NOTE: The balloon pressurization discussion to follow will bypass the powered aspects of flight and will reflect experience gained with free-flying balloons. A brief review of zero-pressure principles will be presented to lead into the superpressure discussion.

3.3.4 ZERO-PRESSURE BALLOONS

When a zero-pressure balloon is flown, it is initially inflated with enough gas to support its own weight plus the payload attached to it. (See section 3.3.5.1 and also AFCRL-TR-73-0633[1], Appendix A, for a discussion of the basic principles of aerostatic lift.) At this point, the balloon is neutrally buoyant, that is, it will support the load but will not rise. To cause the balloon to ascend, extra buoyancy must be added. Normally, enough additional gas is put into the balloon to give it from 6 to 12 percent "free lift." As the balloon approaches its design float altitude, the excess gas is automatically valved off and lost to the system. The balloon is then neutrally buoyant once again. Note that the valving off of the excess gas is not a matter of choice; it has to be done to protect the balloon from rupture. At float altitude the balloon has filled out to its maximum volume, the volume occupied by the amount of gas needed to achieve neutral buoyancy at float altitude. Any excess gas results in a hazardous build-up in balloon internal pressure, which the zero-pressure balloons are not designed to withstand.

> NOTE: Helium is the only inflation gas given serious consideration in this report. Hydrogen is less expensive and has a higher value of specific lift by a factor of 1.08. In theory, hydrogen is very attractive. In practice, it requires so many safety precautions that the choice of helium becomes automatic, providing, of course, that helium is available. Other possible inflatants (hot air, methane, etc) have such low values of specific lift as to be impractical, especially for a long duration, high-altitude, station-keeping mission.

Even after neutral buoyancy has been achieved, more gas will be valved off to prevent undesirable internal pressure rises due to solar heating of the gas. (A daytime flight is assumed here.) At night the loss of heat by radiational cooling to space will cause the residual gas volume to shrink and the balloon's displacement will be reduced correspondingly. As a result, the balloon will start to descend in an attempt to find a new level of neutral buoyancy. The amount of descent is normally limited by the dropping of ballast to lighten the system weight, thus allowing neutral equilibrium to be achieved fairly readily. If the balloon is flown through a second day, the cycle repeats itself. As the gas is warmed by the sun, the balloon volume expands once more and the balloon rises. At night it cools off again, and ballasting is required to keep the balloon airborne. The duration of the flight is controlled by the amount of ballast that can be carried, and, normally, it is not more than a few days, although zero-pressure balloon flights of up to 14 days have been accomplished when long durations were a flight objective. In systems of this type, the gross load carried aloft becomes a function not only of the basic payload being flown but also of the number of days to be flown, with the ballast portion of the load increasing incrementally with each day of flight. As a consequence, very long flights require very large balloons to support the augmented gross loads, thus increasing the cost of the LTA platform chosen to put a given payload on station. Actually, most AFCRL scientific balloon flights are flown for one day or less, but this fact is due to a lack of need for longer duration scientific flights rather than to an inability to achieve them.

3.3.5 THE SUPERPRESSURE BALLOON

3.3.5.1 General Considerations

The superpressure balloon was designed to eliminate the need for ballast an to permit substantially longer flights than are possible or practical with zero-pressure balloons.[22] It is a sealed, pressurized, nonextensible cell that floats at a level of constant air density. Its ability to maintain essentially constant altitude during periods when the lifting gas may be either gaining or losing heat from the environment is contingent upon its ability to retain a constant mass of lifting gas, at a varying pressure that is always higher than external, ambient pressure, without any significant change in volume.

NOTE: According to the Archimedean principle of buoyant lift, the weight of the air displaced by a balloon at floating altitude is

$$V_{\rho a} = G + V_{\rho g}$$

where V is the volume of air displaced and is equal to the volume of the lifting gas; ρa is air density; G is the gross load (payload plus balloon weight) and is considered constant; ρ_g is the density of the enclosed lifting gas. If the balloon is effectively sealed, as is the case with superpressure balloons, the quantity of lifting gas does not change, and, despite changes in gas temperature and internal pressure, the superpressure balloon remains at the altitude where air density is ρa, as long as the volume, V, remains constant. By comparison, a zero-pressure balloon system is incapable of maintaining constant density altitude because, in order to maintain zero pressure, the quantity of its lifting gas, $V_{\rho g}$, is necessarily sensitive to diurnal heat loads (see section 3.3.4). Moreover, the balloon's gross load decreases each time compensatory ballasting occurs. It is not surprising, therefore, that a zero-pressure balloon lacks the altitude stability inherent in superpressure balloons.

From the above discussion, it can be inferred that superpressure is merely a positive difference between balloon lifting gas pressure and ambient air pressure; it depends, as will be shown, on both the free lift originally imparted to the balloon and the temperature of the gas. In theory, flight duration of a superpressure balloon is limited only by permeation or leakage of the lifting gas through the balloon film which, in time, can allow the superpressure to disappear. (In practice there are other destructive factors which are usually more significant, as will be seen.)

3.3.5.2 Superpressure Due to Free Lift

During ascent, the superpressure balloon behaves in a manner similar to the zero-pressure balloon until it reaches float altitude. At that point the excess gas

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22. Grass, Lewis A. (1962) Superpressure Balloon for Constant-Level Flight, AFCRL-62-824. (In the treatment of superpressure balloons which follows, the author has drawn extensively upon this comprehensive report by Grass.)

supplied for free lift purposes is not valved off, as would be done in a zero-pressure flight. Because excess gas is retained within the balloon envelope, the internal gas pressure of the system, P_g, exceeds the pressure of the ambient air at float altitude, P_a, by a certain amount. This amount is referred to as the initial superpressure, ΔP_1, and is directly related to the free lift, F, of the balloon by the equation $F \approx \frac{\Delta P_1}{P_a}$, from which it is seen that $\Delta P_1 \approx FP_a$.

The total superpressure, ΔP, is a function of the initial superpressure, ΔP_1 (or FP_a), and the superheat, ΔT, where ΔT refers to the differential between the gas temperature, T_g, and the ambient air temperature, T_a, so that

$$\Delta P = FP_a + (1+F)\frac{P_a \Delta T}{T_a}.$$

3.3.5.3 Superheat

Superheat is a function of the heat absorption and emission characteristics of the balloon material from which heat is transmitted to the gas. Thus, the value of ΔT at any time in a particular flight depends upon the quantity and wavelength distribution of the incident radiation. In the daytime, the superheat rises to a maximum positive value because the balloon absorbs solar energy faster than does the air. At night, cooling of the lifting gas occurs as heat is radiated to space. This cooling is offset, to some extent, by absorption of terrestrial infra-red radiation, the amount of which varies with the balloon material, the nature of the underlying terrain and the thickness of cloud cover between earth and balloon. In obtaining a design figure for the total superpressure a balloon will experience, solar and terrestrial radiation expected at the time and location of flight are taken into account. Flight records indicate, for example, that for polyester balloons at 70,000-ft (21.34 km) altitude, the superheat has a maximum value of about 45° F (25° C).

If the mass of lifting gas is such that its pressure is higher than the pressure of the displaced air when the temperatures of the gas and air are equal, the superpressure can remain positive even though the gas temperature subsequently drops below that of the air (negative superheat). The maximum permissible value of negative superheat is determined, therefore, by the initial superpressure, ΔP_1, the value of which must be high enough to ensure that the total superpressure never becomes negative, even though the superheat drops below zero. For, if the balloon should cool so far below ambient temperature that the gas pressure drops below ambient, thus decreasing the volume of displaced air, the balloon will descend. On the other hand, the "initial" superpressure must not be so high that, when the gas temperature is at a maximum, the total superpressure stresses the balloon beyond its structural capability. In the latter case, the maximum allowable total superpressure is a function both of the limiting safe stress possible with a particular skin material and of the dimensions and shape of the balloon.

3.3.5.4 Superpressure as a Function of Altitude

If one assumes the same free lift and approximately the same maximum superheat at different levels in the atmosphere, it is evident from the equation for total superpressure above that the magnitude of ΔP is determined by the value of ambient pressure, P_a, at the desired level. Thus, a balloon to float at the lower altitudes, where P_a is high, must withstand much higher superpressures than a balloon destined to float at high altitudes, where P_a is low. (This fact works in favor of the POBAL-S design.)

3.3.5.5 Effect of Superpressure on Balloon Volume

Theoretically, the balloon volume, V, should remain constant while the superpressure varies during flight. Actually, the plastic films used as barrier materials are elastic, even at very low temperatures, and the balloon volume increases slightly when increased superpressure increases the stress upon the film. The balloon then rises to an altitude of lower air density, and equilibrium is re-established. The value of stress produced by a given value of superpressure differs with film-thickness and the shape of the balloon (see section 3.3.6), while the altitude change produced by a particular stress, S, can be predicted from the modulus of elasticity, E, of the balloon material. For example, if the balloon is a sphere of volume, V, when fully inflated, and $\Delta P = 0$, the new volume, V', when it is subjected to the stress, S, is given by:

$$\frac{V'}{V} = \left(1 + \frac{3S}{E}\right).$$

3.3.5.6 Superpressure Balloon Materials

When a balloon is designed, the maximum allowable superpressure at the desired altitude is estimated. Dimensions and material thickness are then chosen so that the stress will not exceed the safe value determined in cold-chamber measurements for the particular material and configuration. For a balloon to maintain a positive, varying superpressure without leakage and without significant change in volume at the very low temperatures in the stratosphere, particular attention must be given to the physical properties of the skin material. It must be available in very thin, large-area sheets, with low-fault count, and be resistant to deterioration from atmospheric constituents and from solar radiation (particularly ultra-violet radiation). Very high tensile strength, 10,000 psia (6.87×10^7 N/m^2) or higher, and low permeability to lifting gases are obvious prerequisites. The material should be nearly transparent to solar radiation in order to limit the buildup of superheat. Moreover, to keep the increase in volume (stretching) small when the superpressure does increase, a high modulus of elasticity is required, about 800,000 psia (5.5×10^9 N/m^2).

NOTE: Stretching is to be avoided not only because it results in balloon instability but also because any perceptible elongation of the plastic film may open up tiny imperfections, causing holes, even though the stress may be within the theoretical elastic limit for the material. The stress-strain curve should be very nearly linear over a wide range of stress values so that the stress produced by the maximum allowable superpressure is well below that value at which the material starts to yield.

It must be possible to seal the material so that seal strength is at least equal to parent material strength in shear, in both transverse and longitudinal directions. (The seals should also possess reasonably high strength in peel.) All of these physical properties, must, of course, be retained over the wide range of atmospheric temperatures encountered from ground level to the stratosphere.

The physical parameters furnished by a manufacturer are generally inadequate for forecasting the ultimate suitability of promising materials for the superpressure balloon application. A very important phase of the superpressure balloon development program, therefore, has been to devise appropriate materials-testing and inspection procedures. Of the many materials evaluated, only a few have been found suitable. To date, a polyester film (for example, mylar, polyethylene terephthalate, manufactured by E.I. Dupont & Co, and celanar, Celanese Corp of America) has been the material principally used. It is tough, durable, and reasonably resilient, even at -70°C (-94°F). Polyester film is not directly heat-sealable; the heat causes it to become brittle and to lose 50 percent of its strength. Instead, pretreated tape, with adhesive, is heat-sealed to the butt joint.

One inherent disadvantage of very thin polyester sheets is the possibility of developing pinholes during balloon fabrication, storage, and launching, which may enlarge under pressure at the low atmospheric temperatures. (Creasing of the film, which is a normal procedure of high-density packing techniques, is particularly to be avoided with polyester film.) Lamination techniques have greatly reduced the leakage rate, thus increasing flight duration and improving reliability. Two sheets of 3/4 mil (0.00075 in, 0.019 mm) polyester film bound together by a very thin layer of adhesive weigh little more than a single 1.5 mil (0.0015 in, 0.038 mm) sheet of the same area. The laminate has greater flexibility, greatly improved abrasion resistance, and, of course, substantially improved leakage characteristics. Nevertheless, the greatest possible care in handling, and meticulous control of every detail in the fabrication process, are necessary to retain the theoretical strength and low leakage of this plastic.

3.3.5.7 Superpressure Balloon Flight Programs

The Grass report[22], from which much of the preceding material on superpressure balloons was derived, was written in 1962 and was based on the results of a rather extensive cold chamber test program conducted on model balloons. It had the benefit of only scanty experimental flight data, however. It has withstood the test of time quite well, nevertheless, as evidenced by subsequent flight programs. Due to a shift in emphasis, Air Force superpressure balloon efforts were terminated in the mid-1960's, and the technique has been exploited mainly by the National Center for Atmospheric Research (NCAR) in its highly successful GHOST Program and in the follow-on Mother GHOST development. The French government has been active in the field also, with its equally successful EOLE program, conducted by the Centre National d'Études Spatiales (CNES) in cooperation with NASA.

The results of tests run on the free-flying GHOST and EOLE constant level balloons through November 1968 are summarized in Table 1 which has been reproduced from the plan for United States participation in the GARP Program.[23] The results show that superpressure balloons perform better in the stratosphere, 200 mb (~40,000 ft, 12.19 km) and above, than they do in the mid-troposphere, 700 - 300 mb (~10,000 ft-30,000 ft, 3.05-9.14 km). The principal cause of premature flight termination is the unwanted accretion of mass due to icing conditions in cirrus clouds or to frost formation in moist atmospheres.

Later EOLE flights (1971-1972) involved 480 4-m (13.1 ft) diameter superpressure balloons released in the Southern Hemisphere to float at the 200-mb (40,000 ft, 12.19 km) level and to trace the horizontal motion of air masses on a hemispheric scale.[24] The mean operational lifetime of those balloons was 103 days, with 66 balloons lasting more than 6 months, and 14 more than 1 year. Several of the balloons strayed over the South Pole, where they disappeared from

23. National Acad. of Sciences (1969) Plan for U.S. Participation in the Global Atmospheric Research Program, Washington, D.C.

24. Morel, P. and Brandeen, W. (1973) The EOLE experiment, early results and current objectives, Bulletin of the American Meteorological Society 54(No. 4):298-306.

Table 1. Superpressure Balloon Performance as of January 1969 (COSPAR Working Group VI, 1969)

(km)	Level (K ft)	(mb)	Number	Average Life (days)	Maximum Life (days)	Outlook for Average Life (days)	Failure Mode
23.77	78	30	10 U.S.	50	116	≈ 365	Ascent damage; pinholes
16.15	53	100	22 U.S. 10 French	> 100	> 439 and still flying	≈ 365	Ascent damage; pinholes
12.19	40	200	60 U.S. 20 French	90	351	170-200 except in tropics	Pinholes; icing in cirrus
9.14	30	300	50 French 5 U.S.	12 43	102 88	50 15 in tropics	Pinholes; icing in cirrus
5.49	18	500	20 U.S.	7	22	—	Icing
3.05	10	700	3 U.S.	14	21	20	Diffusion loss; icing at mid-latitudes possible; mountains
1.46	4.8	850	10 French	11	20	20	Diffusion loss; mountains

the view of the monitoring EOLE satellite, only to reappear at a later date. This was a severe test of the balloons' abilities to withstand large negative values of superheat without losing superpressure.

NOTE: (As a matter of interest, th GHOST and EOLE flights have been confined to the Southern Hemisphere because of political problems which would arise if the flights were carried out north of the equator and the balloons overflew sensitive territorial areas.)

The constant level balloons, which we have discussed thus far, have been relatively small, ranging from 2 - 4 m (6.6-13.12 ft) in diameter for flights up to 100 mb (53,000 ft, 16.15 km) and increasing to 20 m (65.62 ft) in diameter for flights at the 10 mb (102,000 ft, 31.09 km) level. Despite their small size and the fact that they have been free-flying, with little or no station-keeping, they have, nonetheless, served very well to illustrate the long lives available to superpressure balloons if properly constructed. Lally[25] points out that in flights at altitudes above 500 mb (18,000 ft, 5.49 km), loss of superpressure by diffusion of gas through the balloon skin is not a major problem. (Even at lower altitudes where diffusion is greater, icing and/or mountains will usually finish off the balloon before it loses superpressure.) The importance of stress levels is also described by Lally. He recommends prestressing the film to 10,000 psia (6.87×10^7 N/m^2) tensile stress (see section 3.3.6), and then limiting it to 7500 psia (5.15×10^7 N/m^2) in actual flight, with 5000 psia (3.435×10^7 N/m^2) contributed by the initial superpressure caused by free lift.

The Mother GHOST program, as described by Lally[26] is quite relevant to the airborne relay problem in that it covers a superpressure balloon with a carrying capacity of 100 kg (220 lb) and is designed to fly at about 80,000 ft (24.38 km) for two to three months. Preliminary tests of this system have been quite successful. Operational flights near the equator are planned in connection with the GARP/GATE Program in June-September 1974. In those flights an attempt will be made to minimize latitudinal drift, that is, to orbit the globe one or more times while remaining within the zonal flow of the tropics. The Mother GHOST is so named because it carries a supply of meteorological dropsondes in a dispenser which releases the sondes periodically upon receipt of a satellite-relayed command.

The Mother GHOST balloons are not the largest superpressure balloons ever flown, however. Grass,[27] in 1964, flew several 120-ft (36.58 m) diameter superpressure balloons from California. (Test results have not been published.) Those balloons had a unit volume of over 900,000 ft^3 (25,488 m^3) and carried 300-lb (136 kg) payloads (exclusive of their own weight) to 100,000 ft (30.48 km). Longest flight durations were only a few days, due to leakage problems. The Grass balloons were quite heavy, as is typical of superpressure balloons. Made

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25. Lally, Vincent E. (1969) Constant Level Balloons for Sounding Systems, AMS Monographs 11(No. 33), Proc. American Meteorological Society Symposium on Meteorological Observations and Instrumentation, Washington, D.C.

26. Lally, Vincent E. (1972) Meteorological Measurements from Large Superpressure Balloons, Proc. American Meteorological Society, 2nd Symposium on Meteorological Observations and Instrumentation, San Diego, California.

27. Grass, Lewis A. (June 1974) Private communication.

of 1.5 mil (0.0015 in, 0.038 mm) bilaminated mylar, they weighed 600 lb (272 kg) each. The lower flying Mother GHOST balloons are made of 2.0 mil (0.002 in, 0.0508 mm) polyester film, are approximately 70 ft (21.4 m) in diameter, and weigh about 240 lbs (109 kg). More recently (1973), NCAR has been flying 110-ft (33.53 m) diameter superpressure spheres and even launched one with a diameter of 194 ft (59.13 m).[28]

3.3.6 POBAL-S AS A SUPERPRESSURE BALLOON

The foregoing general consideration of superpressure balloon theory and problems should help the reader to understand more clearly the design difficulties associated with the POBAL-S system (and with the Navy's HASPA system to be discussed later).

It should be clear that the balloon material's tensile strength (the point to which the material may be stressed without significant stretching or tearing) is a critically important parameter. Tensile strength, in a given material, is a function of thickness. In other words, thicker balloon films can stand greater values of superpressure. The thicker the film, the greater the balloon weight, however, which means less useful payload for a given volume or a larger volume (relative to that of a thin-gauge balloon) for a given payload. (The volume increases because more gas is required to support the extra weight of the heavy-gauge balloon material.) The larger volume leads to greater drag forces (see section 3.2.2) and correspondingly higher propulsion power requirements, which, in turn, escalate volume, drag, etc even further. Hence, one recognizes the attempts to minimize system size during the design phase.

If a given payload must be flown to a specific height on a balloon which is volume-limited, superpressure balloon size can be kept within bounds only through the use of thinner gauge polyester film or of less dense materials of equal or higher tensile strength.

In the Grass report,[19] Appendix II, it is shown that the circumferential stress, S, on the thin side wall of a cylindrical balloon, inflated with gas at a value of superpressure ΔP, can be found by use of the equation:

$$S = \frac{\Delta P r}{t}$$

where ΔP is the total superpressure (see section 3.3.5.2)
r = radius of the cylinder
t = thickness of the balloon film.

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28. Kurfess, James D. (1974) Superpressure balloons for long duration flight, Astronautics and Aeronautics 12(No. 4):68.

From the formula above, it can be seen that the amount of stress experienced by the balloon film is directly proportional to the radius of the cylinder and inversely proportional to the thickness of the film. Thus, if the balloon designer selects a thinner film to reduce size and mass, he is increasing the stress level on the film and bursting of the balloon becomes possible.

When the POBAL-S design was being established, a "minimized" system size and mass combination was chosen, based on the original 20-kt (10.3 m/s) airspeed requirement, so that the stress level on the balloon film would be 14,250 psia (9.79×10^7 N/m^2). This relatively high figure was chosen initially without regard to actual film densities. When the density of polyester was worked into the design computations, it was found that the polyester would have to be stressed to over 17,000 psia (1.17×10^8 N/m^2) in order to maintain the minimized system size and mass. The 17,000 psia figure exceeds the demonstrated stress capabilities of polyester film. Limited tests run at Raven and at Stevens Institute of Technology under AFCRL study contracts indicated that a promising new film, biaxially oriented Nylon-6, could satisfy the size and mass constraints while staying at design stress levels. Nylon-6 is 15 percent lighter than polyester. Unfortunately, it has not been used in balloon fabrication to date and there is no flight history to assist in the evaluation. As recommended in the Raven study, AFCRL will design and fly some 30-ft (9.14 m) diameter Nylon-6 superpressure balloons in FY1975. They will be unpowered. The tests will provide initial flight experience with Nylon-6, and indicate whether problems exist with respect to the material's radiation (absorption and emissivity) properties as well as with biaxial cold temperature characteristics of parent material and seals. The balloons will float at 65,000 ft (19.8 km) for approximately one week, and will be designed for a material tensile stress level of 12,000 - 14,000 psia (8.24-9.61×10^7 N/m^2). Balloon volume will be slightly above 14,000 ft^3 (396.5 m^3) and the gross load (payload and balloon) will be 69.2 lb (31.4 kg). Pressure and temperature sensors will be carried to measure ambient and internal values of these parameters so that superpressure can be monitored continuously.

The results of the AFCRL tests will be of value to the Navy's HASPA program which has now become the most active powered superpressure balloon program within DOD. The scope of the AFCRL program was sharply reduced with the completion of the POBAL-S study and has become a program of in-house study, consultation to NOL (Naval Ordnance Laboratory) on HASPA (High Altitude Super-pressured Powered Aerostat), and laboratory and field tests of new materials and components. The HASPA program has seized the initiative. Nevertheless, the spirit of POBAL-S lives on in the HASPA program. Thus, it seems appropriate to review the design arrived at in the POBAL-S study, even though there

are no current plans for further Air Force development or operational implementation of the concept.

NOTE: Another Air Force activity, SAMSO, within the last two to three years sponsored a study of high-altitude powered airships under the PASS Program. The vehicle considered resembled POBAL-S in many respects. The PASS program is currently inactive. The classified PASS reports were not available for reference.

3.3.7 THE POBAL-S DESIGN

3.3.7.1 The Balloon Design

As illustrated in Figure 5, the POBAL-S system design features a Class C aerodynamically shaped superpressure balloon (hull), with a fineness ratio of 5:1, powered by a fuel-cell-energized propeller unit, gymbal-mounted at the aft end. An equipment bay is located at the base of the hull, forward of the center of gravity and the center of buoyancy. Vertical and horizontal fins are simple membranes supported by air-inflated cones.

The volume of the balloon is 1,034,000 ft^3 (29,282 m^3). It is 370.8 ft (113 m) long and has a maximum diameter of 72.18 ft (22 m). The system weight is 4,110 lb (1864 kg). The recommended balloon material is the previously mentioned biaxially oriented Nylon-6. Figure 6 shows the proposed method of constructing the balloon, as it appears in the Raven Phase II report.[21] The gores are shown arranged circumferentially over the greater portion of the hull (concentric rings joined end-to-end). The end-section gores are arranged longitudinally. Note the relatively very heavy gore material thicknesses, ranging from 8 mils (0.008 in, 0.204 mm) at the center to 4 mils (0.004 in, 0.102 mm) at the ends. This arrangement is due to the fact that stress on the film is a function of the distance from the balloon center line (axis) outward to the skin, as indicated in the formula for stress discussed in section 3.3.6. Longitudinal gores are used for the fore and aft sections to simplify construction and to provide better shaping in areas of large curvature changes. Butt seals, with inside and outside tapes, are specified, with total tape thickness 1 mil (0.001 in, 0.0254 mm) greater than the thickness of the parent material being sealed.

NOTE: Subsequent hull design analyses at Raven revealed the presence of serious problems with the gore pattern described above. The design has since been changed to conventional, that is, longitudinal, airship gore patterns.[29]

29. Korn, Arthur O. (July 1974) Personal communication.

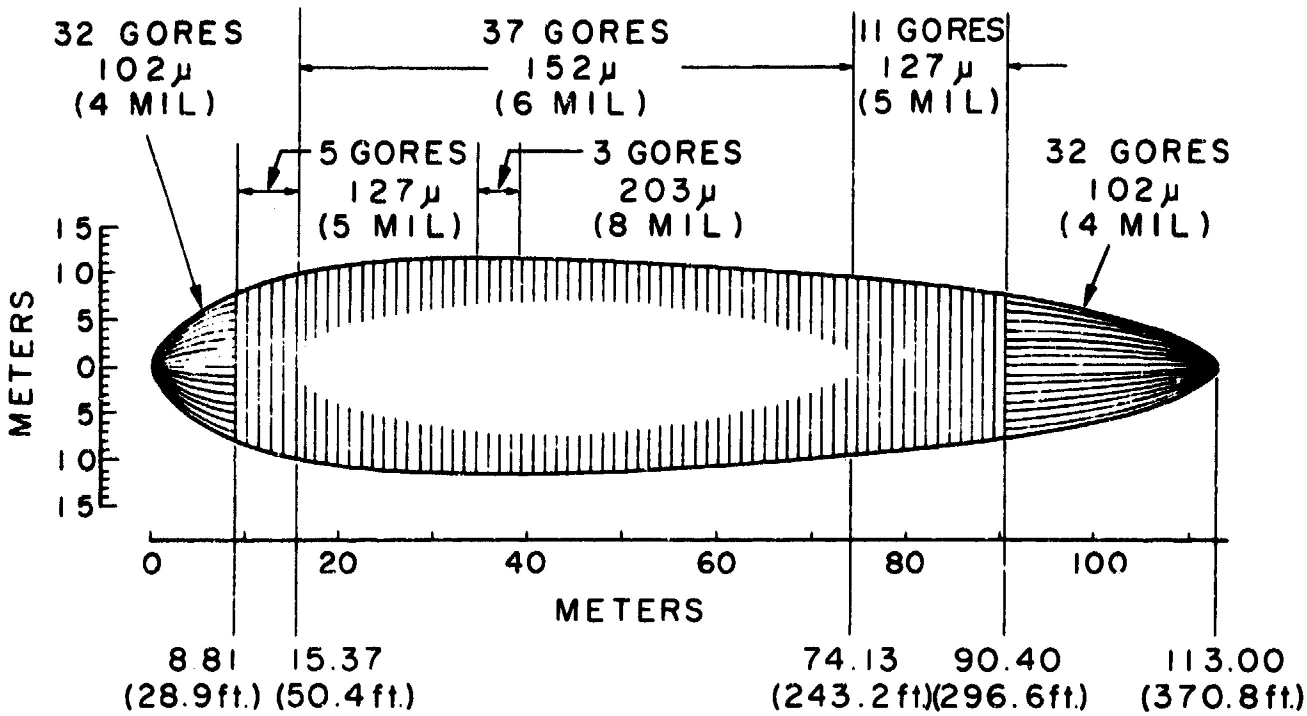

Figure 6. Airship Gore Layout

In the earlier lengthy discussion of balloon pressurization, the emphasis was on maintenance of constant volume. In the POBAL-S configuration developed by Raven, the internal pressure of the balloon takes on an added and very crucial significance. Referring to Figure 5 on page 27, the gimballed motor assembly is seen to be mounted at the stern. In this instance, the balloon is acting as a pressurized beam to support the load at the stern. The obvious concern here is with the possibility of buckling. The Raven study shows that the POBAL-S balloon, with 20 percent free lift, can survive a -10 percent superheat condition without buckling and with some margin of safety. Nevertheless, the design incorporates a provision for shutting down the motor if unexpectedly large negative superpressures are encountered, so that the rotor blades will not damage the hull in the event of buckling.

The POBAL-S design benefited from work that Raven conducted in 1970 for another agency under the classified High Platform II program. A powered, aerodynamically shaped superpressure balloon was designed and tested on that program; the brief flight experience, thus gained, constitutes the only relevant powered superpressure balloon history against which to compare the POBAL-S concept directly. The balloon was only about 1/5th the size of the POBAL-S design, and, because it was very lightly loaded, it was able to use much thinner material than is envisioned for POBAL-S. Nevertheless it did demonstrate that a balloon with a hull configuration, similar to that proposed for the POBAL-S, can be launched successfully and can fly stably at the altitudes designated for the POBAL-S. Limited maneuvering (sun-seeking) at float altitude was also demonstrated in a minimum wind field situation. Because the flight lasted only a few hours, no significant flight duration experience was obtained and, thus, the POBAL-S design must borrow from the previously described experience gained with unpowered superpressure balloon flights to establish flight duration estimates.

3.3.7.2 Propulsion System

Besides being considerably smaller, the High Platform II balloon system differed in another important way from the POBAL-S design. Its propulsion unit was suspended below the hull on a skeletal, rigidly mounted gondola, as opposed to the stern mounting of the propulsion unit proposed for POBAL-S. The latter method of mounting (an aluminum alloy tubular framework laced to the balloon skin at the stern cone) was selected for POBAL-S because of the existence of the heavy equipment bay under the hull (which the solar-powered High Platform II balloon did not have), and because of the very large propeller employed, which would have required a cumbersome amidships frame to insure clearance.

The actual propulsion assembly proposed for POBAL-S consists of a three-bladed 26.9 ft (8.2 m) diameter propeller, a speed reducer, and a gimbal-mounted motor. The speed reducer is a multi-stage belt unit with a reduction ratio of 133:1, weighing about 15 lb (6.8 kg). It is driven by a small brushless DC electric motor which derives its operating power from the fuel cell located amidships in the equipment bay. The stern mounting of the propulsion assembly is designed to react bending, torque, and thrust loads into the envelope. Propulsion power levels and direction of thrust are governed by an on-board control system which actuates or adjusts the outputs of the main propulsion motor and the gimbal motors in response to inputs from various sources. Such signals may come from the pitch and yaw sensors of the autopilot, from the navigation unit (which maintains the airship within the assigned station area), and from the ground-actuated command/control unit. Incidentally, the thrust needed for the Class C hull is only 26.7 lb (118.8 N), 100 percent duty cycle, as compared to the 108 lb (480 N) required for the original natural shape demonstration unit. (See section 3.2.3.)

3.3.7.3 Electrical Power System Survey

A hydrogen-oxygen fuel cell system was selected to supply electrical power to the POBAL-S propulsion unit. This decision was the culmination of considerable research into power sources which covered all practical possibilities.

A preliminary survey at AFCRL in 1971 revealed that a hydrogen-oxygen fuel cell, or an array of cadmium sulfide solar cells with rechargeable silver-zinc batteries, was the energy source most likely to operate reliably at POBAL altitudes, while providing the necessary power at a minimum weight penalty. It also revealed that fuel cells are superior to solar cells for durations of up to 20 days. (Beyond that, solar cell systems are more advantageous.) Both fuel cells and solar cell arrays are very costly, however, and introduce operational complications. For that reason, another survey[30] was conducted at AFCRL in 1972 for a less expensive but equally reliable device. (This second survey was inspired by literature reports citing many advances in the energy source field.)

The following extract from AFCRL-TR-73-0424 (see section 7.2.6)[20] summarizes the result of that second survey:

> Among currently available power sources, turboshaft engines cannot operate at POBAL altitudes. Turbojets are altitude-qualified, but there are none with low enough thrust, and if there were, their fuel consumption would be at least 5 times too high. Electric thrusters fall short of the POBAL requirement by a factor of 10^4. Much higher power output is in the offing, but those systems will be reactor-powered and much too heavy for POBAL. Chemically fuelled thrusters consume fuel at 50 times too high a rate and generally are not throttle-controlled. Several solar-heat converters had excellent weight and power characteristics for POBAL, but they developed unexpected problems and development was abandoned. At the time of this writing, the predicted breakthroughs in low-cost fuel cell development and in high-energy chemical batteries suitable for POBAL have not yet been realized.
>
> Radioisotope thermoelectric generators are a possibility for the future, but they involve operational (safety) restrictions and would be considerably more expensive than fuel cells or solar cells.
>
> In preparation for the Space Shuttle, however, the weight and performance of the H_2-O_2 fuel cell have been significantly improved and lighter weight fuel tanks are available. This is without question the best available choice for the POBAL mission.

3.3.7.4 Fuel Cell Power System Description

Total electric power requirements for the POBAL-S system are 2520 W, of which the main propulsion motor takes 1920 W, the payload 500 W, and control and telemetry together 100 W. Pratt and Whitney Aircraft, under the terms of AFCRL study contract F19628-73-C-0139, developed a conceptual design for an alkaline hydrogen-oxygen fuel cell system capable of providing the required power and of being integrated into the POBAL-S design.[31] The energy density of the system is 600 watt-hours per lb (47.6×10^5 J/kg), about six times greater than that of a good primary battery system, such as was used on the original POBAL demonstration system. (See section 3.2.3.)

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30. Rice, C.B. (1972) Power Sources for a Powered Balloon, Proc. 7th AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

31. Handley, Lawrence M. (1973) Study of Fuel Cell System for Powered Balloon, AFCRL-TR-73-0447, Pratt and Whitney Aircraft.

The fuel cell power system weighs a little over 700 lb (317.5 kg) and, as previously stated, is located in the equipment bay shown at the base of the hull in Figure 5. The system contains cryogenically stored reactants (liquid hydrogen and liquid oxygen), the fuel cell proper, a tank for storing water, which is the product of the $H_2 + O_2$ reaction, and a radiator for dissipating heat from the reaction. A metal framework, which is lashed to the balloon hull, supports the fuel cell power system along with the payload being carried by the balloon and the balloon "housekeeping" components (control/TM systems). The whole package, approximately 1300 lb (590 kg), is intended to be recovered by parachute at the end of the mission and is designed to absorb landing and tumbling shocks.

3.3.7.5 POBAL-S Launching Considerations

In our discussions thus far we have described the POBAL-S system as it might look and behave at floating altitude. Let us go back now to the preliminary steps in the procedure, namely, the inflation and launching operation, which, in some respects poses even greater challenges.

The POBAL-S balloon, at launch, bears a general resemblance to a typical zero-pressure free-floating balloon in that the gas forms a relatively small bubble at the uppermost point in the balloon, while the remainder of the material hangs slack. It is not even obvious that the balloon is cylindrical in shape. Yet, important differences are immediately apparent. First, the balloon may have to be inflated stern end up. This, by convention, is an upside down procedure, at least when compared to the method of launching natural shape balloons. In the Raven R&D Design Evaluation Report,[21] the stern-up method has been proposed as necessary because it is believed that the rotor would not survive a nose-up launch. Figure 7a shows the Raven concept of the launch scene as the initial helium gas bubble is being formed in the balloon. Note that a crane is used to support the stern, so that the propulsion assembly can be laced in position. Figure 7b shows the stern end raised. A tow balloon is employed to achieve this configuration, since the lifting power of the bubble in the main balloon is at this point insufficient. Meanwhile, the equipment bay remains on the ground. The upraised slack balloon material is gathered below the bubble by a special tri-roller clamp secured to two winches. The purpose of the tri-roller clamp is to avoid sudden surges in lift as the equipment bay is eased up off the ground. Figure 7c shows the moment of release, with the clamp removed and the whole balloon airborne.

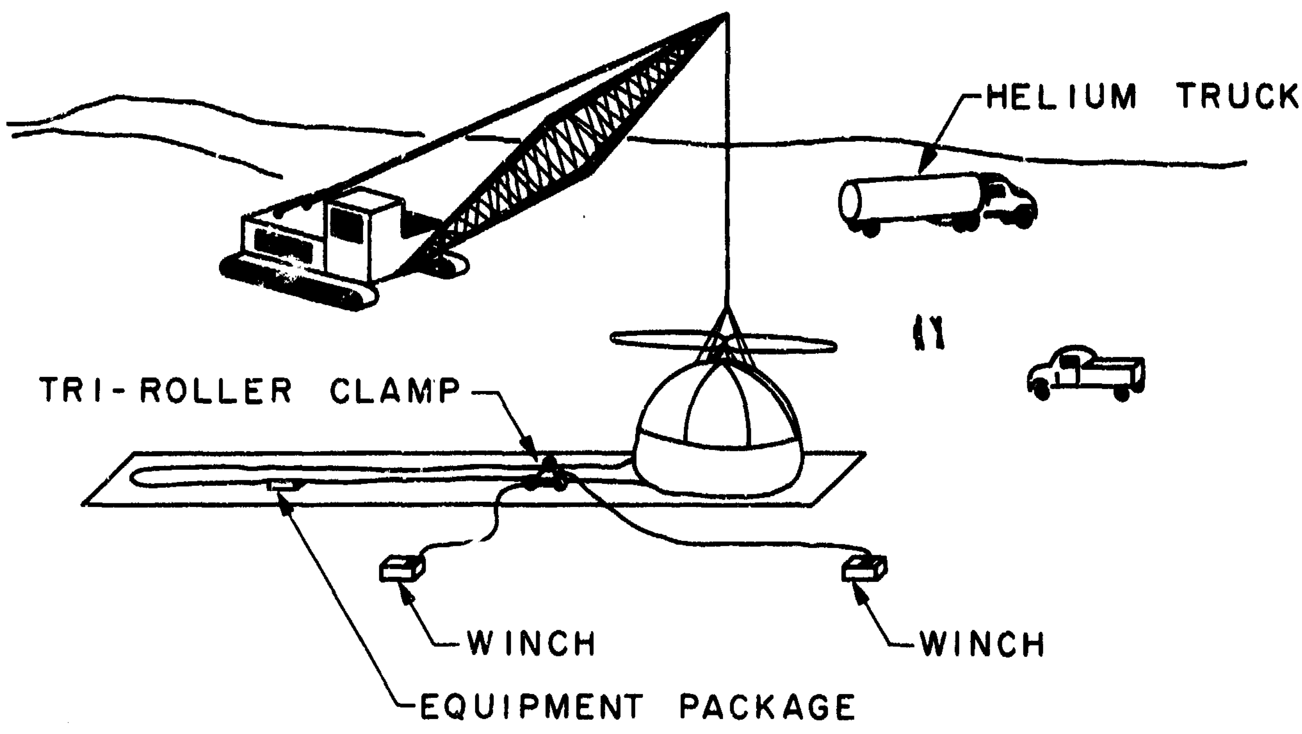

Figure 7a. Launch Configuration, Stern Assembly Installation

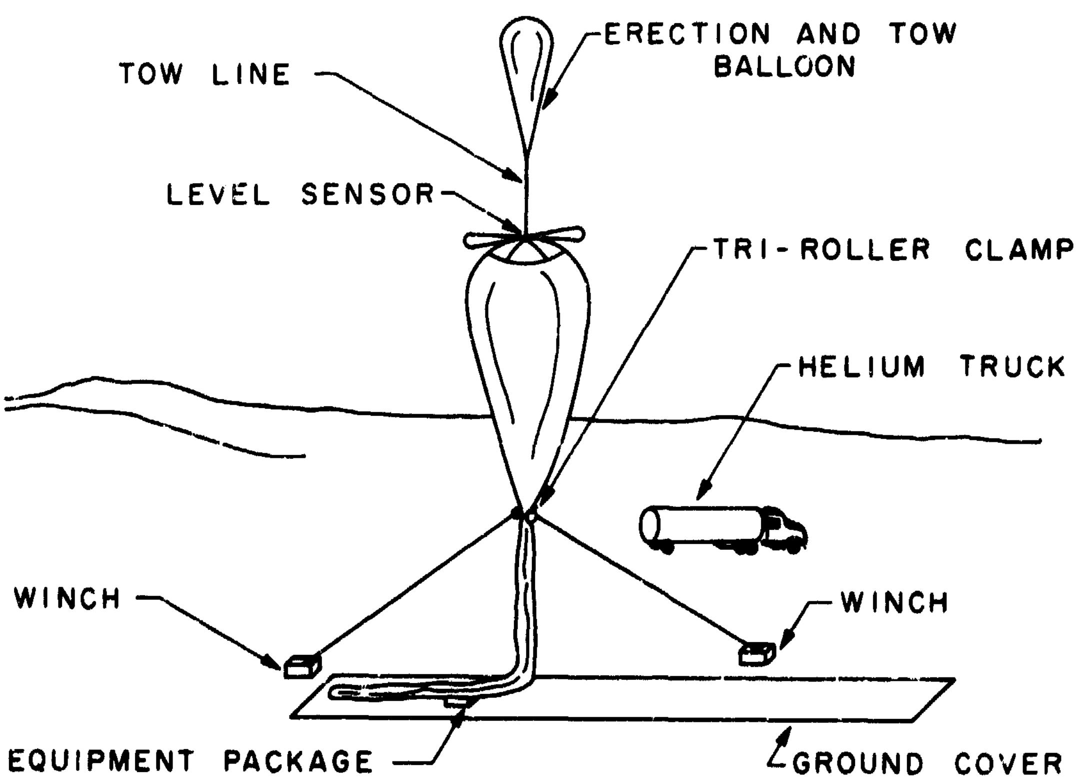

Figure 7b. Launch Configuration, Inflation

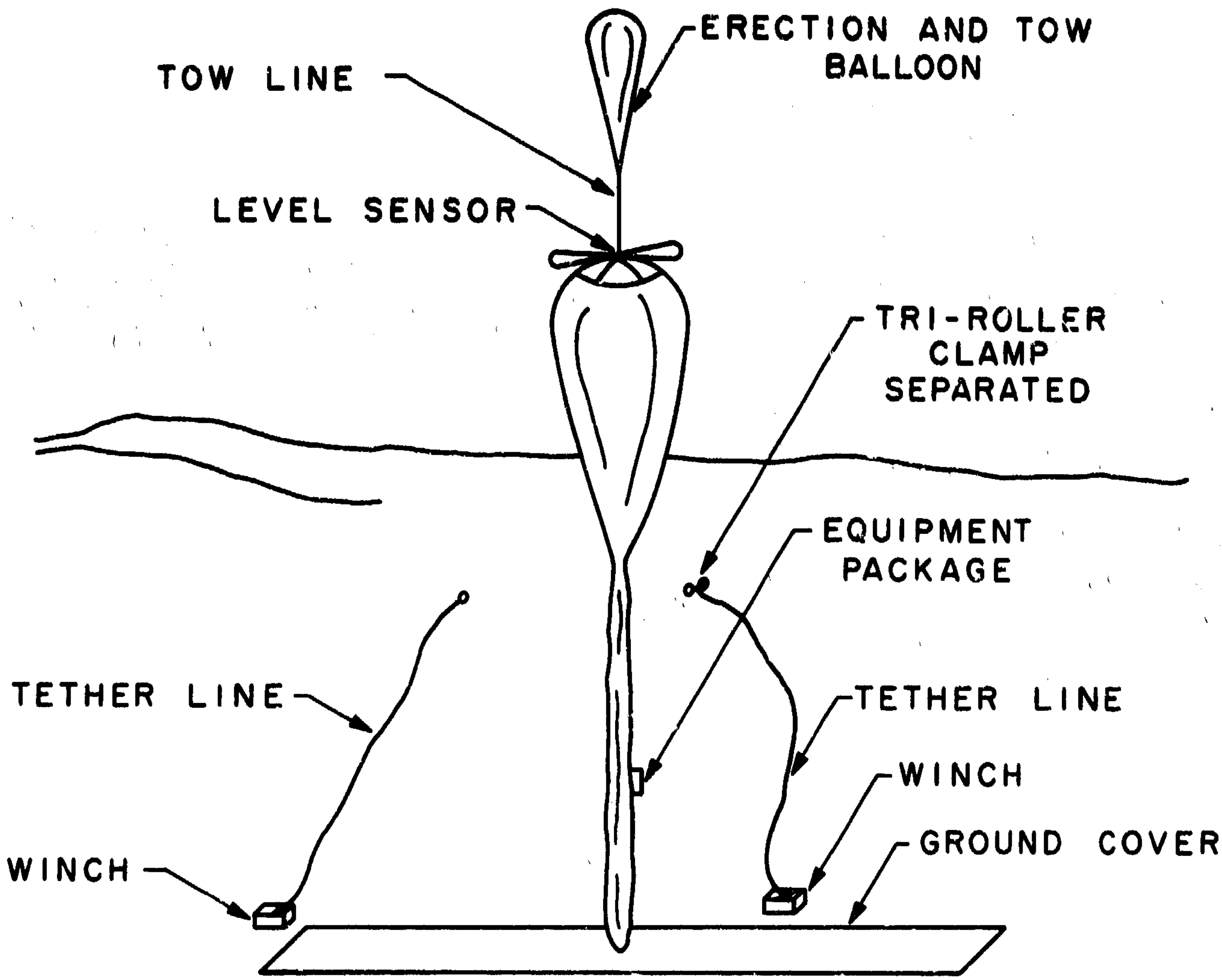

Figure 7c. Launch Configuration, Deployment

NOTE: In his role as consultant to the HASPA program, Korn[32] has outlined a tandem-balloon method of launch which permits more conventional launch techniques to be used. In the Korn method, the stern assembly is not elevated first as proposed in the Raven study.

Anticipated gross inflation is 4950 lb (2245 kg), which represents 20 percent free lift. (See section 3.3.7.1.) Because this amount of free lift would lead to too fast an ascent rate, ballast will be employed to counteract the free lift, reducing it to 2 percent. The 2 percent net free lift is insufficient for the balloon to be launched properly. Hence, the tow balloon's lift will be used to assure the proper degree of buoyancy. (The tow balloon is cut away when no longer needed.) The

32. Korn, Arthur O. (July 1974) Personal communication.

supply of ballast will be released in such a way as to keep the ascent rate within limits and to permit the balloon to ease into float altitude.

The stern structure and the balloon are not recovered in reusable condition after the mission. Through the use of a recovery parachute, the equipment bay, however, is expected to be reused, in order that the anticipated high cost (several hundred thousand dollars) of the fuel cell and housekeeping items may be amortized.

3.3.7.6 Applicability of the POBAL-S System to the SEEK STAR Mission

It appears academic to attempt to evaluate the applicability of the POBAL-S system to the SEEK STAR Mission, primarily because it is only a paper design, with no flight test record on which to base a meaningful judgment, and with no Air Force plans on hand for fabricating and testing such a system. It may be informative, nevertheless, to attempt to predict how the POBAL-S might behave if built to the Raven design and if operated by tactical troops. (These predictions will serve also to help us evaluate the potential usefulness of the HASPA system, and will be referred to in the discussion of HASPA.)

At the very least, launching will be a complex operation, and it is not clear at this point whether it could be carried out within the skill levels and real estate limitations typical of many TRI-TAC unit operations. One of the conclusions of the Raven study covers this area as follows:

> The method of deployment of this system requires that...a scale model test launch sequence...be performed to determine any problem areas which might be associated with this type of launch. This should include a practice attempt for attaching the tail structure assembly. Also, the equipment bay should be simulated to assure that no damage would be incurred during the launch sequence. Finally, the deployment mode of the ascending balloon needs to be analyzed.

Presumably such a test program would also identify the launch weather condition limits, the minimum cleared area required, and the essential ground-support equipment. (All of these items are presently unknown.)

On a more positive note, the predicted flight performance of the POBAL-S system, that is, the anticipation that all design goals will be met with respect to float altitude, wind speed, payload, power, etc, makes POBAL-S an attractive candidate LTA platform for the SEEK STAR mission, even though its 7-day duration capability is far short of the 30 days desired. However, this performance is predicated upon the successful use of biaxially oriented Nylon-6 material which has never been flown in balloons before. This constitutes another area of uncertainty with respect to the operational applicability of POBAL-S. Moreover, if polyester film must be used, instead, system size must increase, with the strong possibility that predicted system performance will be seriously degraded. The 14,250 psia (9.79 x 10^7 N/m^2) stress level proposed for POBAL-S—subsequently reduced to 12,000 - 14,000 psia (8.24-9.61 x 10^7 N/m^2)—appears to be significantly higher than previously allowable maximum film stress values and introduces additional uncertainties. The planned AFCRL tests in FY75 of smaller balloons constructed of Nylon-6 are, indeed, crucial with respect to predicting performance of the POBAL-S design.

The proposed propulsion unit is untried and test data must be developed and analyzed to insure trouble-free continuous operation at the altitudes of interest. Navigation and autopilot equipment likewise require extensive testing.

Load suspensions on superpressure balloons have always been a problem, according to Grass,[33] and, thus, the plan to locate the heavy equipment bay in such a way that it is attached to slack material at launch may create severe problems. Realistically, possible suspension problems can be observed and solved only through extensive tests, for which there are no plans, as far as the POBAL-S design is concerned. (HASPA is another matter.) It should be remembered, too, that two of the items in the equipment bay will be fairly large dewars containing liquid hydrogen and liquid oxygen. Cryogenic storage vessels are becoming more commonplace, but they require very careful handling, particularly with respect to the proper disposal of vented explosive gases. This fact should be pondered by operational system planners.

If we forget for the moment the potential launch problems and the material problems, it seems likely that the POBAL-S design would, theoretically, permit extended (seven days) station-keeping in 15-kt (7.7 m/s) winds at flight altitude. This is based on the generally excellent duration characteristics of free-flying superpressure balloons, on the advanced state of the art of fuel cells, and on the one flight of the aerodynamically shaped High Platform II system. Thus, the picture has its bright spots, too. Even so, the meteorology of the situation still exerts an overriding influence. The system will be limited to those areas and times of the year where minimum wind fields, that is winds whose maximum is about 15 kts, are in existence. In stronger wind fields, station-keeping becomes very difficult or impossible. In this connection, Nolan of AFCRL has been conducting for the HASPA Program a study of winds in the 70 - 30 mb (~60,000-78,000 ft, 18.29-23.77 km) altitude regime over the Mediterranean. The results of that study[34] indicate the potential usefulness of a POBAL-S type of system, by season, over one part of the earth.

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33. Grass, Lewis W. (June 1974) Private communication.

34. Nolan, G. F. (1974) Pilot study of wind conditions over the Mediterranean Sea for the HASPA program. Letter report to NOL, 10 July 1974.

In conclusion, then, it is the author's opinion that the POBAL-S system, in its present semi-dormant state, cannot be considered for the SEEK STAR mission. Even if it were part of an on-going development, the number of uncertainties is too great to predict success on the basis of presently available information. Conclusive answers must come from actual field test programs. For this we must look to the HASPA Program.

3.4 The HASPA Program

3.4.1 PROGRAM SUMMARY

F.J. Petrone of the Naval Ordnance Laboratory has summed up the HASPA Program as follows:[35]

> A demonstration program is now underway in which the feasibility of a High-Altitude Super-pressured Power Aerostat (HASPA) will be determined. Basically, the HASPA is an unmanned platform that would operate continuously at high-altitude for long periods of time and maintain an assigned station through powered maneuverability, taking advantage of the low wind fields between the stratospheric and tropospheric winds. HASPA would serve as an extended-duration, airborne platform from which sensors or communication relay links can be operated. The present 32-month time frame of this program will include four demonstration flights (one unpowered and three powered) with expected flight duration of from a few days to over one month.

It is apparent that the overall HASPA concept resembles the POBAL-S concept very closely, as, indeed, it should, since the HASPA program had its origin in Navy inquiries about the POBAL-S work. Yet it would be a mistake to say that the HASPA program is merely a continuation of the preceding POBAL-S development which had been carried out by AFCRL with the aid of Raven Industries.

3.4.2 POBAL-S AND HASPA: A COMPARISON

Both the POBAL-S and HASPA are 15 kt (7.7 m/s), 70,000-ft (21.34 km) systems, designed to carry 200-lb (90.7 kg) payloads. The POBAL-S is only a 7-day system however, whereas the Navy wants the HASPA to stay on station for 30 days. It also wants the HASPA to be capable of bursts of speed up to 25 kt (12.9 m/s). The Navy's day-to-day payload power requirements are less—only 200 W vs 500 W for POBAL-S. The Navy has also specified that the HASPA stay within 50 NM (92.6 km) of a reference station-keeping location. (This, of course, is a requirement whose fulfillment depends on meteorological conditions as well as on system design.)

35. Petrone, F.J. and Wessel, P.R. (1974) High-altitude super-pressured powered aerostat (HASPA). Abstract of paper submitted for presentation at the 8th AFCRL Scientific Balloon Symposium.

3.4.3 THE DETAILED HASPA PROGRAM

The long duration requirement of the HASPA system necessitates a new look at power sources, and a general reanalysis of configuration preferences, component placement decisions, and design trade-off areas. For this reason, the HASPA system managers are not simply taking the POBAL-S design, modifying it, and rushing into model fabrication. Instead, a carefully phased five-step program has been laid out for HASPA. Contractual assistance will be required in this program; a competitive contractor selection and contract award procedure was in its final stages at the time this report was being prepared.

3.4.3.1 Phase Zero: System Definition and Conceptual Design

The first step, or Phase Zero, of the HASPA Program encompasses system definition and conceptual design. It aims to accomplish the following:

(1) Identify the best power source.

(2) Analyze (through computer simulation) the effect of various loads and propulsion configurations on stability and performance.

(3) System Concept Evaluation: Examine trade-offs between various design possibilities and program goals. (Trade-off areas include materials, stability, propulsion, and optimum system operations.)

(4) Complete the conceptual design of the system, including power sources.

NOTE: Specified design volume is $1 \times 10^6 ft^3$ (28,320 m^3) maximum. POBAL-S hull volume is $1.034 \times 10^6 ft^3$ (29,282 m^3).

3.4.3.2 Phase One: Design

The second step, or Phase One, is the design phase. During this phase, the contractor will:

(1) Provide manufacturing drawings of the airship hull.

(2) Complete a preliminary design of electronic systems, including breadboard fabrication and test of components (for example, autopilot).

(3) Design autopilot and interface it with navigation system (GFE).

3.4.3.3 Phase Two: Fabrication

Under this third step the contractor will:

(1) Fabricate hull and envelope hardware.

(2) Assemble and test electronics.

NOTE: Power system (motor, fuel cell/solar array/primary and secondary batteries) is to be government-furnished.

3.4.3.4 Phase Three: System Integration and Test

Under this fourth step the contractor will:

(1) Integrate all subsystems.

(2) Perform indoor static inflation tests to check out system.

(3) Make a non-powered launch and flight test to verify the launch technique, the ascent deployment sequence, and the recovery techniques.

(4) Furnish analysis of test; offer recommendations.

3.4.3.5 Phase Four: Three Powered Flight Tests

3.4.3.5.1 First Flight Tests (Two)

The first of the two initial flight tests will be less than two days in duration and will be battery-powered. The second flight test will employ a fuel cell which the Navy is in the process of obtaining from the General Electric Company. The duration of the second flight will be from several days to a week. The object of these initial flight tests is to verify design choices and predicted performance over a few day-night cycles. Test conditions have been established as follows:

(1) Launch in winds less than 5 kt (2.6 m/s).

(2) Maintain altitude between 55-70 ft (16.76-21.34 km).

(3) Maintain location within 50 mi (92.6 km) rad in 15-kt (7.7 m/s) winds, counteract 25-kt (12.9 m/s) winds for short periods.

(4) Support a 200-lb (90.7 kg) payload and supply 200 W of power to it continuously.

3.4.3.5.2 Proof Flight Test

This test is meant to subject the final system design to anticipated mission conditions and to ascertain the adequacy of the selected configuration with regard to the stated objectives. It will employ the best available power source (possibly solar cells) for this maximum duration mission. Test conditions have been established as follows:

(1), (2) Same as 3.4.3.5.1.

(3) Same as 3.4.3.5.1 plus the requirement to maintain 15 kt airspeed for any 24-hour period.

(4) Same as 3.4.3.5.1.

(5) Minimum flight duration: 30 days.

(6) Use roll attitude control to minimize number of solar cells.

3.4.4 THE APPLICABILITY OF THE HASPA CONCEPT TO THE SEEK STAR MISSION

As elaborate as are the details of the HASPA development program, one fact is clear as of the date of this report, namely that the true applicability of HASPA to SEEK STAR will not be known for about three years. If the HASPA program milestones are met, and if all of the many technical problems are solved, a flyable model could be integrated into the TRI-TAC test bed at Fort Huachuca in the summer of 1977. This assumes that money is made available in time for a second Proof Flight Test model to be fabricated.

The HASPA system contractor has not yet been announced, so that there is no way of knowing the exact approach to be followed in the HASPA development. (The proposals, submitted by the bidders, call for different choices of materials and hull configurations, among other things.)

Most of the uncertainties pointed out with respect to the POBAL-S design carry over, for the present, into the HASPA program (launching methods, material stress problems, reliability of both the autopilot and navigational devices, etc). On the other hand, if the Proof Flight Test model meets expectations, HASPA will be a strong contender for the SEEK STAR secondary relay back-up mission. It will have a far greater altitude and endurance capability than any RPV and, because the most expensive components will be recoverable and reusable, it will be competitive in cost with RPV's. HASPA may actually be less expensive, on a per diem basis, when direct operating costs of the two vehicles are compared over a given period, such as 30 days. In computing such costs, one would include the amortized cost of recovered flight equipment and of ground launching and tracking facilities plus the cost of labor and expended materials. In the case of POBAL-S, it was assumed that the superpressure balloon and the propulsion assembly would not be recovered. This may or may not be true of HASPA, and the eventual reality, in this case, would have a marked influence on operating costs.

The HASPA design characteristics theoretically equal or exceed the goals for an LTA communications relay platform for SEEK STAR, as presented in the outline to this report. Whether the HASPA will materialize into an operationally useful and cost effective system cannot be predicted at this point. Since the HASPA program is the only active or contemplated program of its kind, and since its goals so nearly match those of SEEK STAR, it should be monitored closely in the years ahead. Also, Air Force resources should be made available to the extent necessary both to keep the program moving forward at a reasonable pace and to allow for the procurement of additional models for Air Force testing.

Any operational planning with respect to the use of HASPA in a tactical situation must, of course, take into account the meteorology of the situation. The station-keeping ability of the HASPA is determined by the wind fields present at the time of flight and the degree to which they exceed the 15-kt (7.7 m/s) airspeed capabilities of the powered balloon.

This will close out the discussion of powered balloons. The remainder of this report will be devoted to a short analysis and discussion of the applicability of free-flying balloons.

4. FREE-FLYING ZERO-PRESSURE BALLOONS

4.1 Ground-Launched Balloons

Ground-launched, free-flying, zero-pressure balloons have been the mainstay of the world scientific balloon program. Their technology is well-advanced, they are comparatively inexpensive, and their reliability is very high. However, they have three major limitations which must be considered when contemplating their use as platforms for communications relays:

(1) They require suitable weather conditions at the time of launch.

(2) Their normal flight durations are relatively short, as discussed earlier (see section 3.3.4), unless sizeable amounts of ballast are carried aloft, leading to larger balloon sizes and increased platform costs.

(3) Their station-keeping ability is marginal, except in minimum wind field situations. Because they are unpowered, their minimum wind field performance is naturally inferior to that expected of a POBAL-S or HASPA system.

Besides being versatile platforms for scientific payloads, ground-launched, free-flying, zero-pressure balloons can serve a useful purpose in SEEK STAR applications, provided that the wind fields are correct, the required flight duration is not too great, and suitable launching conditions are available. (As noted in the Introduction to this report, the SEEK STAR LTA platform requirements specify only a 48-hr duration capability for free-flying balloons vs 30 days for powered balloons. For durations of 48 hrs, ballast provisions do not penalize the system markedly, weightwise.)

NOTE: As a practical consideration, which is not intended to discourage potential users, it must be stressed that any projected tactical use of free-flying zero-pressure balloons, familiar though they may seem, will require extensive training in launching procedures for operational personnel plus the acquisition of the required ground support equipment and vehicles.

Actually, ground-launched, zero-pressure, free-flying balloons offer a very inexpensive way of putting a relay or sensor at altitude on short notice, particularly if the communications payload they carry can be considered expendable (that is, a low-cost, throwaway unit for short-term use). If an inexpensive relay were available, two low-cost methods of utilizing free-flying balloons for SEEK STAR missions would suggest themselves: the first is in the gap-filler role, that is, as a device to insure that a missing airborne link in a tactical communications net is quickly replaced. As the name implies, the free-flying balloon system merely fills a gap, on an interim basis, until a more permanent platform is deployed. It may be necessary to expend more than one free-flying balloon system to fill the gap, depending on the strengths of the winds aloft. (The systems are "expended," in the sense that they are considered lost when they drift permanently out of range.)

The second possible use of free-flying balloons in SEEK STAR missions would take advantage of predictable return-path wind fields where possible, to enable a group of balloon systems to provide the required continuous relay capability. Under this concept, a finite number of balloon platforms, for example, six, would be launched serially, with each system following an elliptical, curved, or other return-path trajectory, so that one or more relays would always be within range. This second method quickly encounters weight problems, of course, because of the need to carry extra quantities of ballast. The return-path trajectory typically requires several days for completion. Therefore, with the serial method of launching, the free-flying subpressure balloon should also be considered. (See section 5.2.)

If the free-flying balloon systems are launched from a ship at sea, as has been demonstrated in the past,[36] adverse ground wind conditions can be nullified and launchings become possible in situations where otherwise land launches would be out of the question. The sea-launch method has another advantage: It permits launchings in remote parts of the world where conventional on-shore launch sites are not available.

4.2 Air-Launched Balloon Systems

4.2.1 GAP-FILLER ROLE

The free-flying, zero-pressure, air-launched balloon system (ALBS) concept is treated at length in AFCRL-TR-73-0633.[1] It is a simple concept, which, when reduced to practice, will allow balloon platforms and their payloads to be deployed quickly over nearby or remotely located areas of interest, regardless of

36. Doherty, F.X. (1967) The "C" Launch Technique for High-Altitude Balloons, AFCRL-67-0672.

local surface weather conditions. Under the ALBS concept, a capsule containing the uninflated balloon, the payload, the inflation hardware, and recovery parachutes is launched in mid-air from a rocket or an aircraft which has transported it to the deployment site. After automatically being extracted, unfurled, and inflated, the balloon is allowed to climb to altitude with its payload. (The inflation hardware is parachuted to earth.)

Once at float altitude, about 80,000 ft (24.38 km), the ALBS is subject to the same limitations with respect to duration and station-keeping as noted previously for ground-launched, free-flying, zero-pressure balloons. Needless to say, those limitations must be kept in mind when planning the use of the ALBS. The most important ALBS consideration, however, is the fact that its use can be made independent of surface weather conditions, which means that it can be launched at any time and on very short notice (from an aircraft or a rocket). Its ability to be deployed over remote or unfriendly territory—regions normally out-of-bounds for ground-launched balloon system crews—is an added advantage, of course.

The all-weather launch, remote-area deployment aspects of the ALBS give it its unique attractiveness. This peculiar capability is obtained at a cost which is excessive for those situations where a ground-launched balloon would suffice. (Sea launches are included in the term "ground-launched" in this discussion.) Nevertheless, there are missions where the costs associated with the ALBS are justified. For example, it is not difficult to visualize the ALBS serving SEEK STAR in a remote-area, gap-filling capacity, in the absence of a ground-launch capability, to complete a network link on an emergency basis until a longer duration platform could be put in place. Serial-launched, zero-pressure ALBS are another possibility. These potential missions justify continued development of the ALBS concept. Work along this line has been authorized and is underway at AFCRL under in-house work unit 66651101, with intended payloads in the 200 - 1000-lb (90.7-454 kg) range. In addition, the Air Force Weapons Laboratory is currently investigating somewhat smaller air-launched systems in its study of hardened alternative means of communications to existing ground-based C^3 systems.

4.2.2 CURRENT ALBS INVESTIGATIONS AT AFCRL

When the development concepts for a large, 200 - 1000-lb (90.7-454 kg payload capacity) ALBS were outlined in AFCRL-TR-73-0633[1], certain technical problems were identified. Some of these had to do with the fact that cryogenic storage techniques were selected for the inflatant. Others were concerned with methods of balloon deployment, choice of balloon material, sizing of system decelerators, and so forth. A major technical problem was designing the cryogenic storage system for maximum efficiency and safety. An associated and equally challenging problem related to the vaporization of the liquefied inflatant (helium) and the rapid warming of the resultant gas to ambient temperatures. The vaporization/warming process had to be carried out automatically, as soon as the packaged ALBS was deployed in mid-air from the aircraft or rocket launch vehicle, so that the balloon could be inflated in minimum time.

Under ESD Project Order No. Y74-898, jointly funded by the 478T Project Office at ESD and by Project 6665, Task 666511, at AFCRL, the Cryogenics Division of the National Bureau of Standards (NBS), Boulder, Colorado is preparing to conduct a series of experiments related to the cryogenic storage and heat transfer problems mentioned above. Thus far, it has been established that a packed bed of heated pellets is the simplest and most promising heat transfer medium. These pellets would be made from a material such as aluminum oxide, with a very high specific heat capacity. (Small reaction motors were also considered for this application but were rejected on the basis of cost and complexity.) The vaporized gas would pass through the pellet bed and extract heat from it. Initial bed temperatures would be close to 1500° F (815.6° C), well above the ignition point of H_2. This would effectively preclude the use of hydrogen as the inflation gas for the balloon, since safety considerations would demand the employment of elaborate inert purging systems. The added cost and complexity of such systems would negate any advantages (less expensive gas, higher specific lift) that might accrue from the selection of H_2 over He as the inflatant.

The NBS will design, fabricate, and test a full-scale laboratory model of the cryogenic storage/heat transfer unit envisioned for the ALBS to ascertain that the amount of liquid helium involved, ~100 lb (45.4 kg), can be conditioned to inflate the ALBS balloon in five minutes, which is the time allowed for this operation in plans derived for the aerial deployment of the ALBS. The "conditioning" of the inflatant is visualized as a nearly instantaneous reaction, that is, there will be virtually no time lost between the initiation of the vaporization/warming step and the admission of warm gas into the balloon.

The NBS tests will include filling small, ~10,000 ft^3 (283 m^3), balloons under varying temperature conditions: these tests may be followed by tests at Holloman AFB in which a regular ground-launched balloon will carry the ALBS inflation module to altitude to test the system (and a model ALBS balloon) under more realistic conditions of temperature, dynamic pressure, and vertical wind fluctuations.

While the cryogenic storage/heat transfer tests are being conducted by NBS, separate in-house investigations and computations will be performed at AFCRL to optimize the choice of material for the ALBS balloon and to establish balloon reefing and deployment parameters as well as decelerator sizes needed both for balloon deployment and component recovery. When all of the above data have been generated and analyzed, a prototype ALBS system design will be completed. If funds are available, one or two Proof-Flight Test ALBS units will be fabricated in FY-76 under contract. These prototypes would be launched initially at Holloman AFB in the summer or fall of 1976, using a C-130 aircraft as the launch vehicle. If these launches prove successful, they could lead to additional launches at Fort Huachuca, in the TRI-TAC test bed, in the summer of 1977. Again, availability of funds for replacement components is assumed here.

5. FREE-FLYING SUPERPRESSURE BALLOONS

5.1 General Considerations

Earlier in this report (section 3.3.5) considerable time was devoted to the theory of superpressure balloon flight, with extensive references to the GHOST, Mother GHOST and EOLE programs. The cited experience proves that long-duration superpressure balloon flights, at SEEK STAR altitude levels, and carrying payloads of over 200 lb (90.7 kg), are feasible and within the state of the art. Are not free-flying superpressure balloons applicable to the SEEK STAR mission, therefore? The answer is a qualified yes.

One of the main requirements for an LTA platform for the SEEK STAR mission is time on station, with flight durations of up to 30 days the desired goal. Even in minimum wind field situations, a powered balloon seems necessary to stay within reasonable distance of the designated hover position for that period of time. Thus, the ability of free-flying (unpowered) superpressure balloons merely to stay aloft for long periods of time is of small value, unless the balloon trajectory somehow keeps the payload close enough to the tactical area of interest to be of use. For individual cases, this question can be resolved only by a study of the wind fields likely to be present, at the time of balloon deployment, over the geographical area of interest.

5.2 Ground-Launched Free-Flying Superpressure Balloons

Let us consider now the argument for the possible use of ground-launched, free-flying, superpressure balloons.

If the anticipated trajectory were such that the balloon would quickly and permanently move out of effective range, we would be in a situation where the balloon and its payload were being expended simply to gain short-term coverage, that is, to serve as an emergency gap-filler. In that situation the superpressure balloon would be a poor choice, cost-wise, as compared to a zero-pressure free-flying balloon. If, however, the balloon were to depart the hover area for a period of time and then return, the possibility of obtaining continuous coverage through serial launches of free-flying superpressure balloons would then arise. If, for example, five such balloons provided adequate coverage, the total LTA platform cost in this case would be significantly lower than the cost of a single powered aerostat of the POBAL-S or HASPA class.

The reasons for the cost differential are not hard to determine. If the balloon propulsion unit (propeller, motor, speed reducer, gimbal system) is eliminated, system unit cost decreases sharply, by virtue of both the reduced number of components and the diminution of system on-board energy requirements and size. In section 3.3.7.4, we saw that the POBAL-S propulsion system takes 1920 W, or 76 percent of the entire output of the heavy fuel cell power system. In the case of an unpowered superpressure balloon system, the energy needs are reduced to those of the payload and the command/control/TM modules. These needs can be satisfied by a few storage batteries recharged by solar cells. The balloon size can also be reduced, of course, because of the much smaller gross payload. Moreover, because the drag resistance is no longer a factor, the balloon shape can revert to the less expensive round configuration. Launching problems are drastically simplified, in addition, since conventional techniques may now be employed, as opposed to the elaborate and unproven POBAL-S launch methods illustrated earlier in Figures 7a, 7b, and 7c. (As noted earlier, the HASPA launch may be simplified by the Korn tandem-balloon method.)

In short, in the special circumstances described above, the unpowered superpressure balloon offers distinct advantages to the SEEK STAR mission. Existing technology could be called upon to engineer a suitable flight system with little or no development. The chief obstacle to use of such a balloon would be the fact that it represents only a partial solution to the LTA relay requirement because of meteorological restrictions governing its employment.

5.3 Air-Launched, Free-Flying Superpressure Balloons

Large, air-launched superpressure balloons, of the size discussed in AFCRL-TR-73-0633, are not considered to be within the state of the art. The reason has to do with the need for high-density packing of the uninflated balloon prior to mid-air deployment. Polyester film, the material responsible for the high success rate of free-flying superpressure balloons to date, tends to form creases when folded compactly, and the creases constitute points of weakness in the film when pressurized. Polyethylene does not exhibit this tendency, but, on the other hand, its modulus of elasticity is too low for use under superpressure conditions; that is, it becomes permanently elongated, thereby reducing wall thickness and inviting rupture.

Even if an air-launched, free-flying, superpressure balloon were available, its use would be constrained by trajectory conditions—just as the use of its ground-launched counterpart would be. Despite this limitation, a superpressure ALBS could be of great value to the SEEK STAR mission at times, especially where serial launches are desired. However, until the material problem is solved, it seems safe to conclude that air-launched, free-flying superpressure balloons offer no practical solution to the SEEK STAR problem.

6. AIR-LAUNCHED POWERED BALLOONS

Of the various combinations and categories of balloon systems considered for the SEEK STAR mission, there is one hybrid system which has not yet been discussed and which deserves brief mention. The reference here is to an air-launched powered balloon system. Actually, such a system has never seriously been proposed. The concept involves the basic ALBS described in AFCRL-TR-73-0633, with the added capability of being self-propelled like POBAL or HASPA. It is an intriguing concept in that it gives the ALBS a much greater station-keeping ability than it currently possesses. The concept is not feasible, however, on two counts.

First, there is the incompatibility between polyester storage properties and the high density packaging requirement of the ALBS, as mentioned in section 5.3. Superpressurization is not possible, with the present state of the art in balloon materials, therefore. Without the superpressure feature, durations of the type sought for the SEEK STAR mission, that is, up to 30 days, are impossible.

Second, there is the seemingly impossible problem of storing the large propeller assembly compactly, and then deploying it at the time of mid-air inflation. It may be that some ingenious solution to this dilemma lurks nearby, such as the use of folded, air-inflated, or foamed-in-place rotors. Suffice to say that the engineering problems of deploying a POBAL-S or HASPA in mid-air from a cargo plane or rocket are enormous, and have not been resolved to the point where feasibility has been assured.

7. SUMMARY AND CONCLUSIONS

In the preceding discussion we have looked at all of the various kinds of large balloons in common use today, or presently under development, with an eye toward their possible employment in the SEEK STAR backup communications relay role. Tethered balloons were found to be very useful in many communications applications but of little value to the SEEK STAR mission. (A promising French stratospheric tethered balloon experiment was mentioned as having possible future applicability to SEEK STAR, however.)

The main body of this report has been given over to a discussion of free (that is, untethered) balloons. The powered free balloon has received the greatest emphasis because its projected performance theoretically best matches (or exceeds) the requirements for an LTA backup communications relay system. Since one of the most important of the SEEK STAR requirements is the ability to hover near a fixed geographical location for long periods of time, early AFCRL attempts at balloon station-keeping were chosen as the starting point of the free balloon discussion. Actually, the early attempts involved free-flying (that is, unpowered) balloons flown in minimum wind fields. Those flights, which required large amounts of ballast, demonstrated that free balloon station-keeping is possible under the right meteorological conditions. They also pointed out the need for self-propulsion on the part of the balloon to exploit minimum wind fields to the fullest and to extend the range of wind speeds allowable for effective hovering operations. (Thus was born the powered balloon, POBAL, concept.)

The two flights of the AFCRL POBAL demonstration unit have been described in detail in the report and the results have been analyzed. (That demonstrator, which utilized a non-streamlined, unpressurized balloon, was judged to have no applicability to the SEEK STAR mission.)

The follow-on POBAL-S system study has also been discussed. The fact that the streamlined POBAL-S system design calls for a superpressure balloon (hull) necessitated our examination of superpressure theory, which disclosed that the POBAL-S balloon film would be subjected to higher tensile stress values than heretofore used in superpressure balloons. It was pointed out that a new material, biaxially oriented Nylon-6, has tentatively been selected for the POBAL-S application, depending on the results of forthcoming tests of small superpressure balloons made of this material. Possible launching difficulties with the POBAL-S design were also covered.

The discussion subsequently made note of the demise of POBAL-S as a full-scale Air Force development program and showed how the Navy adopted the POBAL-S basic concepts under its new HASPA program.

The HASPA goals, and the step-by-step approach to their realization, have been spelled out in the latter part of this report. From an analysis of the Navy approach, as well as from an extrapolation of much of the preceding analysis of the POBAL study, it has been concluded that the HASPA system bears close watching by and support from the Air Force as the most promising long-range candidate for the SEEK STAR communications relay application. (A three-year wait was foreseen as occurring before true feasibility could be established.)

In the remainder of the report we have covered briefly other types of free-flying balloons (ground-launched, air-launched, zero-pressure, superpressure) and the novel concept of an air-launched powered balloon. (The latter type of system was declared beyond the state of the art.)

Free-flying zero-pressure balloons (ground-launched) have emerged from our review as highly competitive and fairly low-cost LTA vehicles for the emergency gap-filler situation and for serial launch applications. (They require the availability of an inexpensive and expendable payload—communications relay—to be truly cost effective, and their use presupposes the availability of a suitable launch site on land or at sea, trained personnel, and favorable launching weather conditions.) Free-flying superpressure balloons (ground-launched) have also been shown useful in SEEK STAR applications, especially in the case of serial launches. Air-launched superpressure balloons have been declared operationally useful in concept but incapable of materialization at the present time.

From the above, it may be concluded that the powered superpressure balloon system, as embodied in the HASPA program, represents a very attractive long-term solution to the SEEK STAR LTA platform requirement. The HASPA program has technical uncertainties, however, which will take time to resolve. Thus, a cautious, but optimistic wait-and-see attitude towards HASPA seems called for. In the meantime, the techniques for fabricating, launching (from the ground), and controlling free-flying zero-pressure balloon systems are well established and reliability is very high. A system package (or packages) could be tailored rather quickly at AFCRL to fill the emergency gap-filler or serial launch role, using standard, off-the-shelf components, should the requirement be levied. In the author's opinion, operational use of the ground-launched, free-flying, zero-pressure balloon should be seriously considered by combat theater communications planning activities.

The ALBS appears to be the most attractive LTA developmental concept at this time. Along with its all-weather launch and remote-area deployment characteristics, both its minimum deployment response time and precise initial geographic positioning capabilities place it in a category by itself. Admittedly, its loiter, or on-station time, is a function of the prevailing winds at the float altitude. However, with the exception of the powered concept (HASPA), which appears to have several monumental development problems in its future, all LTA systems possess the same float-wind dependence. The serial launch proposal, as mentioned earlier, would be a more than adequate solution to this problem under the right meteorological conditions.

With the renewed interest in large superpressure balloon development, breakthroughs in the not too distant future are expected both in materials and in fabrication techniques, which could alleviate problems currently inhibiting the development of air-launched, free-flying, superpressure balloons. The addition of such a balloon to the ALBS, at the appropriate time, would further increase the attractiveness of the ALBS by adding extended duration to its projected list of highly desirable characteristics. Those features were discussed at length, and offer ample promise and justification for the continued pursuit of the present course of development (see section 4.2.2) and for aiming at a flight test of the ALBS system in 1976-1977.

Free-flying superpressure balloons would appear to provide the most attractive ground-launched platform for serial use. However, as opposed to its wealth of experience with zero-pressure balloons, the Air Force has not flown superpressure balloons in recent years, and, thus, a limited systems test and evaluation program at AFCRL would probably be required before an operational superpressure configuration could be recommended.

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