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AN INVESTIGATION OF TECHNIQUES FOR LAUNCHING LARGE BALLOON SYSTEMS FROM AIRCRAFT OR ROCKETS IN FLIGHT

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13. ABSTRACT

The requirements for placing a military payload (communications relay, electro-optical sensor, etc.) in the sky at short notice are identified. A demonstration aircraft-launched balloon system (ALBS) is proposed and the basic assumptions defined. The balloon size and mass of inflatant to be carried aloft are calculated. Compressed gas and cryogenic storage systems are compared. The weight of storage tank/lift ratio is used to demonstrate the superiority of cryogenic storage. The properties of liquid helium and liquid hydrogen are discussed with respect to safe long term storage. The heat needed to vaporize the cryogens and to warm the resultant inflation gases is calculated. Methods of generating and transferring the required heat at the time of inflation are described. The dynamic stresses expected at the time of balloon deployment are considered. The advantages of above-the-main-canopy method of balloon inflation are compared with those of the below-the-main-canopy mode. Deployment module sizes and gross weights are calculated for a range of possible operational payload sizes. Candidate aircraft and rocket transport vehicles are identified.

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Preface

This report considers, in varying degrees of depth, many of the design problems associated with an air-launched balloon system. The treatment is admittedly uneven, with heavy emphasis on the cryogenics problem. The text is replete with calculations which have been included so that others may verify or correct the many numerical values used. The author is particularly indebted to the many tables contained in Barron's "Cryogenic Systems" (see Bibliography) and to the WADD Compendium of Materials at Low Temperatures which served as the source for most of the cryogenic property values cited in the report. Grateful acknowledgement is made to Messrs Doherty, Payne and Kelly of the Aerospace Instrumentation Laboratory for their encouragement in this effort. Thanks are expressed also to Laboratory typists and to the personnel at Emmanuel College, particularly Mrs. Catherine Rice, who assisted in the preparation of this report. Figures 1 and 2 are based on figures originally prepared by the G. T. Schjeldahl Company and are used with their permission. Figure 4, which is extracted from a report prepared under a government contract, is based on a figure originally prepared by the Beech Aircraft Corporation.

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An Investigation Of Techniques For Launching Large Balloon Systems From Aircraft Or Rockets In Flight

1. INTRODUCTION

In the history of man-controlled flight, a rivalry has flourished between lighter-than air aerostatic systems and heavier-than-air aerodynamic systems. The memorable first ascents of the Montgolfier balloons (Paris, 1783) gave buoyant systems a head start of one hundred and twenty years. The equally memorable powered aircraft flights of the Wright brothers, at Kitty Hawk in 1903, ended the balloon's dominance and initiated the era of flight based on aerodynamic principles, i.e., lift generated by the propulsion of a solid body in an airstream. In the succeeding seventy years man's vastly expanded knowledge of aerodynamics has spawned a wide variety of powerful and extremely versatile aerospace vehicles. Despite this overwhelming competition aerostatic systems have survived as useful tools for a number of important scientific and social applications. They are popular today because they can provide lift inexpensively and are better able to carry large, awkwardly-shaped payloads to very high altitudes, maintaining them there for long periods of time.

Many well-known and highly successful military applications have been found for balloon systems over the years. Other envisioned military uses have been unable to be carried out, however, because of technical difficulties. One unfulfilled usage involves deploying a balloon-borne sensor or communications relay station

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at a remote, high-altitude location on short (i.e., a few minutes) notice. Although the basic requirement behind that application has been partially satisfied by the development of orbital and geo-stationary satellite systems, a need still exists for an expendable, relatively low cost sensor or relay platform which does not require the long lead times associated with putting new satellites on station.

Experience has established that the balloon is a capable high-altitude platform for the 200-1000 lb (90.8-454 kg) payloads in question. (Ground-launched balloons routinely carry loads of 10,000 lb (4536 kg.)) It has also made it clear that, when customary balloon launching techniques are used, the placing of a balloon platform at a particular location in space requires careful planning, several hours of flight preparations, favorable wind circulations and the availability of a strategically-located launch site. The envisioned application does not permit the customary approach, however, because of the need to have the balloon-borne sensor or relay on station within minutes of the decision to launch. This time constraint has led to a challenging concept; the development of a system which uses both the superior station-keeping properties of the balloon and the outstanding point-to-point transportation qualities of heavier-than-air vehicles. In such a system, a capsule containing the uninflated balloon, its gas supply and its payload is transported to the geographical area of interest in an aircraft or a rocket and is released in mid-air. Inflation of the balloon occurs automatically as the system slowly begins to drift earthward, supported by a parachute. The balloon and payload then rise to altitude and the inflation hardware descends to earth. The balloon maintains the payload on station for up to 24 hours, using ballast to minimize altitude excursions. Balloon drift will occur, of course, as a function of the existing wind field, a fact to be considered in estimating effective time on station.

In the late 1950's and early 1960's, Mr. James Payne of AFCRL (LCB) carried out some pioneering investigations of air launched balloon system techniques, directed at placing a balloon-borne transmitter in the eye of a hurricane.[1] He successfully inflated in mid-air balloons capable of supporting payloads of 15-50 lb (6.8-22.7 kg). His systems were launched from aircraft at speeds as high as Mach 0.9 (F100 aircraft) and at altitudes as high as 46,000 feet (14 km). Payne's work was used to a limited extent in the following decade, but growth potential, in terms of payloads which could be accommodated, was held down by the systems' inherently very heavy compressed-gas storage tanks.

In the past three years studies by Philco-Ford[2], the Schjeldahl Company[3], the MITRE Corporation[4, 5], General Electric Corporation[6], and by North American Rockwell[7] have addressed the subject of much larger air-launched balloon systems,

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[1] Payne, James C. (1960) Final Report on the Hurricane Positioning Device Feasibility Study, Project 7776, Task 67642, Air Force Cambridge Research Center Report.

making strong cases for their use in support of the objectives of the Advanced Ballistic Missile Defense Agency and as communications relay platforms for two Air Force applications: AWACS (Airborne Warning and Control Systems); and the Tactical Air Command battle area surveillance system. The referenced studies are, for the most part, conceptual in nature and cognizant of the large engineering advances needed to achieve operationally useful systems. They stress, however, the progress made in recent years in related technologies (e.g., Cryogenics, Balloon Materials) as evidence of the feasibility of developing large-scale air launched balloon systems.

In July 1972 T-666511, Air Launched Balloon Techniques, was established at AFCRL to investigate "new techniques for launching heavy balloon-borne military payloads from aircraft and rockets, with the ultimate goal of advancing the technology needed to develop successful systems". This report covers the first fifteen months of that task.

2. OUTLINE OF PROPOSED SYSTEMS

The generalized concept for an Air-Launched Balloon Systems (ALBS) has already been outlined briefly in the Introduction. Reference was made to a "capsule" containing the uninflated balloon, its gas supply and the payload, which would be transported by rocket or aircraft to the mid-air release point. That description was a simplified one. Actually the proposed system comprises six individual subsystems, each of which except for the payload, will be discussed in detail in the sections of the report indicated:

(1) The System Storage and Deployment Module (Section 3).

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2. PHILCO-FORD REPORT MSS-PS-005 (1970) Midcourse Surveillance System Study Program (Phase I), Vols. I, II, III (Philco-Ford, Autonetics Div., Newport Beach, CA).

3. G.T. Schjeldahl Company Report No. SER0137, (1972) Rocket Launched Balloon System Development Concepts and Requirements.

4. Bard, J.F. and Turner, C.R. (1971) Feasibility of An Air-Launched Balloon Communications System for AWACS MITRE Working Paper WP3598.

5. Wood, R.H. (1972) Candidate High-Altitude Airborne Relay Platforms (U) MITRE Technical Report MTR 2296.

6. G.E. REPORT Summary and Conclusions (SOD II) Final Report Vol. 1 (U); Balloon Borne Systems, Final Report Vol. 4 (U) (Contract DAH60-70-C-0076 for ABMDA).

   Note: 4 other vols. issued at same time; e.g. Surface Optical Defense Threat Definition (U) Sensor Requirements (U), Conceptual System (U), Terminal Optics Program Plan (U).

7. North American Rockwell (Autonetics Div) Report (1972) Optical Rocket-Launched Balloon (ORB) Feasibility Study Program Final Report, Contract No. DAH60-71-C-0073 (ABMDA).

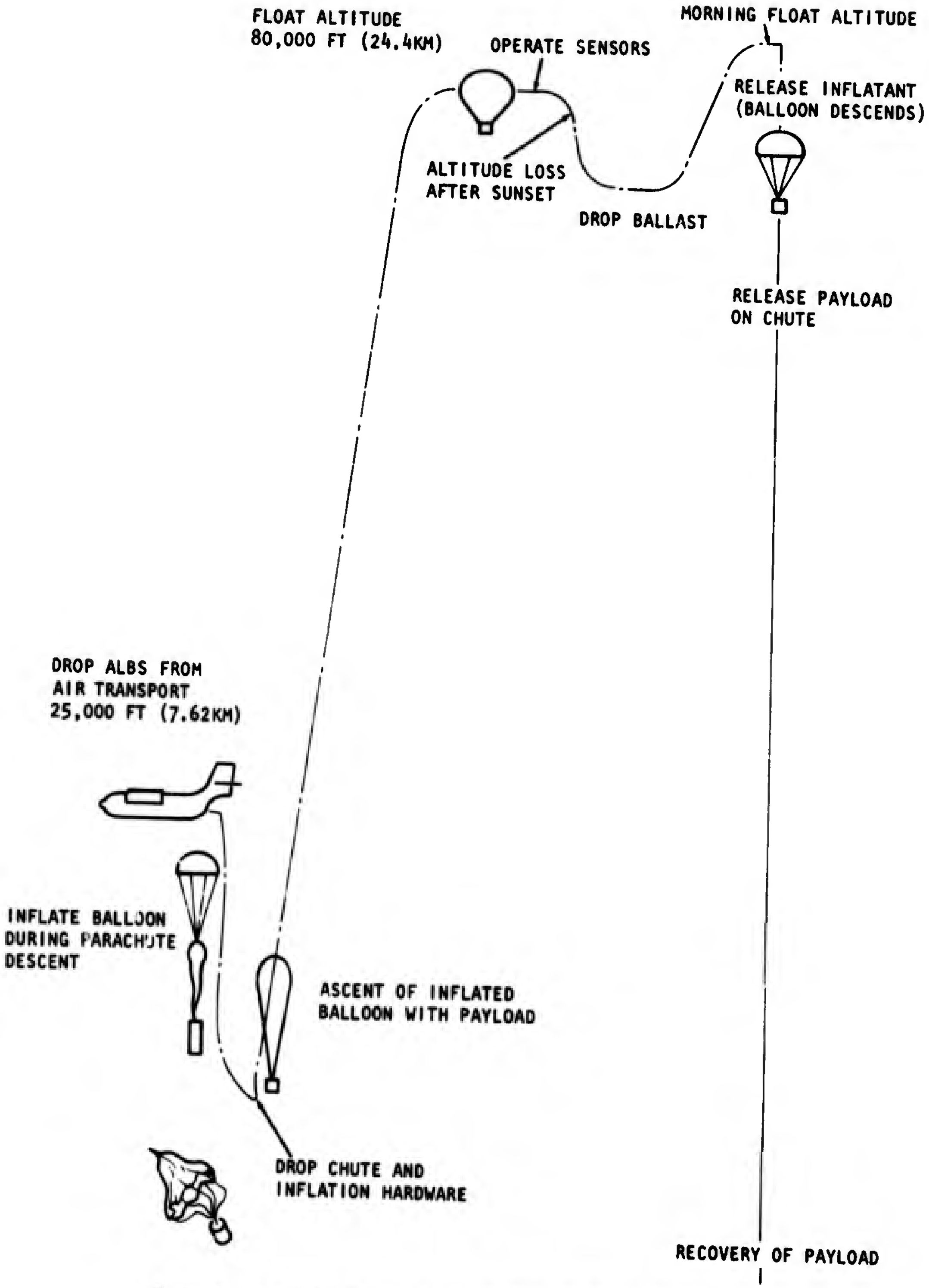
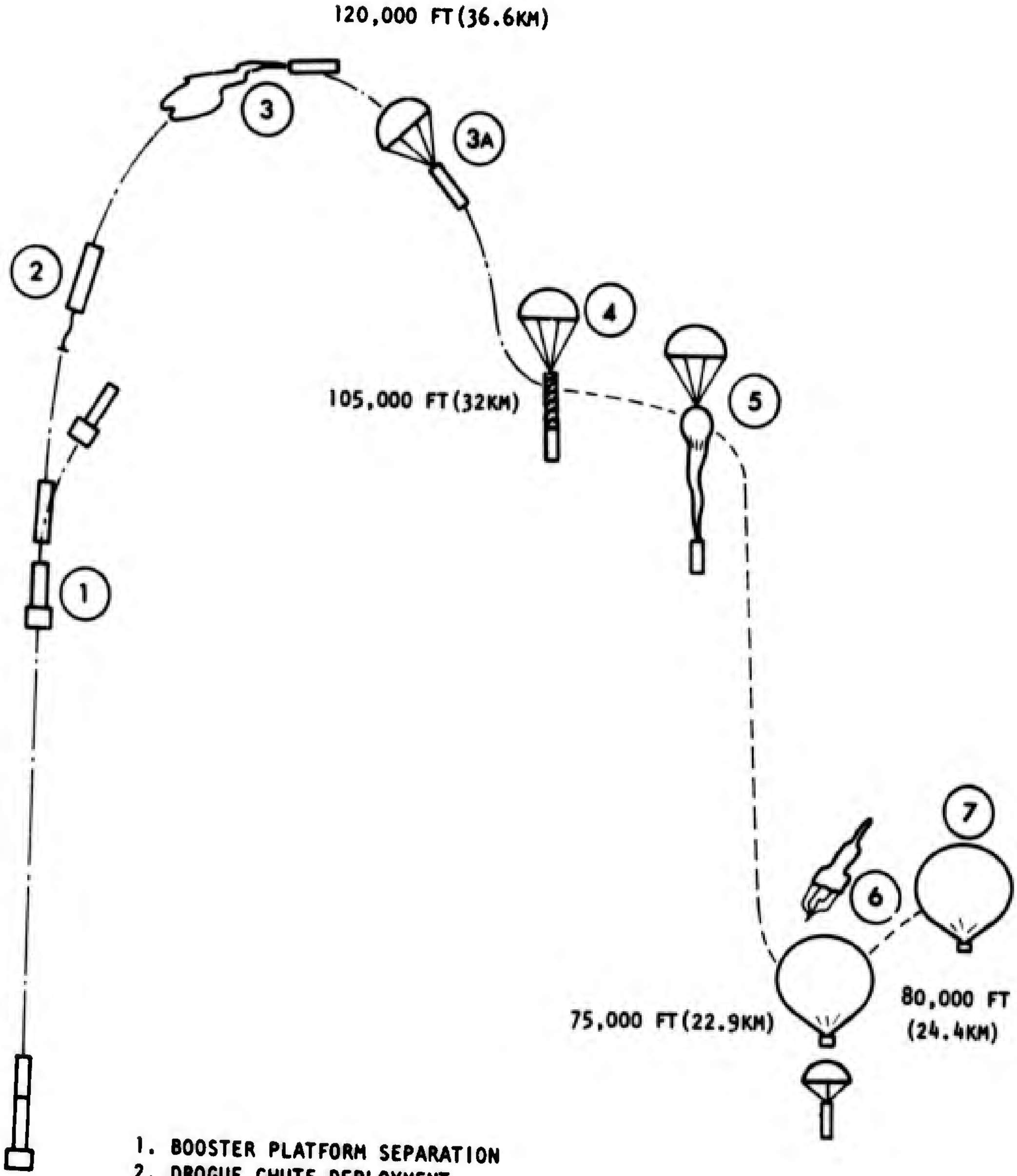


Figure 1. Flight Demonstration and Mission Profile Aircraft-Launched Balloon System



1. BOOSTER PLATFORM SEPARATION
2. DROGUE CHUTE DEPLOYMENT
3,3A. MAIN CHUTE DEPLOYMENT
4. BALLOON DEPLOYMENT
5. INITIATE INFLATION
6. INFLATION COMPLETE (INFLATION SYSTEM AND PARACHUTE SEPARATION)
7. PAYLOAD DEPLOYMENT

Figure 2. Rocket Launched Balloon System Deployment Sequence

(2) The Balloon (Section 4).

(3) The Gas Storage/Heat Transfer Subsystem (Sections 5 and 6).

(4) The Balloon Deployment Subsystem (Section 7).

(5) The Payload (See Note, below.)

(6) The Balloon Control and Telemetering Subsystem (Section 7).

> Note: The ALBS payload will be supplied by the using activity. The details of the payload are not needed for the purposes of this report, which covers only the balloon platform rather than the complete weapons system. It is assumed that the payload weight and size will be compatible with the dimensions selected in the ALBS design considerations.

Some candidate rocket and aircraft vehicles for the ALBS will be identified later (Section 8). They are not considered part of the ALBS even though they are prerequisites to its mid-air deployment. The choice of transport vehicle for a particular application of the ALBS depends on several factors, some of which are mission-oriented (reaction time, range from launch point to station location, time on station, mission importance vs relative cost), while others are related to the size and shape of the payload to be carried aloft. A discussion of the various factors will also appear later in this report.

3. THE SYSTEM STORAGE AND DEPLOYMENT MODULE

The System Storage and Deployment Module is the previously mentioned "capsule" under a more formal name. It consists of all the ALBS subsystems connected together in their pre-deployment state, so as to form an integral, easily-handled and easily-serviced unit. The resultant configuration must provide rigidity and protection commensurate with the conditions to be encountered before and at the time of deployment. It must also permit the sequential separation of the various subsystems as deployment and inflation occur. (Such a configuration is developed later in this report (Section 8) and is depicted in Figure 5.)

Figures 1 and 2 illustrate two air-launched concepts, using an aircraft and rocket, respectively, as the transport vehicles. From those figures (and also from Figure 7, which appears later in this report) several distinct deployment steps can be deduced:

(1) Separation of the deployment module from the transport vehicle.

(2) Deployment of the main parachute canopy.

(3) Deployment of the balloon.

(4) Inflation of the balloon.

(5) Separation of the main canopy and inflation subsystem from the balloon and payload.

(6) Descent of the inflation hardware to the ground.

(7) Ascent of the balloon and payload to float altitude.

(8) Descent of the payload for recovery, subsequent to termination of the mission. (Balloon is deflated but not recovered.)

The programmed, automatically-executed deployment and inflation process demands a high degree of sophistication in the design of the storage and deployment module. The collapsible items (parachutes, rigging lines, balloon, inflation tube, reefing sleeve, etc) must be packed so as to occupy the smallest possible volume and yet be capable of being deployed rapidly, safely, and smoothly at the proper moment. Separation devices must be in place at submodule interfaces to permit positive, instantaneous equipment breakaways to occur. The heavier items (payload, inflatant storage tanks, heaters, program control unit, etc) must be positioned in a manner which compromises neither aerodynamic stability nor functional effectiveness. (See also Para 8.5.)

From the above considerations, the most appealing geometrical shape for the storage and deployment module is that of a cylinder which, fortunately, is highly compatible with aerodynamic design practices. For rocket launches, for example, the cylinder is joined to the booster portion of the rocket and topped off by an appropriate nose cone. Externally, the cylinder can be just what the name implies - a separate tube which sheaths the various components of the module, or it can be formed from the outside surfaces of the joined submodules. The latter approach is favored because it scores more highly in the following areas:

(1) Economy of weight and materials.

(2) Design flexibility.

(3) Simplicity of internal component mounting arrangements.

An immediate ALBS packaging limitation is the maximum diameter which a candidate rocket vehicle can accommodate. The external diameter of the rocket is normally the limiting diameter for the module, although, in some cases, oversize "hammerhead" configurations can be considered. Another equally important constraint is the length of module which the rocket can accommodate without losing aerodynamic stability. Comparable limitations are present in the case of those aircraft launchings where the module is carried in a bomb-bay or under a wing in an aerodynamically shaped configuration.

The foregoing illustrates the constraints imposed on the ALBS by a particular rocket or aircraft. The converse is also true: When a particular module's irreducible minimum size exceeds the dimensions allowable for use with a specific rocket or aircraft, the designer must plan on the use of a larger launch vehicle. The gross weight of the module also affects the choice of the rocket or aircraft launch vehicle. Although today's inventory of operational rockets and aircraft includes vehicles of enormous capacity, there is a limit to the size which can be justified for the ALBS application. This is especially true of rockets which, unlike aircraft, cannot be amortized over many usages. For the purposes of this study, it will be assumed now that the ALBS module (with a 200-1,000 pound (90.8-454 kg) military payload) will have a maximum diameter and a gross weight compatible with the delivery capabilities of large already-developed sounding rockets or missile systems, and of aircraft such as the KC-135. Later in the study (Section 8) some weights and diameters will be matched with existing vehicles to check the validity of that assumption.

Thus far in our discussion of the ALBS Storage and Deployment module, we have examined, in a qualitative sense, the shape it should take and the function it should perform. It is time now to depart from abstract considerations and to arrive at some typical dimensions. In so doing we must recognize that the generalized ALBS concept actually covers a whole family of related but distinct systems with each member tailored for particular launching conditions and delivery modes as well as for a specific range of payload sizes. For example, the design of a rocket-launched ALBS, sent aloft from a land-based or a sea-based missile site and carrying a 250-pound (113.5 kg) net mission payload (See Para 4.1.1), can be expected to differ in some of its details from that of an ALBS with a 500-pound (227 kg) net mission payload deployed from an underwing pylon on a long-range surveillance aircraft. Although the dissimilarity in payload weights is apparent in this example, the resultant large differential in system gross weights (as will be developed in Section 8) is not so obvious at first. Moreover, there are subtle differences, such as those involving flight Mach No. and altitude density experienced by the two systems, at the time of release in mid-air. These less obvious conditions also breed diversity in design detail. Thus, there is no one universally acceptable ALBS configuration.

In this report some preliminary design concepts will be developed for a demonstration prototype version of the ALBS, with a net mission payload weight on the low side of the scale, 200 pounds (90.8 kg). The prototype will be launched through the rear door of a cargo aircraft, with a small chute as the extracting device. The methods used to arrive at those design concepts will be described here and should apply, in general, to other ALBS situations even though the payload weight and/or launching mode may differ.

> Note: In selecting a simple cargo drop (cf Figure 1) as our initial deployment method we have considerably reduced the criticality of the module's shape, so that blunt surfaces and other drag-producing features can be tolerated. Our chief concern now is that the interior clearance dimensions of the cargo aircraft are not exceeded and that the descending array achieves required stability. The generous dimensions of most cargo aircraft (e.g., C-130, C-141) allow considerable freedom in that respect. This simplified launching approach bypasses some of the more difficult

packaging problems associated with an operational system, but it has the virtue of allowing greater concentration initially on the very complex gas storage and heat exchange problem. Aerodynamic refinements can be developed in subsequent studies once the basic feasibility of the ALBS is demonstrated through the air drops of the prototype system.

4. THE BALLOON

4.1 Weight Definitions

An important initial step in establishing the configuration of the selected ALBS is to determine the size of the balloon needed. To do that we must first estimate the system buoyant weight. Before proceeding along that line, however, three definitions will be presented to clarify weights mentioned in the discussion.

4.1.1 NET MISSION PAYLOAD WEIGHT

The Net Mission Payload Weight is the weight of the military payload, (sensor, communications relay station, etc, including its own power supply) which is supported aloft by the balloon. This is the starting point for system sizing calculations.

4.1.2 SYSTEM BUOYANT WEIGHT

The System Buoyant Weight is the weight of that portion of the ALBS which ascends to, and is maintained at, the specified float altitude. This would normally include the balloon, the payload, the ballast system, telemetry and flight control instrumentation and recovery parachutes. This weight determines both balloon size and inflation gas requirements. Excluded from the System Buoyant Weight are the gas itself and the gas storage tanks, heat exchangers and other hardware used for inflation purposes, which are jettisoned upon completion of the inflation operation and descend on their own parachute.

4.1.3 GROSS SYSTEM WEIGHT

Gross System Weight is the weight of the System Storage and Deployment Module. It includes all the components released as a unit in mid-air from the transporting rocket or aircraft vehicle. This weight is needed to identify the transport vehicle and to size the system decelerators used at the time of release. The weight of the stored inflation gas is included in the Gross System Weight.

4.2 Determination of System Buoyant Weight

Determining the system buoyant weight and the balloon size is somewhat of a cut-and-try proposition.

4.2.1 SUMMARY OF ITEMS, LESS BALLOON

Staring with a net mission payload weight of 200 pounds, we add the estimated weights of hardware items required at float altitude by the mission, exclusive of the balloon itself:

	English Units	Metric Units
Net mission payload	200 lb	90.8 kg
Ballast (for altitude maintenance)	60 lb	27.2 kg
Reefing sleeve (for balloon protection)	10 lb	4.5 kg
Recovery chute (end of mission)	25 lb	11.4 kg
TM, Command/Control/Tracking equipment	50 lb	22.7 kg
	345 lb	156.6 kg

4.2.2 ADDITION OF ESTIMATED BALLOON WEIGHT

The 345 lb (156.6 kg) is the estimated weight which the balloon must lift. To this must be added the estimated weight of the balloon itself. For this discussion, a preliminary figure of 230 lb (104 kg) is selected, a weight which includes the basic envelope, the load tapes, end fittings and ducts. (See also Para 4.3.1.) Thus, the total system buoyant weight (estimated) is 345 + 230 or 575 lb (261 kg).

> Note: The balloon whose size we seek to establish here is a natural shape, zero pressure balloon. Superpressure balloons are not considered practical for the ALBS mission because of design and manufacturing problems related to temperature-induced excursions in the balloon's internal pressure during flight.

4.3 Determining the Balloon's Volume

Because inflation gases expand with altitude, the volumetric capacity of the balloon must be sufficiently large to accommodate the number of cubic feet of expanded Helium or Hydrogen required to support the buoyant system weight at the mission flight level:

4.3.1 HELIUM VOLUME

The volume of Helium required in this case, 242,000 ft^3 ($6.86 \times 10^3 m^3$), is obtained by dividing 575 lb by $2.38 \times 10^{-3} lb/ft^3$ ($0.038 kg/m^3$) which is the specific lift (see Appendix A) of Helium at 80,000 ft (24.4 km). The 242,000 ft^3 is a "first cut" value, subject to change, depending on such factors as balloon material actually employed, the need for special end fittings, etc. (The effect of those factors is to increase or decrease balloon weight, and concomitantly, the system buoyant weight. Actually, an iterative computer program is employed to determine exact balloon weight, taking into account the float altitude, payload weight, required strength and other factors.) For our purposes an arbitrary value of 250,000 ft^3

($7.1 \times 10^3 m^3$) will be used in sizing the balloon. This augmented volume permits the addition of enough Helium to support an extra 19 lb (8.6 kg) of system buoyant weight at the specified float altitude, if required. (Alternatively, for the same system buoyant weight, the larger volume will raise the balloon's float altitude by about 700 ft (213m).)

4.3.2 HYDROGEN VOLUME

For inflation with Hydrogen, the "first cut" volume is less, 224,000 ft^3 (242,000 $ft^3 \times 1/1.08$ = 224,000 ft^3 ($6.35 \times 10^3 m^3$)). (See Appendix A.) This means that a smaller balloon could be employed to support the 575 lb or, if the 250,000 ft^3 balloon is used, the capacity for extra buyoant system weight or higher-altitude flight is increased.

> Note: Helium and Hydrogen are the only inflation gases given serious consideration in this study. Other possible candidates, such as Methane, Ammonia, and hot air, have much lower specific lifts and require such large balloons as to be impractical.

4.3.3 BALLOON MATERIAL

The 230-pound (104 kg) balloon weight used above to estimate system buoyant weight is compatible with the selected balloon volume (250,000 ft^3) and is predicated on the use of 1.5 mil (0.0015 in., 0.038 mm) polyethylene material. Thinner gauge (1 mil (0.0254 mm)) polyethylene and other light weight materials, such as bilaminated polyesters and scrim-backed mylars, are also possible candidates for this application. In an actual system design the choice of balloon material is a critical one requiring a more detailed evaluation of stresses involved than is possible here. For that reason, no specific recommendation will be made in this study with respect to balloon material for the ALBS. From a cost standpoint, polyethylene deserves primary consideration, being an order of magnitude less expensive than scrim-backed materials. The heavier gauge of polyethylene (1.5 mil) seems indicated to withstand the severe dynamic forces of the mid-air inflation. (See Para 7.2.6(d).) At the same time, flexibility at the low temperatures found at 80,000 ft (24.4 km) must also be a guaranteed property of the balloon film chosen. (See Para 6.11.1.)

4.4 Determining the Mass of Gas Required

The volume calculations above enabled us to identify the size of balloon needed, and, also, to verify our system buoyant weight estimate. Knowing the latter value, it is now possible to determine the mass of gas which must be carried aloft in the ALBS storage tank, to inflate the balloon in mid-air. A simple way of calculating this is to use the lift of gas/mass of gas (Lgas/Mgas) ratios for He and for H_2.

4.4.1 LGAS/MGAS RATIOS

The Lgas/Mgas ratios are derived as follows (using the standard conditions values of Appendix A):

$$\frac{\text{Specific Lift}}{\text{density}} = \frac{\text{lb lift/ft}^3}{(\text{lb gas/ft}^3)} = \frac{\text{lb lift}}{\text{lb gas}} = \frac{\text{Lift of gas (in lb)}}{\text{Mass of gas (in lb)}}$$

(a) <u>for Helium (100% purity)</u>

$$= \frac{0.06595}{0.01056} = 6.25 \text{ lb/lb} = \frac{1.056 \text{ kg/m}^3}{0.169 \text{ kg/m}^3} = 6.25 \text{ kg/kg}$$

(b) <u>for Hydrogen (100% purity)</u>

$$= \frac{0.07119}{0.00532} = 13.5 \text{ lb/lb} = \frac{1.14 \text{ kg/m}^3}{0.085 \text{kg/m}^3} = 13.5 \text{ kg/kg}$$

4.4.2 MASS OF INFLATANT REQUIRED, INCLUDING FREE LIFT ALLOWANCE

Note that the Lgas/Mgas ratios are independent of volume and altitude. They refer only to the mass of gas involved, irrespective of the volume it occupies. Using a system buoyant weight of 575 lb (261 kg), the masses of Helium or Hydrogen required for lift are, respectively,

$\frac{575}{6.25}$ = 92 lb (41.7 kg); or $\frac{575}{13.5}$ = 42.6 lb (19.3 kg). These masses of inflatant must now be increased by approximately 10 percent, the customary "free lift" allowance to provide the unbalanced buoyant force which makes the balloon rise to float altitude. (See Appendix A.) If the increase is exactly 10 percent, the new value of He mass is 101.2 lb and that for H_2 is 46.86 lb. However, for discussion purposes we will use the convenient values of 100 lb (He) and 47 lb (H_2). (The corresponding metric values are 45.36 kg and 21.2 kg.)

4.4.3 LIFT AS A FUNCTION OF MASS OF INFLATANT

Since there is no change in mass with a change in state between the gaseous and liquefied forms, the above Lgas/Mgas ratios apply also for liquefied H_2 and He. Thus, it is immaterial whether we are discussing pounds (kg) of gas or pounds (kg) of liquid (as in cryogenic storage) when we specify mass required for lift. The lift obtainable from the liquefied inflatant is potential lift, of course, until the gaseous state is achieved. However, the important point in this discussion is that the amount of lift (real or potential) is a function of the mass of the Helium or Hydrogen present in whatever form.

4.4.4 HYDROGEN'S DECEPTIVE ADVANTAGE

At first glance, Hydrogen's high Lgas/Mgas ratio, approximately twice that of Helium, seems to give it a decided advantage as a lifting gas candidate for the ALBS. The high ratio translates immediately into a better than 50 percent lower mass of inflatant for the ALBS, when H_2 is employed (47 lb (21.2 kg) for H_2 vs 100 lb (45.36 kg) for He). The H_2 mass advantage is deceptive, however. Because the mass of the inflation gas is not included in the system buoyant weight computation, the reduced mass of H_2 does not cut 53 lb, or 24.2 kg (100-47 lb; 45.36-21.2 kg) from the system buoyant weight. The H_2 influence on that weight is more subtle and centers about the minor weight savings realizable through the use of a somewhat smaller balloon in a Hydrogen inflation system. (224,000 ft^3 vs 242,000 ft^3. See Para 4.3.2.) The main effects of the smaller mass of Hydrogen are observed in the gas storage and heat transfer subsystem (whose weight is included only in the gross system weight).

5. GAS STORAGE

5.1 The Need for High-Density Storage

It has been established that an ALBS with a 200-pound (90.8 kg) net mission payload has an estimated system buoyant weight of 575 lb (261 kg) and that the mass of He or H_2 (whichever is selected) required to lift that weight to float altitude is 100 lb (45.36 kg) or 47 lb (21.2 kg), respectively. The discussion will now be directed to methods for storing the specified mass of inflatant in the ALBS module for use during the mid-air balloon inflation process. At the outset, low-density storage will be eliminated as impractical. The alternate choice, high-density storage, implies compression or liquefaction of the gas. (A third possibility exists in the case of Hydrogen in which the element is bound chemically as a hydride. That method has been investigated separately by W. H. Barber of the Naval Ordnance Center, Indian Head, Md.[8] and, because of low yields experienced to date, is not considered suitable for the ALBS application at the present time or for some time to come.)

5.2 Compressed Gas Systems

Compressed gas systems have been successfully and universally employed for many years for many different applications. The pioneer ALBS of Payne, mentioned in the Introduction, used such storage. The chief problem with compressed gas tanks is their weight, which is due to the heavy-walled construction required for withstanding high internal gas pressures. Figures developed in the course of Payne's investigation showed that a Helium cylinder stressed for 3000 lb in.$^{-2}$ abs. (204 atm, 2.06×10^7 N/m^2), and providing a nominal 100 lb (45.36 kg) of lift, weighs approximately 250 lb (114 kg) (dry weight). A linear extrapolation of those figures indicates that the ALBS would require seven such tanks: 575 lb + 10 per cent free lift = 632 lb (287 kg), 632/100 = 6.32 ≈ 7. Thus, the weight of the storage system would be 250 lb x 7 or 1750 lb (795 kg). This results in a Weight of Storage Tank to Lift Ratio (W_{st}/L) of 1750/632 or 2.78, which leads to excessive gross system weights for the ALBS. (See Para 8.3 for a discussion of gross weight calculations.) In practice, a smaller tank weight, say 1500 lb (681 kg), seems more realistic since the W_{st}/L ratio normally improves with increased lift. (This is based on the hypothesis that a small number of relatively large compressed gas tanks would be employed in the ALBS system, as opposed to a simple multiple of the 100-lb (45.36 kg) (lift capacity) units used in the extrapolation.) Even the ratio based on the 1500 lb (681 kg) tank weight, 2.38, is too high, however, and effectively eliminates compressed gas systems from further consideration for the ALBS. This leaves us with cryogenic storage as the only viable alternative.

5.3 Cryogenic Storage System Properties

5.3.1 A CLARIFICATION OF TERMS

In discussing cryogenic storage systems, the term "gas storage" is somewhat inaccurate since the substance being stored is actually a liquid (liquefied H_2 or He). This should not pose a problem, if we think of the liquid as a temporary change of state for the gas. Actually, there is not a one-to-one correspondence between compressed gas and cryogenic storage systems, since the cryogenic systems require additional components, namely a heat source and a heat exchanger, to vaporize the stored liquid and to warm the resultant gas to ambient temperature. Consequently, the term "Gas Storage and Heat Transfer Subsystem" seems more appropriate to cryogenic systems. A subsystem bearing that name is actually called out in Section 2 of this report, Outline of Proposed System. For discussion purposes, however, a finer breakdown is desirable and, accordingly, the gas storage and heat transfer units will be covered in detail in separate sections, a treatment that gives each unit of the subsystem due consideration, without lessening the interdependence of one upon the other.

5.3.2 INDUSTRIAL ESTIMATES OF TANK WEIGHTS

Industry sources have reviewed the ALBS requirements and have estimated the combined gas storage and heat transfer subsystem weight at about 350 lb

(159 kg), including the weight of the Cryogen. This gives the Cryogen approach a markedly superior W_{st}/L ratio (350/632 = 0.55) vs the 2.38 ratio for compressed gas, and is the primary reason for selecting the cryogenic storage medium.

> Note: The 0.55 W_{st}/L ratio is based on the direct mixing gas generator (See Para 6.7.2) and is probably conservative for that approach. Even lower ratios (0.4, for example) appear possible with some engineering effort. If the two-fluid heat exchanger is used (See Para 6.7.1, a somewhat higher W_{st}/L ratio is involved: e.g., 450/632 = 0.71, or even 530/632 = 0.84. (450 lb = 204 kg; 530 lb = 240 kg.)

5.3.3 CRYOGENIC TEMPERATURES

In giving preference to cryogenic storage, we are entering the regime of very low temperatures, since both liquid Helium (LHe) and liquid Hydrogen (LH_2) have boiling points near the bottom of the absolute temperature scale. Table 1 shows the densities and boiling points of LHe and LH_2 and also the calculated cryogenic storage tank volumes for the previously determined masses of the two inflatants.

> Note: In this report all mention of liquid Helium will refer to the normal liquid phase, Liquid Helium I. There will be no condition in the proposed ALBS application where the superfluid, Liquid Helium II, will become involved. The superfluid is present only under reduced pressure conditions (0.0497 atm) (5.02×10^3 N/m^2) and at a temperature of 3.91°R (2.18°K).

5.3.4 LHe AND LH_2 COMPARISON

Table 1 reveals two interesting points of comparison between LHe and LH_2.

5.3.4.1 Mass/Volume Relationships

Although the mass of LH_2 (including approximately 10 percent free lift) required to lift 575 lb (261 kg) is less than half that of LHe (47 lb (21.2 kg) vs 100 lb (45.36 kg)), and leads to an immediate reduction of 53 lb (24.2 kg) in the LH_2 system gross weight, the volumes of the two liquids are nearly equal. (The LH_2 volume (10.6 ft^3, 0.296 m^3) is approximately 5/6 of the LHe volume (12.8 ft^3 0.358m^3). This is a manifestation of the low density of LH_2 (less than that of any other liquid) and makes the savings in tank size and empty tank weight considerably smaller, when LH_2 is used, than one might expect from examining the relative masses of Cryogen involved. The savings are important, nonetheless, when overall weight and cost budgets are developed.

5.3.4.2 Expansion Ratios

The Expansion Ratios (ER's) of both liquids are quite high, 739 and 833, as is typical of most cryogenic fluids. The Expansion Ratio gives the number of cubic feet of gas, measured under Standard Day conditions (59°F = 519°R = 288°K = 15°C and 29.92 in. Hg = 1 atm = 1.01×10^5 N/m^2) yielded by one cubic foot of the

Table 1. Various Cryogen Properties of the LHe and the LH_2, plus Calculated Volumes for the ALBS (See Table C-1 for a more complete listing of cryogenic Properties)

Item	Liquid Helium (LHe)	Liquid Hydrogen (LH_2)
1. Normal Boiling Point (n. b. p.) (at 1 atmosphere) (1 Atm = $1.01 \times 10^5 N/m^2$)	7.57°R(4.2°K)$^{a, b}$	36.7°R(20.4°K) (para - or equilibrium hydrogen)
2. Density, at n. b. p., (lb/ft^3) (1 lb/ft^3 = 1.6×10^{-2} g/cm^3)	7.8 (0.125g/cm^3)	4.43 (0.071g/cm^3)
3. Mass of Cryogen, M, required for ALBS (lb)	100$^{c, j}$ (45.36 kg)	47^{c} (21.2 kg)
4. Tank Volume, w/o ullage (ft^3) (Tank Volume = liquid cryogen volume at n. b. p.)	12.8$^{d, k}$ (0.363 m^3)	10.6^{d} (0.296 m^3)
5. Tank Volume, with 10 percent ullage (ft^3)	14.1 (0.395m^3)	11.7 (0.328m^3)
6. Tank Volume, w/o ullage (U.S. gallons)(See notes e-i)	96	79.2
7. Tank Volume with 10 percent ullage (U.S. gallons)	105.5	87.5
8. Expansion Ratio (See Appendix B)	739	833

Notes:

a. 0°R = -459.67°F = 0°K = -273.15°C; 0°C = 32°F = 491.67°R= 273.15°K

b. Value given is for LHe_4, the most common form of LHe

c. The mass is that previously determined for an ALBS with a net mission payload of 200 lb (90.8 kg), and a system buoyant weight of 575 lb (261 kg), plus approximately 10 percent free lift. (See Para 4.4.2)

d. Item 4 was obtained by dividing item 3 by item 2

e. 1 U.S. gallon = 0.1337 ft^3; 1 ft^3 = 7.48 U.S. gallons

f. 1 lb LHe = 0.959 gal.

g. 1 lb LH_2 = 1.693 gal.

h. 1 gal. LHe yields 93.56 ft^3 He (gas, STP)

i. 1 gal. LH_2 yields 105.2 ft^3 H_2 (gas, STP)

j. 1 lb = 0.4536 kg

k. 1 ft^3 = 2.832×10^{-2}m^3

liquid. The significance of the expansion ratio, which is obtained here by dividing the liquid density (at n.b.p.) by the Standard Day gas density, is twofold.

First, it is a measure of the efficiency of the storage system. A high ER means that extremely compact storage has been achieved. The ER's for LH_2 and LHe which are stored under relatively low pressure, usually less than 100 lb in.$^{-2}$ (6.8 atm; $6.87 \times 10^5 N/m^2$), exceed by a factor of almost two the ER's for their gaseous phases stored at 6000 lb in.$^{-2}$ (408 atm, $4.12 \times 10^7 N/m^2$), and by a factor of better than four the ER's of gases at 2400 lb (163 atm, $1.65 \times 10^7 N/m^2$). See Appendix B. This expansion ratio superiority of cryogenic liquids is but another illustration of the better Wst/L ratios obtained with such systems, vis-a-vis compressed gas storage.

Second, The Expansion Ratio is also a measure of the cryogenic fluid's ability to exert tremendous internal pressures within its tank if the liquid phase should undergo conversion to the gaseous phase, followed by a rise in gas temperature to room temperature. This is an important safety consideration. If pressure relief is not provided, tank rupture will surely occur, since unlike compressed gas systems, cryogenic storage tanks are not designed for high internal gas pressures. Assuming that normal pressure relief venting takes place, the ER also gives an indication of the amount of air which will be displaced in a closed room, per unit volume of cryogenic fluid vented. This is another major safety item, if asphyxiation and/or an explosion is to be avoided. Thus, cryogenic systems, particularly when explosive gases are involved, require careful consideration of pressure buildup possibilities and associated venting provisions, both during the design phases and in establishing operating procedures for personnel working with the systems. Hydrogen vapor is flammable with air over the range of 4 to 74 percent by volume. Vented H_2 vapor obviously represents a formidable hazard.

5.4 Cryogenic Storage Tank Considerations

5.4.1 THE HEAT FLUX PROBLEM

5.4.1.1 The Rise in Temperature and Pressure within the Tank

Cryogenic techniques permit extremely compact storage, as has been shown, but there is an economic penalty involved -- the cost of fighting heat flux, which is the enemy of low temperature maintenance. Powerful thermal gradients exist between stored cryogens and the temperature of the air outside the tank. If, for example, LHe is the cryogen stored in the ALBS tank, and it is just below its boiling point, 7.57°R (4.2°K), there is a differential of 511°R (284°K) between the LHe and the outside air at 59°F (519°R; 288°K). The temperature differential is the driving force behind a steady, inexorable transfer of heat (BTU's/hr) through the tank wall to the LHe. If normal methods are used to insulate the tank, that is, there is no supplemental refrigeration, the LHe will eventually acquire the heat needed for boiling. As the fluid starts to boil, the resultant vapor occupies the tank's ullage space above the liquid. If the heat input continues, the temperature, liquid volume and vapor pressure will steadily increase, with boiling continuing at elevated boiling point temperatures. If the critical temperature of the Cryogen is reached, the liquid phase will change over to the all-gas phase, without further temperature change. Further heating then acts to raise the temperature (and pressure of the gas.

5.4.1.2 Venting and Loss of Mass

Because cryogen storage systems are designed for relatively low working pressures, the increase in internal system pressure cannot go on indefinitely. Somewhere along the line venting must be employed to keep system pressures at an acceptable level. Unfortunately, such relief venting necessitates a loss of Cryogen mass and leads to eventual depletion of the inflatant in storage. The actual relief pressure depends on the materials used in the tank construction and on the cryogenic properties of the inflatants being stored. Appendix C covers the various considerations in extensive detail.

5.4.1.3 Safety Aspects of Venting

Ideally, venting of the ALBS tanks should be avoided altogether, with venting provisions in existence only for emergencies. The primary reason for this restriction is the aforementioned loss of mass, which adversely affects the mission capabilities of the ALBS. In the case of LH_2, an equally important reason for avoiding venting is the potential hazard created by the escaping vapors. In some situations the H_2 gas safety aspects will be of overriding importance. The objective, then, is to employ tank insulation methods which reduce the inward heat flux to the point where the system heat gain is insufficient to necessitate venting.

5.4.2 CRYOGENIC INSULATION

5.4.2.1 Normal Methods

Cryogenic specialists have developed multi-layered reflective insulation and vacuum jackets which can be employed on the ALBS to reduce the amount of radiation and conduction heat flux per unit time. (Convective heat transfer is not involved.) Relatively small heat fluxes, of the magnitude shown in Appendix C (Table C-2, Item 16) are within the state-of-the-art when such insulation is employed.

5.4.2.2 Cryogenic Liquid and Vapor Shields

Additional refinements, such as liquid Nitrogen (LN_2) shields and vapor cooling (in which vented Cryogen vapor passes around the inner tank and cools it) reduce the driving force and the heat flux even more, but at added cost. With these arrangements, the thermal gradient, or driving force, is the difference between the temperature of the Cryogen in storage and that of the cold vapor or liquid placed between the storage tank and the ambient air. If LN_2 is the coolant (n.b.p = 139.2°R or 77.3°K), and if LHe is the Cryogen in storage, the gradient is approximately 132°R (73.1°K) (vs the 511°R calculated in Para 5.4.1.1 for storage where a cold barrier is not inserted between the storage tank and the ambient atmosphere.) Shielding and vapor cooling require more complicated and more expensive storage tanks and controls. In addition, they require a source of coolant which must be expended. With vapor cooling the source is frequently the Cryogen in storage, an arrangement which guarantees a certain loss of mass.

5.4.2.3 Supplemental Refrigeration

The flux can effectively be reduced to zero with proper insulation and the addition of a refrigeration circuit, internal or external to the storage tank, in which freshly-cooled circulating liquid Helium draws off any heat absorbed by the fluid in storage. This represents an even greater investment because it requires not only the cooling coils, valves and thermostats, but also, the presence of a Helium refrigeration unit.

> Note: In insulating the cryogenic tank, special consideration must be given to the sometimes gross heat gains (by conduction) through pipes, supports, and so on, which penetrate the insulation. A full discussion of this and other storage tank insulation and refrigeration problems is beyond the scope of this report. There are standard texts on the subject. Suffice it to say that there are methods commercially available which will permit almost indefinite preservation of the liquid Cryogen in storage, if one is willing to pay the price.

5.4.2.4 ALBS Readiness Considerations

It is important that a weapons support system be ready to operate at very short notice rather than require extensive preparation at the time of use. The ALBS concept is one of quick reaction which implies that the inflation gas storage system is always in a ready-to-launch state. Using normal insulation methods, i.e., no shielding or refrigeration, it seems impossible to store liquid inflatants for more than two to three weeks without venting, a situation which would mean frequent changing and recharging of the cryogenic storage submodule during prolonged stand-by periods. The addition of a plug-in refrigeration unit seems highly desirable, therefore, to provide a constant, easily-maintained stand-by readiness. The refrigeration unit would not be part of the ALBS capsule, that is, it would not be transported to the mid-air deployment site. It would be ground support equipment, and would probably cost $50,000 to $75,000 per unit. To employ such a unit or not is an operational decision which present day technology can accommodate very well through modification of existing Helium refrigerators. For the purposes of the ALBS demonstration, however, long range storage will not be a requirement, and no refrigeration unit will be employed.

5.4.2.5 En-route Insulation

It will be assumed that the insulation normally used with high-quality cryogenic storage tanks affords ample protection to the ALBS during the time it is in flight (via rocket or aircraft) to its release point. The heat flux which penetrates to the storage tank during the minutes or few hours involved will be deemed inconsequential, based on known insulation efficiencies.

5.4.3 CRYOGENIC TANK DIMENSIONS

5.4.3.1 Cylindrical vs Spherical Shapes

Figures 3 and 4, reproduced from the North American Autonetics ORB report (Ref. 7, Page 116, 118), illustrate LH_2 cryogenic tank schemes applicable to the ALBS. (Note the internal refrigeration coil in Figure 3). The dry weight of the tank in Figure 3 is 152 lb (69 kg). It is designed to carry 104 lb (47.2 kg) of LH_2, with 3 percent ullage. Its length is 4.3 ft (1.31 m) and its diameter is 40 in. (1.02 m). Since the demonstration ALBS system covered in this report uses less than half the mass of LH_2 specified in the ORB system, a smaller tank will suffice. The general configuration will be the same, however. Theoretically, a spherical tank such as in Figure 4, is a more efficient cryogenic storage medium in that the surface area/volume ratio is less. The cylindrical shape, with domed ends, is more suitable to the ALBS module configuration, however, and that consideration outweighs the slight loss in storage efficiency.

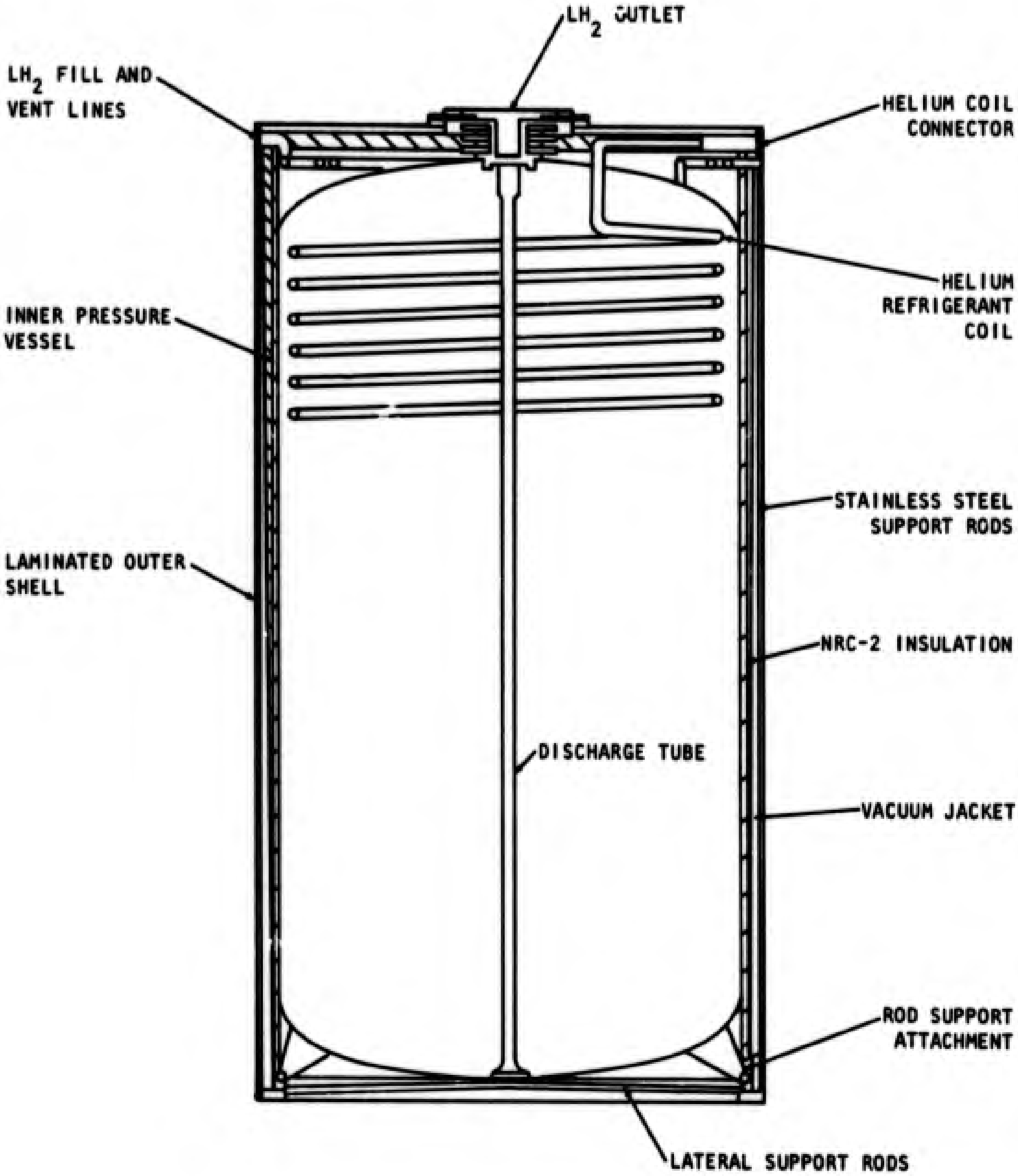


Figure 3. Liquid Hydrogen Tank

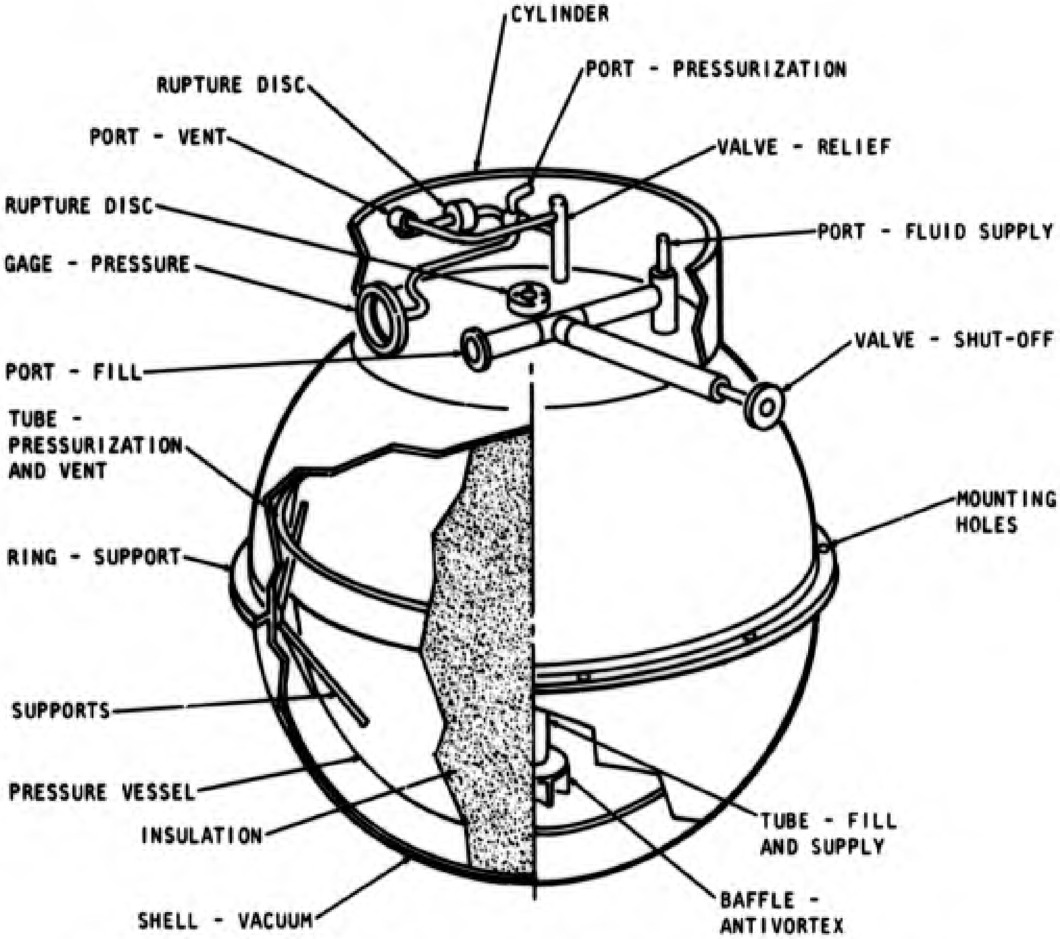


Figure 4. Liquid Hydrogen Cryogen Tank - Alternate Configuration

5.4.3.2 Sizing the Demonstration Unit Tank

The following calculation shows the approximate size of the demonstration ALBS LHe tank, assuming a cylindrical shape, with hemispherical ends (See Figure 8 for an illustration of this configuration.)

$$\text{Volume of tank} = 14.1 \text{ ft}^3 \ (0.395 \text{ m}^3) = \frac{\pi}{4} d^2 \times h + \frac{\pi}{6} d^3$$

where $\frac{\pi}{4} d^2 \times h$ = volume of the cylindrical section

and $\frac{\pi}{6} d^3$ = volume of the two hemispheres (taken as a whole sphere)

d = diameter of the cylinder and sphere

h = length of the cylindrical section

If we choose $d = 30 \text{ in.} = 2.5 \text{ ft} = \frac{5}{2} \text{ ft} \ (0.762 \text{ m})$

$$V = 14.1 = \frac{\pi}{4} \frac{(25)}{(4)} h + \frac{\pi}{6} \frac{(125)}{(8)} \quad \text{and}$$

$$h = (14.1 - \frac{125\pi}{48}) \times \frac{16}{25\pi}$$

$$= 1.2 \text{ ft} \ (0.366 \text{ m})$$

Using 14.1 ft^3 (0.395 m^3) as our internal volume, the internal diameter of the tank is 2.5 ft (0.762 m) and the internal length of the tank is 2.5 ft + 1.2 ft (0.366 m) = 44.4 in. = 1.13 m.

Adding 4 in. to the internal diameter and length to compensate for the inner tank wall thickness, the insulated vacuum space and the outer tank wall thickness, we obtain the following outside dimensions of the ALBS storage tank for LHe:

diameter = 30 in. + 4 in. = 34 in. (0.862 m)

length = 44.4 in. + 4 in. = 48.4 in. (1.23 m)

This is still smaller than the LH_2 tank shown in Figure 3. The 30 in. (0.762 m) diameter was chosen arbitrarily for the sake of illustration. It was also chosen on the low side with the thought of minimizing cross section at the expense of length. Actually, with the volume in question, 14.1 ft^3, a spherical tank is really not that much larger in cross section:

$$V = \frac{\pi}{6} d^3 \; ; \; d = \sqrt[3]{\frac{6V}{\pi}} = 2.99 \text{ ft} \cong 36 \text{ in. } (0.914 \text{ m}) \text{(internal diameter).}$$

If we add 4 in. to the internal diameter as in the previous example, we obtain an external diameter, for the double-shell dewar of 40 in. (1.016 m).

5.4.3.3 Tank Cross Section Considerations

The tank cross section is a parameter which is subject to some manipulation, depending on tradeoff considerations present in a particular case. (See Para 8.6 for further discussion of this point.) In general, the more slender the tank shape the less efficient is its thermal protection. In addition, long cylinders are more vulnerable to bending moments and create aerodynamic stability problems when carried on rockets.

5.4.3.4 Tank Weight Estimate

The computation of the weight of the ALBS tank is outside the scope of this report, involving the thicknesses and densities of the particular alloys suitable for cryogenic use, the support struts, welds, fittings, connectors, seals, insulation and so on. For the demonstration ALBS the dry LHe tank weight is estimated at 150 lb (68.1 kg) based on the ORB study (See ref. 7) and on systems proposed by industry. The LH_2 tank for ALBS would be about 10 percent lighter based on its somewhat smaller volume .

6. HEAT TRANSFER

6.1 Similarity to Storage Problem

Having devoted considerable discussion (in the preceding section and in Appendix C) to the problem of keeping the Cryogens cool during storage, we must now consider the opposite situation-- the warming of the liquids at the time of balloon inflation. Fortunately, many of the concepts and coefficients used on the storage problem will apply here also. (One important difference is that we will not be dealing with a closed system, with inhibited vaporization, as was the case in storage. Here we are anxious to complete the vaporization process quickly.)

6.2 Initial Conditions

Before starting any calculations, let us examine qualitatively our initial conditions and what we are attempting to accomplish.

6.2.1 MASS AND TEMPERATURE OF CRYOGEN

We have a suitably insulated cryogenic storage tank containing 100 lb (45.36 kg) of LHe or 47 lb (21.2 kg) of LH_2 which has been transported by a rocket (See Note) or an airplane to the mid-air inflation location. The ALBS capsule has been deployed from the transport vehicle and is falling slowly, supported by the main parachute. The balloon has been unfurled and awaits its charge of inflation gas. The Cryogen is in liquid form, at its boiling point.

> Note: In this discussion we will consider the situation of the ALBS demonstration unit launched from an aircraft at 25,000 ft (7.65 km) and the additional situation of a unit of similar size launched from a rocket above 80,000 ft (24.2 km).

6.2.2 OVERALL HEAT REQUIREMENT

For inflation to occur, a quantity of heat must be supplied which is equivalent to the sum of: (a) the previously-discussed heat gain for vaporization (See Appendix C, para. C-5.) and (b) the heat necessary to warm the gaseous phase to the ambient temperature at the altitude at which inflation will take place. (The warming of the gas is necessary both to achieve temperature equilibrium with the atmosphere and to avoid shattering the balloon material, which would become extremely brittle if exposed to Helium or Hydrogen vapors at near-cryogenic temperatures.) We have approximately five minutes in which to accomplish the inflation.

6.3 Computation of Gas Warming Requirements

To compute the heat requirements for warming the vaporized gas, we must multiply the specific heat of the gas by the mass of the gas and by the number of degrees through which the temperature must rise. In addition, in the case of H_2, we must add the heat of conversion, to accommodate the change from the parahydrogen state to the normal Hydrogen state. This change is endothermic and involves the distribution of left and right hand spinning motions of the H_2 protons. (In orthohydrogen the spins are in the same direction; in parahydrogen they are in opposite directions. "Normal" Hydrogen contains 75 percent ortho-H_2, 25 percent para-H_2. "Parahydrogen" is the name given to the equilibrium composition at 20.3°K. It contains only 0.21 percent ortho-H_2.)

6.3.1 HEAT GAIN EQUATION

The general equation for the heat gain needed to warm the gas is:

$$\Delta H(T_f - T_{b.p.}) = C_p \times M \times \Delta T(T_f - T_{b.p.}) + (\text{for } H_2 \text{ only}) \Delta H_c$$

where: ΔH = Heat gain (BTU) or (Joules)[a]

C_p = Specific Heat Capacity of the gas (BTU/lb/°R) or (J/g/°K)[c]

M = Mass of Cryogen/Gas (lb or kg)

ΔT = Temperature Change °R or °K

T_f = Final temperature, at the end of warming

= Atmospheric ambient temperature (°R or °K)

$T_{b.p.}$ = Boiling Point Temperature (°R or °K)

ΔH_c = Heat of conversion for Hydrogen = 304.8 BTU/lb[b] at n.b.p.

= 708 J/g

Note: a. 1 BTU = 1.055×10^3 Joules
b. 1 BTU/lb = 2.33 J/g
c. 1 BTU/lb/°R = 4.19 J/g/°K

6.3.2 TWO ALTITUDES OF INTEREST

$\Delta T(T_f - T_{b.p.})$ is calculated for two altitudes:

6.3.2.1 High Altitude Launch

If we assume an ambient air temperature of -62°F or 397.7°R at 80,000 ft. (24.4 km) altitude, (rocket delivery) the number of degrees R through which the inflatants must be heated is:

He		H_2	
397.70°R (ambient)	220.0°K	397.7°R	220.0°K
-7.57°R (n.b.p.)	-4.2°K	-36.7°R	-20.4°K
390.13°R	215.8°K	361.0°R	199.6°K

6.3.2.2 Lower-Altitude Launch

For the cargo drop from 25,000 ft. (7.62 m) proposed for the ALBS demonstration system, the gain in heat must be even greater. Here we use an ambient temperature of -30°F or 429.7°R.

He

$$\begin{array}{r} 429.70^{\circ}R \\ -7.57^{\circ}R \\ \hline 422.13^{\circ}R \end{array} \qquad \begin{array}{r} 238.5^{\circ}K \\ -4.2^{\circ}K \\ \hline 234.3^{\circ}K \end{array}$$

H_2

$$\begin{array}{r} 429.7^{\circ}R \\ -36.7^{\circ}R \\ \hline 393.0^{\circ}R \end{array} \qquad \begin{array}{r} 238.5^{\circ}K \\ -20.4^{\circ}K \\ \hline 218.1^{\circ}K \end{array}$$

6.3.3 HEAT CAPACITY

The specific heat capacity (C_p) values for gaseous Helium and gaseous Hydrogen are higher than those shown in Table C2 for their liquid phases at the boiling points.

(a) For He (gas) at 10°R (5.55°K), C_p is 1.45 BTU/lb/°R (6.08 J/g/°K). It becomes 1.25 at 50°R (27.8°K), and, at 200°R (111°K) it becomes 1.24 and stays at that value to room temperature. 1.25 BTU/lb/°R (5.24 J/g/°K) will be the value used in our warming calculations.

(b) The C_p for H_2 (gas) is 2.85 BTU/lb/°R (11.9 J/g/°K) at 36.7°R (20.4°K), dipping to 2.51 at 100°R (55.5°K) and then slowly rising to 3.30 at 400°R (222°K). At 450°R (250°K), it becomes 3.36 BTU/lb/°R (14.1 J/g/°K). The value of 3.30 BTU/lb/°R (13.8 J/g/°K), which is considered conservative when applied across the range from 36.7°R (20.4°K) to 430°R (238.5°K) will be used in our calculations.

6.3.4 GAS HEAT REQUIREMENTS

The heat requirements for warming the gas are, then:

(a) for an 80,000 ft. (24.4 km) inflation altitude:

He

$$\begin{aligned} &1.25 \times 100 \text{ lb} \times 390.13^{\circ}R \\ &\quad = 48{,}766 \text{ BTU} \\ &\quad = 51.5 \times 10^{6} J \end{aligned}$$

H_2

$$\begin{aligned} &3.30 \times 47 \text{ lb} \times 361^{\circ}R \\ &\quad = 55{,}991 \text{ BTU} = 58.9 \times 10^{6} J \\ &\quad \underline{+\ 14{,}316 \text{ BTU}} \ (\Delta H_c \times M) = 15.2 \times 10^{6} J \\ &\text{Total} \quad 70{,}307 \text{ BTU} = 74.1 \times 10^{6} J \end{aligned}$$

(b) for a 25,000 (7.62 km) inflation altitude:

He

$$\begin{aligned} &1.25 \times 100 \text{ lb} \times 422.13^{\circ}R \\ &\quad = 52{,}766 \text{ BTU} \\ &\quad = 55.7 \times 10^{6} J \end{aligned}$$

H_2

$$\begin{aligned} &3.30 \times 47 \text{ lb} \times 393^{\circ}R \\ &\quad = 60{,}954 \text{ BTU} = 64.3 \times 10^{6} J \\ &\quad \underline{+\ 14{,}316 \text{ BTU}} \ (\Delta H_c \text{x} M) = 15.2 \times 10^{6} J \\ &\text{Total} \quad 75{,}270 \text{ BTU} = 79.5 \times 10^{6} J \end{aligned}$$

6.4 Total Heat Requirements

The total heat requirements for: (a) vaporizing the liquid; and (b) warming the gas, are obtained by adding the values determined in Para 6.3.4(a) and 6.3.4(b) above to the heat vaporization values and are shown in Table 2.

Table 2. Total Heat Required to Convert Liquid Cryogens to Inflation Gas at Ambient Temperatures

Item	LHe	LH_2
1. Mass of Cryogen, M	100 lb (45.36 kg)	47 lb (21.2 kg)
2. Heat Gain for Vaporization (ΔH_vxM)(ΔH_v for LHe=8.92 BTU/lb; for LH_2=191.9 BTU/lb. See Appendix C.)	892 BTU (9.43 x 10^5J)	9019 BTU (9.5 x 10^6J)
3. Heat Gain, Boiling Point Temperature to Ambient Temperature. $\Delta H(T_f - T_{b.p.})$ (See para. 6.3.4 (a) and (b)).		
a. for 80,000' (24.4 km)	48,766 BTU (51.5 x 10^6J)	70,307 BTU (74.1 x 10^6J)
b. for 25,000' (7.62 km)	52,766 BTU (55.7 x 10^6J)	75,270 BTU (79.5 x 10^6J)
4. Total Heat Requirement, ΔH Item 2 plus Item 3		
a. for 80,000'	49,658 BTU (52.5 x 10^6J)	79,326 BTU (83.6 x 10^6J)
b. for 25,000'	53,658 BTU (56.7 x 10^6J)	84,289 BTU (88.7 x 10^6J)
5. Enthalpy Change Item 4 divided by Item 1		
a. for 80,000'	497 BTU/lb (1152 J/g)	1685 BTU/lb (3920 J/g)
b. for 25,000'	537 BTU/lb (1245 J/g)	1790 BTU/lb (4160 J/g)

Note: In the above table, no heat inputs are provided to compensate for possible cooling of the inflation gas upon expansion into the evacuated balloon. In the calculations, it was assumed that the pressure within the heating chamber is only 1-2 atmospheres and the temperature of the gas at this point is 398°R (220°K) or above. Under those conditions, Joule-Thompson cooling does not take place with the expansion of either Helium or Hydrogen. The adiabatic expansion process through a work-producing device was judged not to be a factor here also. (As a matter of interest, compressed H_2 and He gases stored at room temperature are warmed by Joule-Thompson expansion. If used in the ALBS, compressed gas systems would probably require gas cooling to reach temperature equilibrium with the atmosphere at the inflation altitude.)

6.5 A Consideration of Electrical Heating Methods

Having determined the amount of heat needed to vaporize and warm the inflatant , let us examine possible methods of providing the required heat. Depending on the inflatant chosen and the inflation altitude, the total heat requirements (Table 2) range from 49,658 BTU (52.5×10^6J) to 84.289 BTU (88.7×10^6J). With a 5-minute inflation cycle, this equates to heat inputs of about 10,000 to 17,000 BTU/min. ($1.7 - 3 \times 10^5$J/s). In terms of electrical energy, this is equal to about 175-300 kilowatts (3940-4300 kg cal/min) of power, far beyond the capacity of any airborne electrical system of reasonable weight.

6.6 Chemical Methods

With electrical energy ruled out, we must turn to chemical energy sources. Here we find that our heat requirements appear capable of being satisfied with greater or lesser amounts of difficulty, depending on which of the several possible approaches we choose to pursue. In general, the chemical approach consists of a gas-generating combustion process, the heat of which is exchanged with or transferred to the cryogenic fluid. The term "combustion" also covers exothermic catalytic decomposition processes, such as is the case with hydrazine and hydrogen peroxide. The fuels burned in the combustion chamber can be liquid, gaseous or solid and, ideally, have a very high heat content per lb. Candidate chemical reactions are described in paragraph 6.8 , following the discussion of heat exchange methods, below, which help to determine the relative merits of various fuels.

6.7 Alternate Approaches to the Gas Warming Problem

The gas produced in the combustion chamber may be used in two ways to warm the cryogenic fluid:

1. By means of a gas-to-gas or two-fluid heat exchanger.
2. By direct mixing of the cryogenic fluid with the hot gas.

6.7.1 TWO FLUID SYSTEM

The two-fluid system relies on a conventional approach which is both heavy and costly. It is also a relatively slow heat transfer method. It involves a network of pipes with radiating fins, through which the hot gases flow and about which the cryogenic fluid circulates or vice versa. The difference in temperature across the wall of the heat exchanger can be 2000-4000°F (1092-2202°C) depending on the heat of combustion of the chemicals employed. This calls for considerable design sophistication with respect to choice of materials, solution of fluid dynamics problems, etc. Despite the difficulties of designing a light-weight, highly efficient two-fluid exchanger, the method has some redeeming features, however.

First, it isolates the inflation gas from the combustion products, which are dumped overboard. Those products can be solids, such as ice, and various gaseous compounds (H_2O vapor, H_2, NH_3, N_2, CO_2) which dilute the inflation gas if allowed to mix with it directly. With the two-fluid heat exchanger, the only gas which enters the balloon is the warmed He or H_2 and the specific lift is as calculated previously in Para 4. 3. 1 and 4. 3. 2.

Also, the two-fluid system completely separates flammable cryogenic Hydrogen from the fuels used in the combustion, and from the combustion process itself, by virtue of the wall between the two fluids. By contrast, in the direct-mixing method, wherein the Cryogen merges with the exhaust gases downstream of the combustion process, positive pressure differentials are relied upon to achieve separation from the combustion and the unburned fuel, an approach which appears less foolproof than the physical isolation afforded by the two-fluid exchanger.

6. 7. 2 DIRECT MIXING PROCESS

The more novel direct-mixing process employs a spray or jet system to atomize the cryogenic fluid and expose maximum surface area to the hot gases resulting from the combustion. Through proper chamber design turbulent mixing is augmented to produce uniform elevated inflation gas temperatures quickly. This approach has been used in reaction motors and system designers can call upon an extensive fund of experience to arrive at the specific configuration needed for the ALBS. In terms of design simplicity, and overall efficiency, it appears to have the edge over the two-fluid approach, and, on that basis, is quite attractive. There are disadvantages to the method, however, which must be taken into consideration. They arise from the fact that the gaseous combustion products are carried into the balloon with the inflatant.

Because H_2O is a combustion product in many of the reactions it will be present in the mixing chamber and in the diffuser leading to the balloon. It can be there as a gas or in liquid or solid form, depending on the degree to which it is cooled by the cryogenic fluid entering the mixing chamber. Care must be exercised in designing flow passages to avoid blockage by ice or snow. If the ice, snow or liquid water enters the balloon itself it can be expected to cling to the balloon film and to produce a degradation in material flexibility and also in net lift, equivalent to its mass. If the water enters the balloon as a vapor and stays in vapor form it will increase the volume of gas in the balloon and create a gas mixture of lower specific lift than that of the pure inflatant. It is more likely, however, that the H_2O will condense out quickly because of the low equilibrium temperatures at inflation altitudes.

Other gaseous combustion products such as CO_2, N_2 and NH_3 remain as gases in the balloon and form a mixture with the inflatant, which can either degrade or augment the calculated lift performance of the balloon depending on their molecular weight. A sample calculation follows:

(1) The total volume, V_T, of the gas mix in the unpressurized balloon is represented by the formula:

$V_T = V_{\text{inflatant}} + V_{\text{products}}$,

where $V_{\text{inflatant}}$ is the volume of gas obtained from the conversion of the liquid Cryogen. (See Appendix B, Table B-1.)

V_{products} is the volume of gas generated in the chemical combustion. (Condensation of H_2O vapor is not considered in this example.)

(2) V_{products} (ft^3) = lb mol of product x 454 x 22.4 x 0.0353 where 454 is the conversion factor, lb to gm.; 22.4 is the volume in liters, per gm. mol (at STP); 0.0353 is the conversion factor, liters to ft^3.

(3) If the reaction resulted in 1/2 lb mol of CO_2, for example, where 1/2 lb mol equals one half the molecular weight of CO_2 in lb, or 44/2 = 22 lb (9.98 kg), the gas generated would occupy a volume of 1/2 x 454 x 22.4 x 0.0353 or 179 ft^3 (5.06 m^3) at STP. If we divide that volume by the density ratio for 80,000 ft, 0.036, we get the volume occupied by the CO_2 at that height, 4000 ft^3 (113.3 m^3). This adds about 1.6 percent to the "first cut" volume (242,000 ft^3 (6.86 x 10^3 m^3)) estimated for the ALBS balloon with He as the inflatant (see Para 4.3.1). The increased volume is well within the working volume of 250,000 ft^3 (7.1 x 10^3 m^3) chosen for the balloon. However, since the CO_2 gas is heavier than air, there is some degradation of calculated system lift. The molecular weights of CO_2 and air are 44.01 and 28.96, respectively. This leads to 15.05 lb (6.83 kg) of negative lift per lb mol of CO_2.

(4) In the case cited above, 1/2 lb mol of CO_2 would reduce the system net lift by 7.50 lb (3.41 kg). Greater amounts of CO_2 product gases would require a larger balloon, thus further adding to the weight penalty.

(5) The above calculation illustrates the kind of effect produced by mixing the inflatant with a heavier-than-air exhaust product. If the product gas is lighter than air (e.g. NH_3, N_2, H_2 which are products of the decomposition of hydrazine N_2H_4), there is actually some additional lift provided by the product gases which could even lead to a reduction of the required amounts of liquid He or H_2. In each case, the figures have to be worked

out for the specific reaction, for the reaction and product quantities, and for the specific lift of the product.

6.7.3 COMPARATIVE WEIGHTS

Figures submitted by Industry indicate that the two-fluid exchanger would weigh about ten times as much as the direct-mix exchange system. (The weights of 150-200 lb (68.1-90.8 kg) vs 15-20 lb (6.8-9.1 kg) are considered reasonable estimates at this time.) In comparing the weight penalty of the two-fluid system with that of a particular direct-mix system, it should be remembered that the heavy two-fluid heat exchanger adversely affects the gross system weight but has no effect on the system buoyant weight. The direct-mix method can reduce gross system weight, at the possible cost of increasing the system buoyant weight by requiring a larger balloon. This is an area where the final choice will result from consideration of the tradeoffs applicable to a particular mission. In any event, a scale model demonstration of the selected heat exchange approach seems called for, before committing the ALBS to that method.

6.7.4 FUEL STORAGE

The heat exchanger and gas generator weights stated above do not include the weights of the tanks required for storing the fuels used in the combustion process (e.g. liquid hydrazine, gaseous oxygen). No attempt will be made here to calculate the weights of the various components needed for the combustion process and the expulsion process described in the following paragraph. This omission is based on the large number of possible variations. The overall gas storage and heat transfer subsystem weight estimate of Para 5.3.2 includes an allowance for the combustion and expulsion items which is believed adequate, whatever the method used.

6.7.5 EXPULSION GAS STORAGE

In addition to the fuel storage tanks, various control valves, pipes, metering orifices and the like are required, regardless of the heat generation process. There must also be provided a means of expelling the liquid Cryogen from its storage tank to the heat exchange area. The most straightforward way of accomplishing this seems to be through the introduction of a pressurized inert gas, such as He, from a separate tank where it has been stored for this purpose. If the pressure of the expelling gas is maintained at 100 lb in^{-2} (6.87 x 10^{5} N/m^{2}) inside the cryogenic storage tank, the vapor portion of the two-phase mixture (See Appendix C) will disappear both in the He and H_2 cases, provided that $T < T_c$ for He, and $T < 52^{o}R$ ($28.8^{o}K$) for H_2, thus insuring transfer of the Cryogen as a liquid as it is forced through the transfer pipe. (Presumably the 100 lb in.$^{-2}$ pressure relief valve will be disabled, if that relief pressure is chosen, or there will be a compromise pressure differential established between expulsion and relief pressures.) A method must also be provided for sensing the depletion of the Cryogen in the storage tank and of shutting down the gas warming process. This step will initiate the separation of the balloon from the inflation subsystem. It should be evident that the problem of cryogenic expulsion and control is more extensive than the treatment afforded it in this paragraph and will require additional investigation during the detailed design phase of the proposed ALBS prototype development program.

6.8 Candidate Chemical Reactions for Heating the Cryogenic Inflatant

6.8.1 SOLID MATERIALS

The solid gas-generating materials of interest in the ALBS heat transfer problem are basically propellants, such as are used in solid-fueled rockets and in pyrotechnics. Their reaction rates are very fast and they produce high gas pressures in the reaction chamber. This calls for rugged chamber construction. Because of their fast reaction rates, these propellants appear suitable only for the direct mixing process. They expel the warmed gaseous inflatant with considerable force (on the order of 40 lb (18.1 kg) of thrust), thus creating a significant jet blast problem which the still folded (lengthwise) and uninflated balloon could not accommodate without tearing. (The employment of a diffuser, such as that described in Para 6.11.3, is a questionable method of alleviation in this case since the pyrotechnic chemicals generate large quantities of H_2O as a reaction product and diffuser blockage by ice is a very likely occurrence. One of the high-yield propellants considered produces 2.5 lb (1.14 kg) of ice, per 15 lb (6.8 kg) of propellant, when the gas generator products are mixed with the cryogenic fluid. This figure is believed to be typical for propellant fuel systems.) On the above basis alone, pyrotechnic combustion systems should not be recommended. An additional disadvantage is their relatively low heat content, 1800BTU/lb (4.2×10^3 J/g), about 1/10 the value of hydrocarbon fuels.

6.8.2 LIQUIDS

The two most frequently considered liquid chemicals for the ALBS application are Hydrazine and Hydrogen peroxide, both of which undergo exothermic catalytic decompositions.

H_2O_2 decomposes into water and O_2. The disadvantages of water (ice blockage, loss of lift due to condensed vapor, etc) have already been discussed. O_2 is heavier than air which also leads to degraded lift.

Hydrazine N_2H_4, is a more attractive chemical (despite its poisonous nature) in that its products are lighter than air. It decomposes exothermally into gaseous ammonia, NH_3, and gaseous Nitrogen, N_2. Then the NH_3 further decomposes endothermally into gaseous N_2 and H_2. The second reaction does not always go to completion, however, and an intermediate value of decomposition is usually employed, leading to a heat of reaction which is less than that of the initial exothermic reaction alone. In general the average amount of heat obtained per lb of N_2H_4 is low, 800-1500 BTU (1.9-3.5×10^3 J/g), thus requiring a fairly sizeable quantity of N_2H_4 for the ALBS application. This quantity of N_2H_4 will generate a substantial amount of lighter-than-air products, however, and can, thereby, reduce the amount of needed cryogenic inflatant by 10-15 percent. There is some question about the compatability of the NH_3 with mylar balloon film. On the other hand, the combustion products of N_2H_4 are compatible with Hydrogen and do not constitute a safety hazard with that inflatant. The Hydrazine is stored as a liquid under pressure. Its reaction rate is easily controlled. It has been used frequently in rocket motors, and the experience level with it is quite high. The average combustion temperature is about 2000°F (1092°C), which permits the use of non-exotic materials in the fabrication of the gas generator.

6.8.3 GASEOUS FUELS

Hydrocarbon fuel-air mixtures are known to provide easily controlled combustions with high heat content. Because of the altitudes involved in the ALBS application, however, the amount of atmospheric air available to the system is insufficient for efficient combustion and self-contained Oxygen/Hydrocarbon fuel mixtures are preferred. These fuels typically provide 18-23,000 BTU/lb (42-53.6×10^3 J/g), and are suitable for use with either the two-fluid type of heat exchanger or the direct mixing process. The gaseous Oxygen/gaseous Propane (C_3H_8) mixture is a leading candidate in this category of fuels. In the ALBS, the two gases would be stored in separate pressurized tanks at 3000 lb in.^{-2} (204 atm, 2.06×10^7 N/m^2) and connected to the gas generator. The ultimate exhaust products of the combustion are water and heavier-than-air CO_2.

Gaseous Oxygen and gaseous Hydrogen constitute another, even higher energy combination. Hydrogen yields 61,000 BTU/lb (14.2×10^4 J/g) when burned. In a GO_2/GH_2 system, the GO_2 would be stored in a pressurized tank while the GH_2 could either be stored separately as a gas under pressure or be taken from the cryogenic LH_2. The exhaust product is steam which condenses into water and ice.

6.9 Stored Heat

A third possibility exists with respect to heating the cryogenic fluid rapidly. It involves the use of solid materials of high specific heat capacity which have been pre-warmed. The cryogenic would be brought into contact with a bed of such material and, in passing over it, would acquire the heat stored in the material. The Cryo-Jet Start Company, of Newport Beach, California, uses hot aluminum oxide in this fashion in a patented process for warming liquid Nitrogen for use in starting jet engines. The stored heat method appears to be very simple, compared to the combustion and pyrotechnic processes described above. It does have some practical operating problems in the ALBS situation, however, which require further evaluation. They include such considerations as:

(1) The size of the beds needed for efficient heat transfer;

(2) The problem of isolating the pre-heated beds from the cryogenic storage tanks during long-term storage. (It is assumed here that the beds are kept in a ready-to-go state, i. e., are preheated, rather than being heated at the time of the launch.)

(3) The effective heat transfer.

6.10 Need for Modeling

No recommendation will be made in this report with respect to a specific method of heating the cryogenic inflatant. The stored heat method appears very attractive in that it requires the least amount of plumbing and controls. The direct mix system, with a GO_2/GH_2 fuel mixture seems to be the next most attractive. Further investigation, including some modeling, is required to provide positive guidelines in this area.

6.11 Gas Generator/Balloon Interface

In the preceding discussion almost no attention was paid to the interface between the gas generator and the ballon. Some thoughts on that subject are in order now.

6.11.1 AMBIENT TEMPERATURE CONSIDERATIONS

The unfurled balloon is very temperature-responsive and can be assumed to be at, or close to, the ambient temperature of the inflation altitude. In our earlier discussion of heat requirements, we established the ambient temperature for an 80,000 ft (24.4 km) inflation at -62°F and that for a 25,000 ft (7.62 km) inflation at -30°F (397.7°R or 220°K and 429.7°R or 238.5°K, respectively). These are standard atmosphere values and by no means represent temperature extremes which can be experienced at those altitudes. They are acceptable values, nonetheless in determining heat input requirements for warming the cryogenic vapor to ambient temperature since, should lower ambient temperatures actually be encountered, the system design would end up with a slight surplus of heat energy. The surplus is present by virtue of the fact that $\Delta H(T_f - T_{b.p.})$ is less than the standard quantity. (See Para 6.3.1.) Experience has shown that ambient temperatures as low as -90°F (370°R, 206°K) may be experienced by the balloon film. This means that, in a mid-air inflation at -80°F (380°R; 211°K) to -90°F (370°R;

206°K) temperatures, we are attempting to insert gas through the gathered (lengthwise) folds of balloon material at a time when the strength of that material is extremely low. (This does not consider dynamic loading on the balloon due to the descending motion. That problem is discussed later in connection with balloon deployment.)

6.11.2 CONTROLLED GAS FLOW

Because the cold balloon film is very weak, controlled insertion of the gas appears mandatory. The controls would apply both to the temperature and the flow rate of the gas coming into the balloon from the gas generator. Insofar as temperature is concerned, the gas will, ideally, warm the balloon material slightly as it enters, thereby making at least part of the balloon more flexible and stress resistant. (Whether or not the localized warming will, in itself, introduce stress points remains to be determined.) In Para 6.10, it was recommended that further investigation be made of potential heat transfer methods. As part of that investigation the predicted end temperatures of the generated gas should be shown, along with the anticipated balloon film temperatures during the inflation process. It is to be hoped that the gas temperature and the balloon temperature figures will show that any effect of the gas temperature on the balloon is in the direction of augmented film strength.

6.11.3 DIFFUSER NOZZLE

In the matter of gas flow rates, the inflation techniques employed with ground-launched balloons appear relevant here. Such balloons are customarily inflated from high pressure compressed gas tanks, using a small, 1-2 in. (2.54-5.08 cm) diameter supply line which terminates in a large diameter, 10-15 in. (25.4-38.1cm), diffuser nozzle. The diffuser nozzle reduces the velocity of the gas as it enters the balloon, thereby preventing damage to the balloon material from the gas jet. In the ALBS situation, it may be desirable to employ a similar diffuser nozzle at the interface between the balloon and the inflation gas generator to moderate the velocity of the gas. The diameter of the nozzle would depend on the size of the gas generator outlet tube, and, if the latter is sufficiently large, the diffuser nozzle may become a straight-through flow pipe. It may be desirable also to place baffle plates inside the nozzle to break up the flow.

> Note: The term "gas generator" is used loosely here to refer to the ALBS gas storage and heat transfer subsystem. Strictly speaking, the inflation gas is not generated in the usual sense, i.e., by the interaction of chemicals to produce gas as a reaction product. Rather, it is simply converted from the liquid to the gaseous state.

6.11.4 NOZZLE EXTENSION

A flexible tubular extension to the ALBS diffuser nozzle seems desirable so that the gas can rise to the upper portion of the balloon without damaging the gathered folds of balloon material hanging from the gas bubble area. (See Para 7.2.6.) The extension tube, which would be supported internally in the balloon by a cord attached to the balloon's apex, would conduct the gas upward along the balloon's central axis. It would be made of non-porous film material, except at the top.

6.11.5 SPECIAL END FITTING

In ground-launched natural shape balloons the gas is normally inserted via a special inflation duct attached to the balloon peripnery. The diffuser is attached to that duct temporarily for the inflation. In the ALBS the situation is different. The inflation must be through the balloon's bottom end fitting, which, in addition to accommodating the diffuser nozzle must also provide the usual function of that fitting: securing the lower ends of the balloon gores and serving as a load attachment point. A very special bottom end fitting is required for the ALBS balloon, therefore. Also, since the inflation tanks drop away once inflation is complete, there must be a quick-release connection between the end fitting and the gas generator outlet.

6.11.6 VARIABLE FLOW RATES

An additional method of gas flow rate control seems necessary to achieve ideal fill rates for the conditions present at particular times during the inflation operation. It is probable, for example, that the early stages of the filling operation will require low flow rates, to minimize stress on the balloon material, with progressively higher flow rates being established as quickly as possible to allow overall fill time constraints to be met. Such variations in the flow rate could be effected through adjustments to the flow rates of the chemicals involved in the combustion process and of the Cryogen being warmed. It is anticipated that the control system designed for the automatic inflation operation will incorporate preprogrammed variable flow rate valve actuators adequate for the purpose.

6.11.7 INFLATION TIME CONSTRAINTS

The inflation time limit of five minutes established earlier in this report seems reasonable. Table B-1 of Appendix B shows that the yielded volumes of He and H_2 are less than 9000 ft^3 (255 m^3) at standard day conditions. Despite the high altitudes at which inflation will occur the density of the gas passing through the diffuser is expected to be close to the standard day value of density. This is predicated on the backpressures anticipated in the balloon and nozzle extension and on the pressures inside the gas generator. Thus, a volume of 9000 ft^3 (255 m^3) averaged over five minutes equals a fill rate of 1800 ft^3/min or 30 ft^3/sec (0.85 m^3/

sec). This rate is less than that employed with ground-launched balloons. Expansion of the gas to the volume appropriate to the inflation altitude will be assumed to occur after the gas is in the balloon.

6.11.8 DESCENT DURING INFLATION

During the five-minute inflation period, the ALBS descends towards the earth at a rate which is a function of altitude and the specified terminal dynamic pressure, q. The equilibrium or terminal dynamic pressure value, in turn, depends on the weight being decelerated and the size of the decelerator (parachute) selected. There is a desirable upper limit to the value of q, 0.5 lb ft^{-2} (2.44 kg/m^2), to protect the balloon from excess flutter stresses. (Refer to Para 7.2.6.) Once achieved, that value of q remains constant throughout the descent. However, the descent velocity varies with altitude, being greatest at high altitudes where atmospheric density is least. The descent rates at the two inflation altitudes are quite different.

For the 80,000 ft (24.4 km) inflation, which presupposes a rocket delivery of the ALBS capsule, and ejection from the rocket at 120,000 ft (36.6 km), balloon deployment should actually start at about 105,000 ft (32 km). This is the point at which a stable descent, at a q value of 0.5 lb ft^{-2} (2.44 kg/m^2), is expected to be achieved. Balloon inflation will begin shortly thereafter. The descent will continue until neutral buoyancy is achieved, at about 75,000 ft (22.9 km). Inflation is then completed, the main canopy is separated, if so programmed (See Para 7.2.4), and the inflation hardware drops away. The balloon then climbs to the 80,000 ft (24.4 km) float altitude at a rate of approximately 1000 ft/min (5.1 m/sec). During the five-minute inflation, a 30,000 ft (9.14 km) drop in altitude will have been experienced, at an average descent rate of 100 ft/sec (30.5 m/sec). Actually, at the start of the inflation, the descent velocity will be about double that figure, decreasing rapidly as atmospheric density increases.

For the 25,000 ft (7.62 km) inflation altitude, the average descent rate is much slower, only about 26 ft/sec (7.9 m/sec). Even so, the ALBS will have descended about 8000 ft (2.44 km) during the inflation, achieving neutral buyoancy at only about 17,000 ft (5.18 km) above ground (MSL). The climb to float altitude at 1000 ft/min (5.1 m/sec) will take a long 63 min, a fact which points up the less-than-quick reaction time of an ALBS launched from an aircraft.

7. OTHER ALBS SUBSYSTEMS

7.1 The Matter of Emphasis

When this report was conceived the intent was to go into considerable detail on each of the major subsystems outlined in Section 2, except for the payload. As it turned out, however, much more attention was devoted to the gas storage and heat transfer problems than was originally planned. The heavy emphasis on that relatively exotic problem is believed justified on the basis that the application of cryogenics to scientific ballooning is novel and not well documented in the literature. In trying to decide how much emphasis to devote to the remaining subsystems consideration has been given to the amount of available knowledge and, particularly, of existing standard components suitable for the required functions. Fortunately, parachute systems, telemetry, ballasting and control devices are well covered in both categories, and can be treated on a brief descriptive basis. However, the balloon deployment subsystem stands out as a difficult problem about which not too much is known. It, too, will be discussed on a descriptive basis, for the reason that more definitive information can be obtained only through experimentation.

7.2 The Balloon Deployment Subsystem

7.2.1 PARACHUTES

Referring back to Figures 1 and 2, and ahead to Figure 7, we see that the deployment of the balloon is parachute-controlled. There are four possible types of parachutes involved:

(a) The extraction chute, used primarily to extract the ALBS capsule from the transport vehicle.

(b) The drogue chute used to withstand the initial shock of vertical deceleration, to stabilize the descent of the ALBS, and to deploy the main canopy.

(c) The main canopy which stabilizes and supports the balloon and inflation hardware during the inflation process.

(d) The recovery parachutes which permit expended hardware and the payload to float safely to earth. The main canopy ideally will also function as one of the recovery chutes, with the inflation hardware as its most likely cargo.

7.2.2 DROGUE CHUTES

The drogue chutes, which can also serve as extraction chutes, are relatively small, less than 20 ft (6.1 m) in diameter. The ring slot design seems to be most favored for this application. (See note.) The drogue chutes are normally jettisoned upon deployment of the larger main canopy, which has a diameter of 40 ft or greater, and which may be reefed to lessen opening shock.

> <u>Note:</u> In general, parachute types will be selected for best performance under ALBS mid-air release conditions. High Mach No., high altitude releases call for parachutes whose porosity is a function of geometry (e.g. Disk-Gap-Band) rather than of the material employed. Ribless guide surface canopies represent the latter type and appear more appropriate for subsonic, lower altitude releases. In any event, each chute must provide both the stability and

the minimum level of dynamic loading specified for the phase of the ALBS system deployment in which it is operative. The sizes of the individual chutes are functions of the weights to be decelerated and supported and of the terminal dynamic pressures (see Para 7.2.3) desired at each stage.

7.2.3 BALLOON DEPLOYMENT BELOW THE MAIN CANOPY

Figures 1 and 2 show the balloon deployed below the main canopy. This is a possible method, but not necessarily the best approach, since a strong case can also be made for deploying the balloon above the main canopy, instead of below it. That approach has been used quite successfully in previous, much smaller ALBS developments, such as the earlier-mentioned Payne system and one developed in 1965 for the Air Force by Raven Industries in conjunction with the Hallicrafters Co. The Goodyear Co. PARD program also successfully demonstrated this concept.

7.2.4 PROBLEMS

When the balloon is deployed below the main canopy there are two main problems:

As the balloon becomes inflated its wake interferes with the flow of air to the parachute canopy and causes the canopy to collapse on top of the balloon. This necessitates cutting the canopy loose to prevent it from degrading the balloon's lift capacity. Using the released canopy for any useful purpose, such as a recovery chute for the inflation hardware is difficult, and leads to redundancy in the system parachute complement, thereby increasing cost and system gross weight.

A second, more serious problem is that of lowering the balloon to its fully extended position without damaging it. The basic approach is that the payload and inflation hardware are separated from the main canopy and fall towards the earth, pulling the balloon downward with them, unfurling it from its container which is still attached to the main canopy. This method of deployment carries with it an obvious threat to the integrity of the balloon, particularly if the balloon film is expected to absorb all of the deceleration stresses attendant to reaching the limit of downward travel. Some means of controlling or moderating the deceleration of the free-falling hardware seems called for here. There are various possible solutions, although a weight penalty is usually involved. The Schjeldahl Co. has recently developed a balloon unfurling device for the National Center for Atmospheric Research which has application to the ALBS problem. It employs a mechanical friction brake in which a pair of fabric tapes passes over a series of cylinders. That approach represents the heavier, more sophisticated type of solution. A simpler, but unproven approach is to use a rope inside the balloon, or a rope array outside the balloon. The rope(s) would be connected at one end to the balloon container and, at the other end, to the falling hardware. Rope length is slightly less than that of the unfurled balloon. In theory, the deceleration shock is absorbed by the rope(s) rather than by the balloon material.

7.2.5 BALLOON DEPLOYMENT ABOVE THE MAIN CANOPY

When the balloon is deployed in the sheltered wake area above the main canopy the unfurling process is relatively gentle. A pilot chute is released which posseses enough drag with respect to the main canopy to extract the balloon from its container, which is mounted at the apex of the canopy. This deployment method is not without problems, however.

The main canopy's effectiveness is degraded by top loading and there is a limit to the amount of weight that can be placed at the apex. It is probable that only the balloon and its container can be safely accommodated there. This means that the payload, ballast, controls and telemetry equipment, which are to be carried to float altitude, must be positioned at the base of the parachute during the inflation process, along with the expendable inflation hardware. When inflation is complete, and the balloon rises to float altitude, it must take the main canopy along with it because that parachute constitutes the method of attaching the items to be carried aloft to the balloon. This eliminates any use of the main canopy to recover the inflation hardware but does allow its use in eventual recovery of the hardware lofted to float altitude. Since it is larger than needed for the latter function, the net effect is a weight penalty which reduces the payload lifting capacity of the balloon by the difference between the weight of the main canopy and that of the smaller recovery chute actually needed. This is a significant difference, 45 lb (22 kg) or greater, since the recovery chute is sized to support about 260 lb (118 kg) including payload, controls and TM equipment. (See Para 4.2.1. Remember that the balloon is not recovered.) The main canopy is sized to support the approximately 1200 lb (545 kg) gross weight of the ALBS demonstration system. (The gross weight includes inflation hardware as well as the items carried to float altitude.) A system employing the above-the-main-canopy balloon deployment technique must make use of a somewhat larger balloon, therefore to compensate for the weight penalty resulting from retaining the main canopy.

> Note: Heavier loading of the apex of the main canopy may be possible through judicious use of the drogue chute to support part of the apex load. If successful, this would allow direct attachment of the payload and other flight level hardware to the balloon, thus eliminating the need to haul the main canopy to flight altitude. The weight penalty mentioned above would then disappear.

If the balloon is deployed above the main canopy, complications arise also with respect to the inflation process. The best filling method is to have the outlet of the gas supply system as close to the balloon as possible. The reason for this is that the short inflation period (five min) and the low pressure gas generator demand a fairly large diameter inflation duct to achieve the necessary mass flow. A diameter of 12-15 in. (0.305-0.382 m) seems to be required. If the duct has to extend upward through the height of the main canopy to reach the bottom of the balloon, the system is encumbered by the added weight of the extended duct and the need to make it easily deployable when the main canopy is deployed.

7.2.6 NEED FOR FURTHER INVESTIGATION

This report will make no recommendation with respect to deploying the balloon above or below the main canopy, although deployment below appears simpler and more straightforward. Further investigation is required for adequate resolution of this problem. In any such investigation full attention should be given to the primary goal of the deployment operation, which is to position the balloon so that it can be inflated safely and quickly and then released for ascent to altitude. In pursuing that goal the following points should be considered:

(a) The unfurled (completely extended) balloon, descending and ready for inflation, resembles in many respects a large free balloon under inflation on the ground. Thus, the sizeable body of experience gained over the years with ground launching techniques has relevance here. Since the descending ALBS balloon is bottom loaded and extended vertically it will follow the usual inflation pattern, that is, a bubble of gas will collect at the apex, leaving the material below the bubble slack and vulnerable to the wind.

(b) Ground-launched balloons are very sensitive to horizontal winds in excess of 10 knots (kn) (5.2 m/s). The chief problem is that the dynamic pressure forces associated with the wind introduce severe buffeting stresses in the limp balloon material which can result in tearing of the film and loss of the integrity of the balloon envelope. Reefing sleeves are commonly employed with ground-launched balloons to reduce the stresses on the uninflated material and are quite effective. (They protect the balloon by keeping the uninflated balloon material within the confines of a flexible plastic tube which can be progressively split as the gas bubble expands downward.) The natural question here is whether or not a reefing sleeve should be used also with the ALBS. To answer that question we should look at the wind forces acting on the descending ALBS balloon.

> <u>Note:</u> Because of the difference in altitude between a ground launch and an ALBS launch it is more meaningful here to discuss wind loading on balloon film in terms of dynamic pressure values. Dynamic pressure, or q, is expressed in pounds per square foot (psf) and is represented by the formula $q = 1/2\ \rho V^2$, where ρ = atmospheric density and V = wind velocity in knots. Since ρ decreases with height, a much higher wind velocity is required at altitude, for a given value of q, than would be the case near the ground. For example, a q value of 0.5 psf (2.44 kg/m^2) results from a 12.2 kn (20.7 f/s; 6.3 m/s)

wind at sea level. At 25,000 ft (7.62 km) and 80,000 ft (24.4 km) the corresponding wind values, for the same value of q, are 18.2 kn (31 f/s; 9.35 m/s) and 64 kn (108 f/s; 33 m/s) respectively.

(c) Previous studies and experiments with small ALBS systems, in attempting to ascertain the most favorable inflation environment for the descending balloon, have indicated that the horizontal velocity of the system should be reduced to zero, and that the dynamic pressure associated with the descent should be limited to the same 0.5 psf value employed in the example above. That figure then becomes a determinant with respect to the size of the main canopy. (Lower values of q are possibly through the use of very large parachutes but are not considered cost effective.)

(d) As noted above, the vertical winds associated with a q of 0.5 psf are in excess of 60 kn (31 m/s) at 80,000 ft and are above 18 kn (9.3 m/s) at 25,000 ft. These values are considerably higher than the acceptable wind speed values for a ground launch. It is true that these wind speeds involve air of lower density, and, in addition, are generally parallel to the length of the extended balloon but they are believed to be capable of exerting destructive local stresses in the limp balloon material. For that reason, a reefing sleeve appears mandatory for safe inflation of the ALBS balloon in mid-air.

(e) A reefing sleeve adds to the system buoyant weight, but seems to be an inexpensive weight penalty (approximately 10 lb or 4.5 kg) for the protection it affords the balloon. Even with a reefing sleeve, however, the balloon is not positively protected from rupture under conditions of very low ambient temperatures. (See Para 6.11.1.) This fact represents one of the highest risk elements in the whole ALBS concept.

7.3 The Balloon Control and Telemetering Subsystem

The second of the "other" subsystems is the Balloon Control and Telemetering Subsystem. That term covers a variable array of devices aimed at accomplishing some or all of the following functions, depending on mission requirements:

(a) Controlling altitude excursions of the balloon
(b) Terminating the balloon flight
(c) Monitoring balloon performance
(d) Tracking the balloon.

7.3.1 NORMAL MISSION FLIGHT PROFILE AND BALLAST CONTROL

Normally, with a daytime launch, the balloon will rise to float altitude upon inflation and stay at that approximate height for several hours. Any heating (and subsequent expansion) of the gas by solar radiation will be accommodated by venting through the pressure relief valve. Thus, the gas maintains constant volume, even though the loss of mass in venting reduces gas density. Since the volume and weight of air displaced are unchanged, while the weight of the displacing gas decreases, a slight gain in system lift ensues-leading to upward altitude excursions. (Refer to Appendix A for the basic lift formula.) At night, radiational cooling occurs and the volume of the gas contracts. Less air is displaced per unit weight of gas, and system lift is sharply degraded, particularly in view of the earlier loss of inflatant through venting. The balloon starts to descend to a new equilibrium altitude which it may not find before reaching the earth's surface. The usual corrective procedure in this situation is to counterbalance the loss of lift by discarding system weight, by heating the inflatant or by replenishing the inflatant from a storage tank. In the ALBS demonstration system only the weight elimination or ballasting method will be considered. Standard ballasting systems have been developed and lend themselves to this application. A weight of 60 lb (27.2 kg) was used earlier in this report, Para 4.1.3, to cover the ballast controls and the ballast material. This represents about 10 percent of the buoyant system weight.

> Note: A ballast system will be provided operationally only if required by the mission. Payloads with short duration flight regimes may not need it. In the ALBS demonstration system ballasting will be employed to test the system's ability to remain on station for periods of up to 24 hours.

7.3.2 FLIGHT TERMINATION ARRANGEMENTS

It was shown in the preceding paragraph that the balloon will automatically descend earthward as a result of the diurnal loss of lift, unless some corrective action is taken. For some operational missions this may be satisfactory and no special flight termination provisions will be needed. The ALBS demonstration unit will be subject to FAA regulations, however, and will have several termination arrangements which can be used in whole or in part by any future operational systems:

(a) Destruction of the balloon will be accomplished by a tear panel activated by the pull of the payload when it is cut away (by squib action) from the balloon. (The payload descends to earth by recovery parachute.)

(b) The use of a pyrotechnic cord to tear a hole in the balloon will be planned as a backup destruction device.

(c) Venting of inflatant through the relief valve will also be possible, to insure destruction by loss of lift.

(d) Actuation of squibs or pyrotechnic cords, valves, etc will be accomplished by automatic and/or manual means. The automatic actuation will rely on the presence of a timing device and a lower-altitude limit pressure switch. The manual actuation will be accomplished through a radio link from the ground or launch aircraft to a balloon-borne command receiver/decoder combination.

(e) All of the above methods can be implemented with existing equipment developed specifically for free balloon operations.

7.3.3 TELEMETRY

The ALBS demonstration unit will be equipped with telemetry packages for diagnostic evaluation purposes. The data to be telemetered will cover both the inflation operation and the performance of the system at float altitude. Such data are unlikely to be required in any operational system. Although standard transmitters, sub-carrier oscillators, etc are available for this purpose some tailoring of the diagnostic system is anticipated.

7.3.4 BALLOON TRACKING

Balloon tracking is a requirement for research flights and the ALBS demonstration will use standard active and passive tracking aids. Future operational missions may not have this need. The ALBS system will also carry collision warning lights as required to meet FAA requirements.

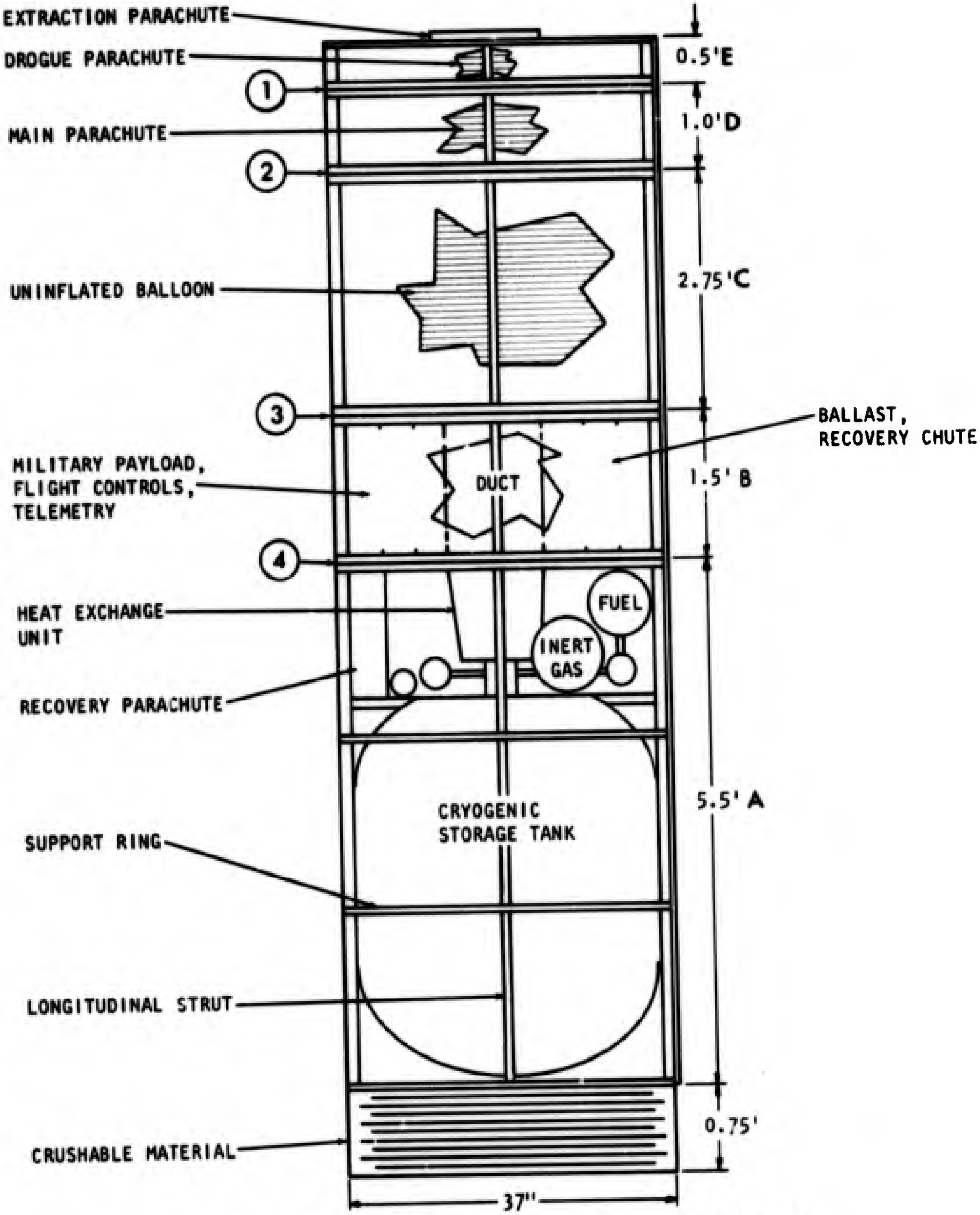
8. TRANSPORT VEHICLES

8.1 The Need to Complete the Investigation

Early in this report (Para 3.4) a cylindrical configuration was advocated as ideal for packaging the ALBS. Later on (Para 5.4.3.2), the dimensions of the cryogenic storage tank for the demonstration ALBS unit were calculated: 34 in. (0.862 m) diameter, 48.4 in. (1.23 m) length. In the intervening pages various design problems were discussed in general terms but little progress was made in the direction of attaining a specific set of ALBS module dimensions. In the interest of completing this investigation, certain design choices will now be made so that overall dimensions can be assigned to the demonstration prototype module. A range of sizes for possible operational modules will also be suggested, allowing us to consider possible candidate transport vehicles (rockets and aircraft).

8.2 Proposed Design

Figure 5 shows a proposed design of the ALBS demonstration system storage and deployment module. The design features a direct-mix type of heat transfer unit. Fuel for combustion and gaseous Helium for cryogenic expulsion are stored in separate small tanks. Balloon deployment below the main canopy (see Para 7.2.3) is also featured. With these choices the overall dimensions of the module can be estimated with reasonable accuracy: diameter. 37 in. (0.94 m); length, 12 ft (3.66 m).



NOTES: 1. ITEMS 1-4 ARE SEPARATION SURFACES (INTERFACES)
2. APPROXIMATE LENGTH OF MODULE IS 12 FEET.
3. LIFTING EYES ARE NOT SHOWN.

Figure 5. Proposed ALBS Module Design

8.3 Sub-Modular Construction

The module is made up of five sub-modules (A-E) joined together at the separation surfaces (interfaces) indicated in Figure 5.

8.3.1 THE GAS STORAGE SYSTEM

The longest sub-module, (A), approximately 5.5 ft (1.68 m), houses the gas storage and heat transfer subsystem. The components are mounted inside an open cylindrical frame constructed as shown in Figure 6, except that the container wall shown in that figure is not used in this sub-module. The weight of this sub-module is approximately 350 lb (159 kg) exclusive of framework. At the bottom surface of sub-module A is a 9 in. (0.225 m) pad of crushable material to absorb landing shock at the time of recovery. (The recovery parachute for this sub-module is shown next to interface 4.)

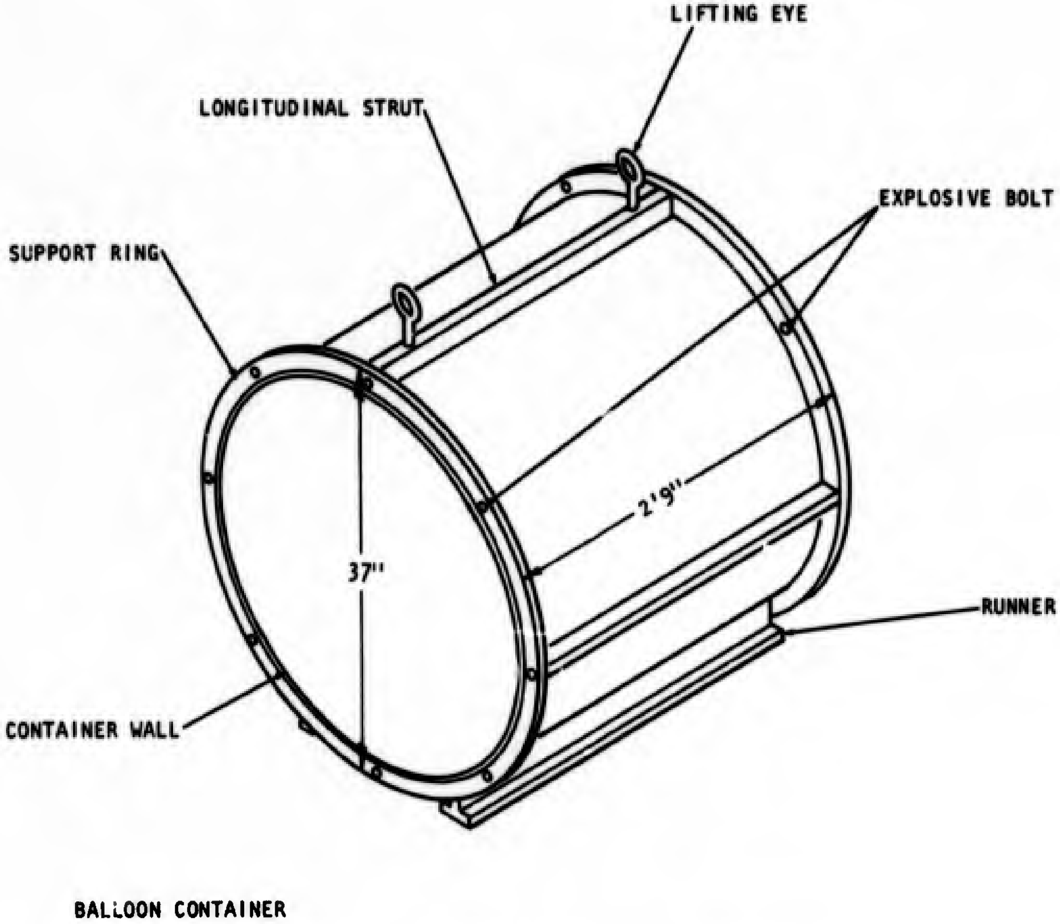


Figure 6. Typical Sub-Module Construction

8.3.2 THE PAYLOAD

The 1.5 ft (0.457 m) sub-module (B) between interfaces 3 and 4 is the payload to be carried up to float altitude by the balloon. Its components are arranged around an inflation gas duct which runs through the center. This sub-module has an exterior container wall as shown in Figure 6. Including frame, its weight is 345 lb (156.6 kg).

8.3.3 REMAINING ITEMS

The remaining three sub-modules (C, D, E), which also have container walls, house the balloon, the main parachute, and the drogue chute/extraction chute combination. Their weights and lengths are, respectively: (C) 250 lb (113.5 kg), 2.75 ft (0.84 m); (D) 70 lb (31.7 kg), 1 ft (0.305 m); (E) 30 lb (13.6 kg), 0.5 ft (0.152 m). (Weights used here are exclusive of frame weights.)

8.3.4 THE FRAME

The cylindrical frame, minus that portion of it incorporated in the payload sub-module (B), is estimated to weigh 100 lb (45.4 kg). This weight includes the weight of the crushable material.

8.3.5 WEIGHT SUMMARY

If we summarize the weights of the various components of the ALBS demonstration module we obtain a total weight of 1175 lb (532.9 kg):

Gas Storage and Heat Transfer Sub-module (A)	350 lb	158.5 kg
Gas Storage and Heat Transfer Recovery Chute	30 lb	13.6 kg
Payload Sub-module (B)	345 lb	156.6 kg
Balloon (230 lb (104.4 kg)) and Balloon deceleration Mechanism (20 lb (9.1 kg)) (C)	250 lb	113.5 kg
Main Parachute (D)	70 lb	31.7 kg
Drogue and Extraction Parachutes (E)	30 lb	13.6 kg
Frame	100 lb	45.4 kg
	1175 lb	532.9 kg

8.4 The Problem of Size

It is obvious that we are talking about a large, heavy unit, even for a net mission payload weight of only 200 lb (90.8 kg). The size of the demonstration module poses no problem with respect to launching from a C-130 aircraft, but it does hint at problems with other transport vehicles, especially if the net mission payload weight is increased. The design shown in Figure 5 is considered to be as compact as one would find with an operational design, despite the lack of streamlining at the forward end. Thus, a larger net mission payload would require a scaling up of the dimensions shown, thereby leading to increased volume, increased drag (larger diameter) and/or increased bending moment (longer length). (See Para 8.6 below.)

8.5 Separation Sequence

Before leaving Figure 5, a brief discussion of the separation sequence is in order. Figure 7 should also be consulted in this discussion.

8.5.1 EXTRACTION CHUTE /DROGUE CHUTE DEPLOYMENT

When the module is ready for launching from the cargo aircraft at 25,000 ft (7.62 km) the extraction chute will be deployed in the airstream aft of the cargo opening. Its drag will pull the module clear of the aircraft (Figure 7a). Explosive bolts will fire at interface 1, causing the drogue chute to be deployed and to effect the initial vertical deceleration of the system. (The extraction chute and drogue chute container are cut free.) (Refer to Figure 7b.)

8.5.2 MAIN CHUTE DEPLOYMENT

Explosive bolts at interface 2 are then fired (by automatic programming). The main chute is extracted from its container by the weight of the falling system. (The drogue chute supports the container. Upon inflation of the main chute the drogue chute and container are cut free.) (Refer to Figure 7c.)

8.5.3 BALLOON DEPLOYMENT

When the desired dynamic pressure value (0.5 psf, see Para 7.2.6.3) is attained the bolts at interface 3 fire, causing the balloon to be pulled down from its container (Figure 7d).

8.5.4 BALLOON INFLATION

When the balloon is fully deployed, inflation begins. (Safe balloon deployment, incidentally, is attained through use of a reefing sleeve (Para 7.2.6.5) and a deceleration mechanism (Refer to Para 7.2.4) to relieve stresses on the balloon material. Neither device is shown in Figure 7.) Near the completion of the inflation the balloon container and main chute are cut free (Figure 7e), because the wake of the nearly-inflated balloon interferes with the airstream to the main chute, causing it to collapse.

8.5.5 HARDWARE SEPARATION

Upon completion of the inflation process the bolts at interface 4 are fired. This causes the gas storage and heat transfer sub-module to separate from the balloon and its payload. The inflation hardware then descends to earth on its own recovery chute while the balloon and payload ascend to float altitudes (Figure 7f).

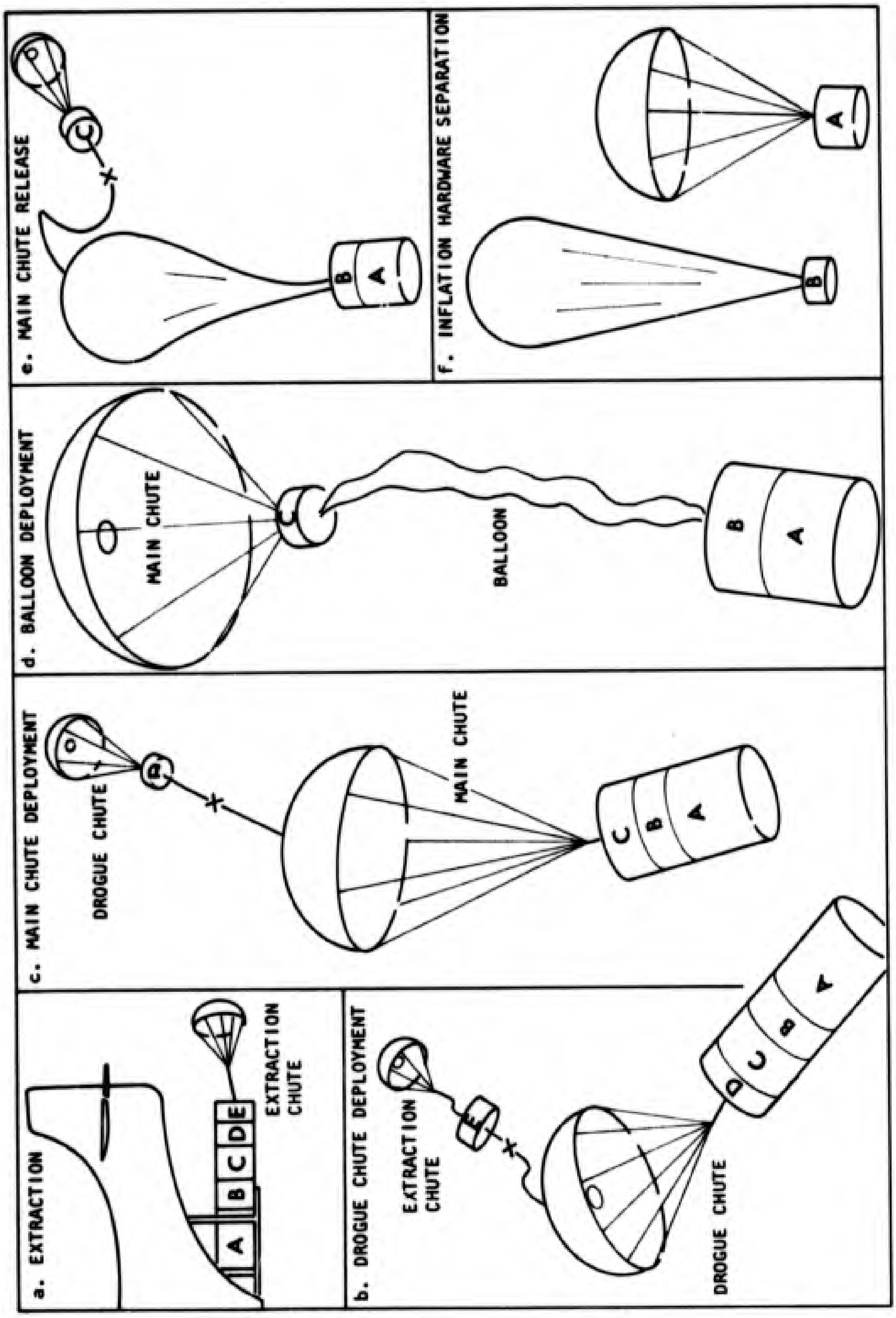


Figure 7. Deployment Sequence (ALBS Demonstration Unit)

8.6 A Range of Size for Operational Systems

Calculations performed earlier in this report enable us now to establish a range of sizes for possible operational ALBS modules. Although the earlier calculations considered both Helium and Hydrogen, the following discussion will be for Helium only. The principles involved apply equally to Hydrogen, but the values presented illustrate the more severe accommodation problem as far as potential transport vehicles are concerned, namely the large systems required when Helium is the inflatant.

8.6.1 100 LB LHe NEEDED FOR DEMONSTRATION SYSTEM

Having established that a net mission payload of 200 lb (90.8 kg) would lead to a system buoyant weight of 575 lb (261 kg) (Para 4.2.2), we went on to determine the mass of LHe needed to lift the 575 lb. This turns out to be 100 lb (45.36 kg) including free lift (Para 4.4.2).

8.6.2 STORAGE TANK DIMENSIONS FOR DEMONSTRATION SYSTEM

As noted on Table 1, 100 lb of LHe requires an internal storage tank volume of 14.1 ft^3 (0.395 m^3), including ullage. In Para 5.4.3 the length of a 2.5 ft (0.762 m) diameter tank with this internal volume is calculated to be 44.4 in. (1.13 m). With a 4-in. wall thickness and insulation allowance, the external tank dimensions become: (diameter) 34 in. (0.862 m); (length 48.4 in. (1.23 m). Those dimensions are the pacing factors in the ALBS design shown in Figure 5.

8.6.3 USEFUL RATIOS

If we resort to approximations, we note that the Helium-inflated system buoyant weight, plus 10 percent free lift, is roughly three times the net mission payload weight: (575 lb + 10 percent) vs 200 lb. The gross weight, 1175 lb, is roughly six times the net mission weight. Assuming that these convenient ratios are valid for larger systems, we can derive the range of approximate system buoyant weights and gross weights shown in Table 3 below:

8.6.4 WORST CASE VOLUME

If we take the worst case, a net mission payload weight of 1000 lb (454 kg) and divide the corresponding system buoyant weight, 3000 lb (1360 kg) by the LHe Lgas/Mgas ratio, 6.25 (see Para 4.4.1) we obtain the mass of LHe required, 480 lb (218 kg). If we now divide that figure by the density of LHe, 7.8 lb/ft^3 (0.125 g/cm^3) we obtain the volume occupied by that mass of LHe at its normal boiling point, 61.5 ft^3 (1.74 m^3). Adding 10 percent for ullage, we arrive at an internal tank volume of 68 ft^3 (1.93 m^3).

Table 3. Range of Helium-Inflated ALBS Operational System Weights (Approximate)

Net Mission Payload Weight (lb)	(kg)	System Buoyant Weight (lb)	(kg)	System Gross Weight (lb)	(kg)
200	90.8	600	272	1200	545
300	136	900	408	1800	816
400	182	1200	545	2400	1090
500	227	1500	680	3000	1360
600	272	1800	816	3600	1635
700	318	2100	952	4200	1905
800	363	2400	1090	4800	2180
900	408	2700	1226	5400	2450
1000	454	3000	1360	6000	2720

8.6.5 TANK LENGTH, WORST CASE VOLUME (2.5 ft (0.762 m) dia)

Using the formulas expressed in Par 5.4.3 we can calculate the internal length (L) of a domed LHe storage tank with an internal diameter (d) of 2.5 ft and an internal volume (V) of 68 ft^3 (1.93 m^3):

$L = h + d$ h = the length of the cylindrical section (See Figure 8)

$= 12.2 + 2.5$ $= \left(V - \frac{\pi d^3}{6}\right) \left(\frac{4}{\pi d^2}\right)$

$= 14.7$ ft (4.49 m) $= \left(68 - \frac{125\pi}{48}\right) \left(\frac{16}{25\pi}\right) = 12.2$ ft (3.72 m)

Adding 4 in. to cover tank wall thickness and insulation, we obtain an external tank length of 15 ft (4.58 m).

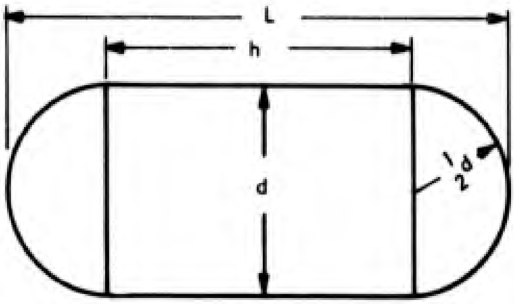


Figure 8. Domed Tank Configuration

8.6.6 NEED TO GO TO LARGER DIAMETERS

Note that the inflation tank alone is now longer than the demonstration ALBS module described in Figure 5. If we add the other sub-modules, appropriately increased in size, we can expect a total ALBS module length in excess of 23 ft (7.02 m) when the net mission payload is 1000 lb (454 kg). Bending moment and aerodynamic stability problems are most likely with such a configuration and a shift to larger diameter seems appropriate here.

8.6.7 EFFECT OF DIAMETER ON TANK LENGTH

Table 4 shows how the 68 ft^3 (1.93 m^3) cryogenic tank length is shortened as the tank diameter is increased. This leads to a corresponding shortening of the overall ALBS storage and deployment module. With a doubling of the tank diameter, from 30 in. (0.762 m) to 60 in. (1.524 m), it is estimated that the overall module length could be reduced by 50 to 60 percent.

Table 4. Cryogenic Storage Tank Length vs Diameter

Internal Diameter $(d)^5$			$h^{1,2}$		Internal Length $(L)^{3,4,5}$	
in.	ft	m	ft	m	ft	m
30	2.5	0.762	12.2	3.72	14.7	4.49
36	3.0	0.915	7.61	2.32	10.6	3.24
42	3.5	1.067	4.72	1.44	8.22	2.51
48	4.0	1.220	2.75	0.84	6.75	2.06
54	4.5	1.372	1.27	0.39	5.77	1.76
60	5.0	1.524	0.12	0.04	5.12[6]	1.56

Notes: 1. h is the length of the cylindrical section as shown in Figure 8.

2. $$h = \left(V - \frac{\pi d^3}{6}\right) \quad \left(\frac{4}{\pi d^2}\right)$$

3. The internal volume of the tank, V, is 68 ft^3 (1.93 m^3)

4. $L = d + h$

5. Add 4 in. (0.103 m) for wall thicknesses and insulation to get external dimensions.

6. Note that when $d = 60$ in. (5 ft) (1.52 m) the value of h is nearly 0, that is, the tank is spherical in shape. As a cross check, we can compute the diameter of a spherical tank of 68 ft^3 volume: $V = \frac{\pi d^3}{6}$:

$$d = \sqrt[3]{\frac{6V}{\pi}} \qquad \sqrt[3]{\frac{6 \times 68}{\pi}} = 5.11 \text{ ft } (1.56 \text{ m})$$

8.7 Drag Considerations, Aircraft Mounting ALBS

For aircraft wing pod mounting, the ALBS module presents a drag problem which has an impact on mission effectiveness. Thus, if we consider the situation where a KC-135 aircraft is the transport vehicle, each large (1000 lb (454 kg) net mission payload) ALBS module carried externally is roughly the equivalent (drag wise) of a spare jet engine mounted under the wing. (The J-57 turbojet (KC-135A) has a diameter of 39 in. (0.99 m) and a length of 14 ft (4.27 m). It weighs about 4200 lb (1905 kg). The TF-33 turbofan (KC-135B) has a diameter of 53.0 in. (1.36 m), a length of 12 ft (3.66 m) and weighs about 4600 lb (2040 kg)). Jet transports have frequently been used to carry spare engines under the wing over long distances to solve engine logistics problems. Even the very large diameter 95.6 in. (2.44 m) JT9D engines used on the Boeing 747 are carried this way, as a faired pod. The drag penalty is considered economically acceptable by the airlines employing this method. There appears to be no reason why one suitably faired large ALBS module could not be carried under the wing of a KC-135, provided that the drag penalty does not reduce mission range and loiter time to an unacceptable level. It is to be remembered here that the size figures given in Table 4 are for the worst case, i.e. for a 1000 lb (454 kg) net mission payload (gross weight 6000 lb (2720 kg). Smaller net mission payloads would, naturally, require less bulky and lighter ALBS modules with reduced drag penalties. Two such modules might possibly be carried by a KC-135.

8.8 Possible ALBS Transport Aircraft

The KC-135 method of transport has the obvious disadvantage of external mounting which limits the number of modules which may be carried, reduces aircraft range and prevents inflight access to the payload. Launching from the underwing pod is not expected to pose any major problems however, with the deployment sequence essentially as shown in Figure 7 (once the pod is released from the aircraft). The main advantage of using a KC-135 (or C-135) is that it allows the ALBS to be added on to an aircraft dedicated to a corrollary mission. The C-141 aircraft, on the other hand, allows internal storage thus permitting more units to be carried without a drag penalty. Launching is the same as for the C-130. The use of that type of aircraft on an operational ALBS mission, however, means its diversion from its primary role as a logistics support aircraft, which may not always be possible. A third possibility is the employment of a bomber type of aircraft, such as the B-52, where both internal and external storage is feasible and higher launching altitudes can be attained. Whether such an aircraft could be made available for ALBS operations is not known.

8.9 Other Factors in Choice of Aircraft

The decision to employ a particular type of aircraft in the ALBS transport mission is an operational one which depends on such factors as itinerary, time on station, need to adjust payload in flight, aircraft availability, etc. Those factors can only be mentioned in passing here, but it should be clear that they will affect not only the choice of aircraft, but also the ultimate design of the ALBS it is to carry. In a similar way, the design of the rocket-borne ALBS is a function of its transport vehicle.

8.10 Rocket Trajectories

Envisioned rocket launchings include the short range "straight-up" or vertical trajectory and the long-range remote target area trajectory, as well as intermediate length trajectories. The long range 1000-1500 miles (1609-2413 km) trajectory implies a high Mach No. release of the capsule from the rocket and the need to dissipate horizontal as well as vertical velocity energy. On the other hand, a straight-up trajectory imparts little horizontal motion, and, in addition, vertical acceleration problems can be minimized.

8.11 Available Rocket Systems and Points to be Considered

There are rocket motors in the inventory today whose diameters are in the range shown on Table 4 and whose thrust is such that they are capable, as a class, of putting the ALBS capsule on station. They are the motors used with such rocket systems as the Scout, Athena, Polaris, etc. There will be no attempt here to single out specific vehicles. Rather the emphasis will be on points to be considered in selecting a rocket motor for a particular application.

8.11.1 ACCELERATION FORCES

In general, a slower burning motor is to be preferred, to minimize "g" forces on the cryogenic storage systems.

8.11.2 AEROELASTIC STABILITY

The more slender rocket motors, e.g. 30 in. (0.762 m) diameter, require that the payload be distributed over a longer length when the payload diameter is the same as the motor diameter. This leads to aeroelastic stability problems.

8.11.3 HAMMERHEAD CONFIGURATIONS

Hammerhead configurations (i.e. ALBS module diameters are greater than rocket motor diameters) are possible but require special care to avoid excessive bending moments.

8.11.4 CLUSTERING

Clustering (multiple rocket motors) may be necessary to compensate for serious payload-motor diameter mis-matches.

8.11.5 STAGING

Staging may be necessary for long range trajectories.

8.12 Feasibility of Rocket-Launched ALBS

The choice of a rocket for a particular mission is a subject worthy of a separate report. Nevertheless, it seems feasible, at this point in time, to include a family of rocket-borne ALBS systems within the broad planning concepts.

9. SUMMARY AND CONCLUSIONS

This report has examined many aspects of the problem of putting a balloon-supported payload in the sky at short notice. It has covered past endeavors and the need for larger, more flexible systems. Cryogenic storage of the inflatant has been singled out as the most feasible method of overcoming the traditional gas storage tank weight problem. The relative merits of liquid Hydrogen and liquid Helium have been defined in sufficient detail to allow a choice to be made between the two inflatants for a specific operational use. The various types of fuels needed to heat the Cryogen to ambient temperature have been identified. Safety hazards, particularly with Hydrogen, have been pointed out. Cryogenic storage problems were discussed at length and the need for supplemental refrigeration has been described. Calculations have been carried out to determine component sizes, Cryogen and fuel quantities, and overall system sizes. Transport vehicles have been matched with calculated system dimensions.

In several cases no definitive answers were obtained (e. g., identification of the best balloon material, choice of heat transfer method, type of balloon deployment (above or below main canopy)). However, an attempt was made in each such case to point out the advantages and disadvantages of possible approaches and to suggest methods of resolving the various issues.

In general, it is concluded that the ALBS concept is sound, technically. No impediments were uncovered which would prevent the concept from being feasible. On the other hand, it is obvious that many of the details must be verified by laboratory and field tests before the concept can be considered valid as an operational tool. This is particularly true of the deployment sequence and the heat transfer method.

There is some doubt as to the cost feasibility of the system. The components of the basic ALBS module will be expensive and non-recoverable in a typical operational mission. The rocket vehicle will also be very costly and expended after one usage. The justification for the cost must come from the mission value of the payload on station.

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Appendix A

Specific Lift

A1. BASIC AEROSTATIC FORMULA

When a volume of a gas which is lighter than air, such as Hydrogen or Helium, displaces an equal volume of air, the potential for providing lift is present. If the gas can be contained in a light-weight envelope, such as a balloon, and if there are lines from the balloon to support an attached object, the balloon will lift the object in accordance with the basic aerostatic formula (which derives from the ancient Archimedean principle of buoyant lift):

$$W_T = W_{air} - W_{gas}$$

where W_T = weight of the object lifted, plus weight of the balloon

W_{air} = weight of the volume of air displaced

W_{gas} = weight of the volume of gas displacing the air

A2. SPECIFIC LIFT VALUES FOR HELIUM AND HYDROGEN

A2.1 'Standard Day' Conditions

From the above relationship has come the very useful concept of specific (or unit) lift, that is, the lift provided by each cubic foot of the gas used in the balloon. The specific lifts of pure Helium (He) and Hydrogen (H_2) are calculated as follows (for the "standard day" temperature and pressure conditions of 59°F (15°C) and 29.92 in. Hg ($1.01 \times 10^5 N/m^2$):

$$\begin{array}{rl|rl}
W_{air} & = 0.07651\ \mathrm{lb/ft^3}(1.225\ \mathrm{kg/m^3}) & W_{air} & = 0.07651\ \mathrm{lb/ft^3}(1.225\ \mathrm{kg/m^3}) \\
-\ W_{He} & = 0.01056\ \mathrm{lb/ft^3}(0.169\ \mathrm{kg/m^3}) & -\ W_{H_2} & = 0.00532\ \mathrm{lb/ft^3}(0.085\ \mathrm{kg/m^3}) \\
\mathrm{Sp._{He}\ Lift} & = 0.06595\ \mathrm{lb/ft^3}(1.056\ \mathrm{kg/m^3}) & \mathrm{Sp._{H_2}\ Lift} & = 0.07119\ \mathrm{lb/ft^3}(1.140\ \mathrm{kg/m^3})
\end{array}$$

Note that the specific lift of H_2 is $\frac{0.07119}{0.06595}$ or 1.08 times that of He.

A2.2 Effect of Increasing Altitude

From the above, it can be seen that 1000 $\mathrm{ft^3}$ (28.32 $\mathrm{m^3}$) of He and H_2 will lift gross weights (weight of balloon is included) of 66 and 71 lb (30 and 32.2 kg) respectively, at standard day conditions, which are basically sea level conditions. If we wish our balloon to float at a particular altitude, we must take into account the fact that the inflation gas expands greatly with increasing height (to match the decreased atmospheric density) and, at the same time, experiences a sharp decrease in specific lift.

To obtain the specific (unit) lift of a cubic foot of inflation gas at float altitude, we multiply the "standard day" value by the density ratio $\frac{\rho}{\rho_0}$ appropriate to the height in question. (The density ratio is from standard tables and reflects atmospheric temperature and pressure changes with altitude.) Table A-1 illustrates the changes with height for He of 95.5 percent purity. Note that at 50,000 ft (15.3 km), 1000 cu ft (28.32 $\mathrm{m^3}$) of He will lift only 9.6 lb (4.56 kg), less than 1/6 of the sea level lift of the same volume of gas. At the same time, each cubic foot (0.028 $\mathrm{m^3}$) of the gas at sea level has now expanded to over 6 cu ft (0.17 $\mathrm{m^3}$) at 50,000 ft. (Expansion is determined by dividing the standard day volume by the appropriate density ratio.)

Table A-1. Density Ratio and Unit Lift as a Function of Altitude
Helium - 95.5 Percent Purity

ALTITUDE		$\frac{\rho}{\rho_0}$	UNIT LIFT	
ft	km		lb/cu ft	kg/m^3
Sea Level		1.000	0.063	1.04
1,000	0.30	0.971	0.0612	0.98
2,000	0.61	0.943	0.0594	0.95
5,000	1.52	0.862	0.0543	0.87
10,000	3.05	0.738	0.0465	0.74
20,000	6.10	0.533	0.0336	0.56
50,000	15.24	0.153	0.0096	0.15
80,000	24.38	0.036	0.0024	0.04
100,000	34.48	0.014	0.0009	0.01

A similar table can be prepared for H_2 by multiplying the standard day specific lift of H_2 (0.07119) by the appropriate standard values of $\frac{\rho}{\rho_0}$.

The specific lift concept deals with equilibrium conditions, that is, it tells the volume of gas needed to support a particular load when the system is floating at a given altitude in the standard atmosphere. In actual practice, an unbalanced condition of excess lift (approximately 10 percent) is introduced initially to cause the balloon to ascend from the launch point to float altitude. At float altitude, which is a function of the volume of the fully expanded balloon, the gas which supplied the excess lift is valved to the atmosphere.

Appendix B

Expansion Ratios

B1. CRYOGENIC SYSTEMS

The expansion ratio for a liquefied gas is obtained by dividing the density of the gas in its liquid state by the density of the gas under standard day 59°F (15°C), 29.92 in. Hg ($1.01 \times 10^5 N/m^2$) conditions. The dimensionless result is the factor of expansion for the liquid. It tells how many feet of gas (at standard conditions) a cubic foot of the liquid will yield upon vaporization. It is a very useful factor, as explained in Section 5 of the text.

For LHe the expansion ratio is $\dfrac{7.8\ \mathrm{lb/ft^3}}{0.01056\ \mathrm{lb/ft^3}} \quad \dfrac{(0.125\ \mathrm{g/cm^3})}{(0.169 \times 10^{-3} \mathrm{g/cm^3}} = 738.6$

For LH_2 the expansion ratio is $\dfrac{4.43\ \mathrm{lb/ft^3}}{0.00532\ \mathrm{lb/ft^3}} \quad \dfrac{(0.071\ \mathrm{g/cm^3}}{(0.085 \times 10^{-3}\ \mathrm{g/cm^3}} = 832.7$

> Note: Cryogenic textbooks show the expansion ratios for LHe and LH_2 as 780 and 865 respectively, based on warming to 300°K (80°F).

The above expansion ratios furnish a check on the balloon volume computations carried out in Para 4.3.1 of the text. If we multiply the ER for each Cryogen by the required tank volume (in cu ft, less ullage) of that Cryogen, we obtain the gaseous volumes (under standard day conditions) resulting from the liquid to gas conversion. If we divide those volumes by the density ratio for 80,000 ft, we obtain the expanded volumes of gas needed at float altitude. Table B-1 shows results of those calculations, which are in good agreement with the earlier computations.

Table B-1. Balloon Volumes Calculated from Expansion Ratios

Item	Description	LHe	LH_2
1	Expansion Ratio (ER) of Liquefied Gas	739	833
2	Required Volume of Liquid, w/o ullage (2)	11.8 ft^3 (0.334 m^3)	9.62 ft^3 (0.272 m^3)
3	Yielded (Standard Day) Volume of Gas (3)	8720 ft^3 (247 m^3)	8013 ft^3 (227 m^3)
4	Density Ratio (ρ/ρ_0) for 80,000 ft altitude	0.036	0.036
5	Expanded Volume of Gas at 80,000 ft altitude	242,000 ft^3 ($6.86 \times 10^3 m^3$)	223,000 ft^3 ($6.32 \times 10^3 m^3$)

Notes:

1. Figures are accurate only to three places.
2. Item 2 is less than the Table 1 (Main text) value by 10 percent because it does not include the free lift allowance. Free lift is not a balloon size determinant.
3. Item 3 is the product of items 1 and 2.
4. Item 5 is obtained by dividing item 3 by item 4.

B2. COMPRESSED GAS SYSTEMS

For compressed gas systems the expansion ratio refers to the number of cubic feet of gas (under Standard Day conditions) yielded by one cubic foot (0.028 m^3) of gas stored under high pressure. If we take the example of a 2400 lb $in.^{-2}$ (163 atm, $1.65 \times 10^7 N/m^2$) compressed gas cylinder which yields 240 ft^3 (0.68 m^3) of gas at standard conditions, we can determine its expansion ratio through Boyle's and Charles' Laws (T = constant):

(1) $V_2 = \frac{P_1V_1}{P_2}$ where V_2 = compressed volume (ft^3)

V_1 = volume at standard conditions

= 240 ft^3

$= \frac{14.7 \times 240}{2400}$ P_1 = pressure at standard conditions

= 14.7 lb $in.^{-2}$

= 1.47 ft^3 P_1 = 2400 lb $in.^{-2}$

= 0.042 m^3

(2) Expansion Ratio = 240/1.47 = 163

(3) If we assume that the gas in the cylinder is He, and divide this expansion ratio into the expansion ratio for LHe, we see the factor of merit (FOM) for the cryogenic storage system: $\frac{739}{163} = 4.52$

With higher gas cylinder pressures, the expansion ratio will rise and the factor of merit for cryogenic systems will decline: At a working pressure of 6000 lb $in.^{-2}$ (408 atm, $4.12 \times 10^7 N/m^2$) (which is considered a very high pressure), the ER is calculated as follows:

(1) $V_1 = \frac{V_2P_2}{P_1}$ where V_1 = yield at standard conditions

V_2 = 1.75 ft^3 (0.05 m^3) = compressed volume

$= \frac{1.75 \times 6000}{14.7}$ P_1 = 14.7 lb $in.^{-2}$(1 atm, $1.01 \times 10^5 N/m^2$)

P_2 = 6000 lb $in.^{-2}$

V_1 = 714 ft^3 (20.2 m^3)

(2) Expansion Ratio = 714/1.75 = 408

(3) The FOM for cryogenic storage in this case is 739/408 = 1.81

> Note: Van der Waals forces have been ignored in the above illustration. If included they would have the effect of reducing compressibility of the gas system. This makes the factor of merit for cryogenic systems correspondingly higher.

It may be concluded from the above that cryogenic systems are inherently more efficient storage systems for inflation gases, their relative efficiency, with respect to compressed gas systems, being more pronounced when normal working pressures (2400-3000 lb in.$^{-2}$; 1.65-2.06 x 10^{7}N/m^{2}) of the latter systems are considered. Storage efficiency is only one consideration, however, storage life, cost and ease of maintenance must be considered in choosing a storage system for a particular application. Even so, the growing proliferation of cryogenic railroad tank cars and over-the-road tank trailers indicates the general acceptance by industry of the superiority of cryogenic storage. No-loss cryogenic shipments of LHe to Europe and to Japan are now being carried out routinely and economically, via ship transport of the over-the-road tank trailers--a tribute to modern insulation techniques.

Appendix C

Cryogenic Tank Relief Pressures

C1. DETERMINATION OF RELIEF PRESSURE SETTING

In an unrefrigerated and unshielded cryogenic storage system (see Para 5.4.2) the problem is to avoid undesirable loss of mass through premature or unnecessary relief venting. Because strength limitations of the storage tank place an upper limit on the permissable pressures inside the tank, the conservative relief pressure setting of 100 lb in^{-2} abs (6.8 Atmospheres, $6.87 \times 10^5 \mathrm{N/m}^2$) was chosen initially in this study as a preferred value, consistent with industrial practice. We shall now examine the ramifications of venting at that pressure setting, to see whether it is the most desirable value with respect to storage potential, safety, and economy of design. As part of our examination we shall look at the complexities of cryogenic storage in somewhat greater detail, and, to establish a basis for comparison, we shall calculate allowable heat gains for LHe and LH_2 under ideal storage conditions prior to the need for relief venting.

C2. ULLAGE SPACE

A 10 percent ullage space, that is, volume not occupied by the liquid, is customarily provided to allow for vapor which forms over the liquid during filling operations and as the result of heat leaks into the cryogenic fluid. Without such a vapor space rapid pressure rises would occur in the tank and a severe loss of Cryogen would be experienced as the liquid percolated through the vent line. The ALBS tanks have been sized, initially, in this study, to have the usual 10 percent ullage. In our closer examination of cryogenic storage problems we shall also assess the adequacy of the selected ullage volume.

If venting of the Cryogen must occur for pressure relief, as would be necessary with a large heat influx, it is far better that it be in the low density gaseous state, to conserve mass. When the preset relief pressure is exceeded in tanks equipped with ullage space, venting will always occur in the form of a gas if a liquid-vapor mixture is present in the tank, under the subcritical conditions described in Para C3., following. (This assumes that the tank is maintained in the proper (vertical) attitude or an all-attitude vent system is employed.) Venting in the form of vapor will also occur when the system's internal temperature, T, exceeds its critical temperature, T_c, since only the gaseous phase is then present. This can happen when the selected venting pressure (100 lb in^{-2} abs) has a higher value than the system's critical pressure, P_c, which is the pressure associated with T_c. For example, in the case of LHe, P_c is only about 33 lb in^{-2} abs and is, therefore, too low to initiate pressure relief venting. In the case of LH_2, the value of P_c is 191 lb in^{-2} abs. Since this value is well above the selected vent pressure, relief venting would occur long before T_c could be attained in the tank. Venting LH_2 at temperatures above T_c requires vent pressure settings of almost 200 lb in^{-2} abs and should be avoided because of the dangerous internal stresses. (See Para C3 for definitions of T_c and P_c and Para C5 for fuller explanations of P_c/T_c relationships.)

C3. TWO-PHASE EQUILIBRIUM

The Cryogen can exist in the tank as a liquid or as a vapor, or as a combination of the two, depending on the system temperature and pressure. Figure C-1 is a simplified phase diagram which covers the liquid and vapor phases over the temperature range from $T_{b.p.}$ to T_c. (The solid phase portion of the curve is omitted.) Note that for a particular temperature, the cryogenic system exists only as a liquid when the system pressure exceeds the value of P indicated by the curve. When P is less than the curve value the Cryogen exists as a vapor. If P equals the curve value the liquid and vapor phases coexist, with the system pressure being equal to the saturated vapor pressure of the Cryogen for the corresponding temperature. As long as the system pressure P stays at the saturated vapor pressure values (curve values) associated with the various system temperatures, i.e., moves along the liquid-vapor interface, the two phases will stay in equilibrium and the system is said to be in the sub-critical state.

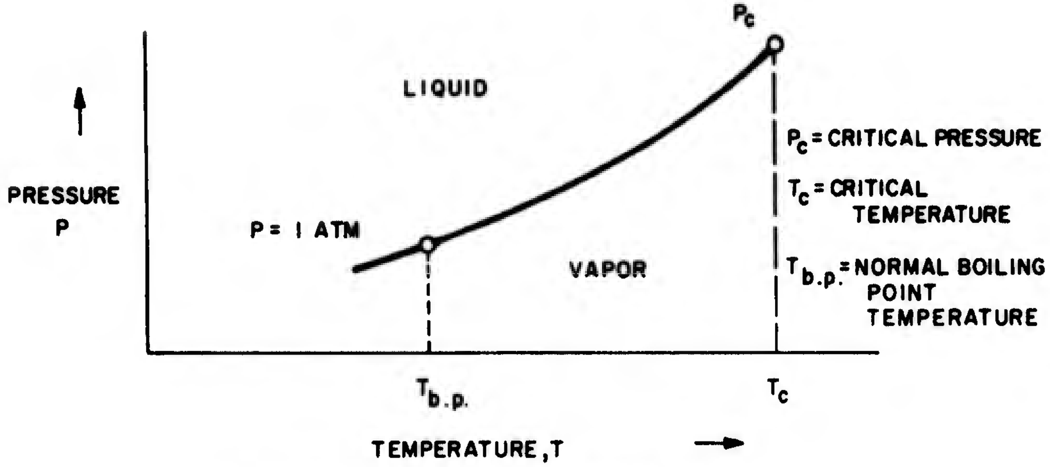

Figure C-1. Simplified Phase Diagram

The critical temperature T_c is the temperature at which the densities of the liquid and the vapor become equal. (As T rises towards T_c, the liquid density decreases and the vapor density increases.) The liquid phase disappears at this point (T_c). The saturated vapor pressure at temperature T_c is called the critical pressure P_c and it is the pressure needed to liquefy the gas at T_c. Above T_c, the Cryogen must be treated as a gas no matter what the pressure in the tank, since liquefaction is impossible above T_c.

In the above description of the conditions under which the system would exist as a liquid, vapor or liquid-vapor mixture no mention was made of how the various conditions would come about under actual storage of the Cryogen in an ALBS tank. We will now undertake that explanation.

It should be expected that a system maintained at atmospheric pressure (through pressure relief venting) will behave differently from one stored in an unvented tank. Thus, in the vented tank only the liquid will be present at temperatures below the normal boiling point temperature because the pressure of 1 atmosphere exceeds the curve values of P. Also, the Cryogen will start to boil in the vented tank when $T = T_{b.p.}$ and we will then have a two-phase (liquid/vapor) system in equilibrium, with the saturated vapor pressure of the system equal to atmospheric pressure. Boiling continues in this case, at the normal boiling point, as long as heat is supplied, until the Cryogen has been completely vaporized (and lost to the system). The heat used here is the heat of vaporization, ΔH_v.

Within the unvented tank, the ALBS system becomes a closed, constant-volume system. Assuming that filling took place at one atmosphere, the closed tank will behave like the vented tank at temperatures below $T_{b.p.}$. At the normal boiling point temperature, boiling will commence, as before, but there will be relatively little vaporization, percentage-wise. This is so because the comparatively small ullage space (10 percent) does not permit any substantial amount of vapor to exist above the liquid at the saturated pressure values. Continued heat inputs will raise the system temperature and pressure and boiling will continue at elevated boiling points, as long as T does not exceed T_c. There is no boiloff or loss of Cryogen mass, as was the case with the vented tank. In the meantime another change is occurring. With the rise in the temperature the density of the liquid decreases. This means that the volume of the liquid phase expands, compressing the vapor and raising the vapor pressure above the curve values. This condition leads to a conversion of some of the gas in the ullage space back to the liquid phase. The amount of gas actually converted back is a function of the compressibility factor, Z, which considers that the gas density is increasing at the same time the liquid density is decreasing. (See Para C5.) This increase in gas density is an inherent consequence of the rise in system temperature towards T_c and the accompanying reduction in gas volume compensates in some extent for the loss in ullage space as the liquid expands. It should be recognized that the behaviour of the gas in the vicinity of T_c marks a departure from the behaviour predicted of ideal gases.

With further heating the temperature of the system tries to rise still more in the direction of the critical temperature, the point at which complete liquid phase-to-vapor phase transformation will occur. The effects of the liquid expansion now seem dominant, however, and relief venting at temperatures below T_c is indicated.

If we assume that the expanded liquid phase is incompressible, we must conclude that the 10 percent ullage space shrinks drastically as the volume of the expanding liquid approaches the internal volume of the ALBS tank. Actually, in the case of LHe, this condition occurs just below T_c. With LH_2, on the other hand, it happens well below T_c.

Note: Referring the table C-1, let us take the case of LHe, for example, at 9°R(5°K), where the density of the liquid has a value of 6.30 lb/ft^3 (0.101g/cm^3). If only the liquid phase is present in the tank, it occupies a volume of 15.9ft^3 (0.45m^3) which exceeds the tank volume, 14.1ft^3(0.395m^3). If we arbitrarily say that 16 percent of the Helium is in the form of vapor, we are left with the 84 percent of 100 lb or 84 lb (38kg) of liquid, which, when divided by the liquid density at 9°R, occupies a volume of 13.3ft^3 (0.38m^3). This leaves a volume of 14.1-13.3 or 0.8ft^3 (0.023m^3) for the gas. Referring ahead to Para C5 we see that the 100 lb of He, as a gas, occupies approximately 20.4ft^3 at Tc, where the density of the gas is at a maximum. Inasmuch as the density of the gas at 9°R is not greater than it is at Tc (9.36°R, 5.2°K), the 16 percent or 16 lb (7.3Kg) of gas would occupy a minimum volume of 20.4 x 0.16 or 3.27ft^3 (0.092m^3). Since we have only 0.8ft^3 (0.023m^3) left in the tank for the gas, the gas pressure must increase. Changing the liquid/gas ratio to another value from that used in the example above does not alter the condition of a disappearing ullage space. Thus, as the liquid expands to fill the tank, premature relief venting must occur, with some of the Cryogen probably vented in the undesirable form of a liquid.

The above picture ignores the condition of stratification, which may be an alleviating factor insofar as venting in liquid form is concerned. Stratification occurs when the liquid is at rest, not subject to stirring, rocking, or other motions which would insure temperature homogeneity in the mass. With stratification, the upper portion of the liquid tends to be warmer than lower levels and the vapor pressure, which is a function of the surface temperature of the liquid, may be higher than would be the case if the liquid were warmed uniformly throughout. Under this condition pressures and temperatures in the upper portion of the tank may exceed critical and/or venting values, before the whole mass of Cryogen has expanded significantly. Premature gas venting would be expected in this case, until the system pressure fell below vent pressure. Repetitive ventings of this type are typical of stratified storage conditions. (One consequence of this aspect of storage is that moving cryogenic storage vessels, in which stratification is minimized, typically experience much longer non-venting periods than stationary vessels).

C4. THE NEED FOR GREATER ULLAGE

At the start of this discussion we defined the conditions of storage, which are essentially worst case conditions: a closed tank, with 10 percent ullage, whose insulating properties have not been augmented by refrigeration or vapor shielding, and whose pressure relief valve has been set at 100 lb in^{-2} abs. At this point it seems safe to say that the 10 percent ullage space will accommodate only that expansion of the liquid Cryogen which is associated with modest heat gains by the system. With any significant heat gain, venting can be expected to occur fairly rapidly and may involve percolation of the liquid. The very large unrelieved driving force resulting from the room temperature - Cryogen temperature differential makes substantial heat gains certain with time, of course. Therefore, if extended, unvented storage is a serious requirement under the specified conditions, tanks with a larger ullage space than 10 percent will be required. An ullage space of 40-50 percent would probably suffice for both LHe and LH_2. The decision to employ larger tanks would have serious overall ALBS system design repercussions, however. (See Section 8.) The costs and difficulties associated with the larger size appear to bias the argument heavily in favor of minimum size and refrigerated storage. This is a tradeoff area and it requires additional investigation of operational considerations for proper resolution.

Table C1. Expansion of Cryogenic Liquid in Closed ALES Tank as Temperature Increases

Item	LHe	LH_2
1. Mass (lb)	100 (45.36 kg)	47 (21.2 kg)
2. a. Density (lb/ft^3)	7.8 (0.125 g/cm^3)	4.43 (0.071 g/cm^3)
b. Volume (ft^3) *	12.8 (0.363 m^3)	10.6 (0.30 m^3)
c. Temperature ($^{\circ}$R) (n.b.p.)	7.57 (4.2°K)	36.7 (20.4°K)
d. Pressure (lb in^{-2} abs)	14.7 (1.01x10^5 N/m^2)(1 atm)	14.7 (1.01x10^5 N/m^2) (1 atm)
3. Tank volume, with 10% ullage (ft^3)	14.1 (0.395 m^3)	11.7 (0.328 m^3)
4. a. Density (lb/ft^3)	7.53 (0.120 g/cm^3)	4.02 (0.064 g/cm^3)
b. Volume (ft^3) *	13.3 (0.377 m^3)	11.7 (0.331 m^3)
c. Temperature ($^{\circ}$R)	8 (4.45°K)	45 (25°K)
d. Pressure (lb in^{-2} abs)	18.12 (1.24x10^5 N/m^2) (1.23 atm)	47.64 (3.25x 10^5 N/m^2) (3.22 atm)
5. a. Density (lb/ft^3)	6.30 (0.101 g/cm^3)	3.71 (0.059 g/cm^3)
b. Volume (ft^3) *	15.9 (0.45 m^3)	12.7 (0.361 m^3)
c. Temperature ($^{\circ}$R)	9 (5°K)	50 (27.8°K)
d. Pressure (lb in^{-2} abs)	28.6 (1.97x10^5 N/m^2) (1.95 atm)	81.88 (5.63x10^5 N/m^2) (5.57 atm)
6. a. Density (lb/ft^3)	----	3.19 (0.051 g/cm^3)
b. Volume (ft^3) *	----	14.7 (0.416 m^3)
c. Temperature ($^{\circ}$R)	----	55 (30.5°K)
d. Pressure (lb in^{-2} abs)	----	130.4 (8.97x10^5 N/m^2) (8.88 atm)
7. a. Density (lb/ft^3)	5.0 (.079 g/cm^3)	1.80 (0.029 g/cm^3
b. Volume (ft^3) *	20 (0.566m^3)	26.1 (0.739 m^3)
c. Temperature ($^{\circ}$R) (T_c)	9.36 (5.2°K)	59.74 (33.2°K)
d. Pressure (lb in^{-2} abs) (P_c)	33.22 (2.28x10^5 N/m^2) (2.26 atm)	191 (13.1x10^5 N/m^2) (12.98 atm)

*In all cases the volume shown is obtained by dividing the liquid density at a particular temperature into the Mass (item 1).

C5. UNVENTED 'IDEAL' STORAGE CAPABILITIES, LHe vs LH_2

If we can assume, for exercise purposes, that there is sufficient ullage space to accommodate the expanded liquid and an associated gas phase, we can compare the unvented storage capabilities of unrefrigerated and unshielded LHe and LH_2 under what amounts to ideal storage conditions. Such an examination is believed to be informative, but it has to be remembered that other factors may not allow ALBS tanks to have more than the minimum 10 percent ullage.

The task of preventing vent losses in "ideal" storage appears to be inherently far more difficult with LHe than is the case with LH_2 because of cryogenic property differences. (LHe and LH_2 cryogenic properties are summarized in Tables C-1 and C-2).

LH_2 has a higher boiling point, 36.7°R (20.4°K), than LHe 7.57°R (4.2°K). If LH_2 is stored at a temperature a few degrees below its boiling point, say at 34°R (18.9°K) the room air-Cryogen temperature differential is 519° - 34° or 485°R (269°K). This is 26°R less than the 511°R differential previously cited for LHe (see paragraph 5.4.1 in main text) and represents a relatively smaller driving force. If the temperature of the LH_2 is 10°R (5.55°K) below the boiling point initially (LH_2 freezes at 24.8°R (13.8°K), the driving force is increased somewhat, but the heat influx needed just to raise the liquid H_2 to the boiling point is considerable. (See table C-2, items 2, 3, and 6 for calculation of this heat gain when the initial temperature is 30.7°R).

In addition, there are large differences in the values of three other properties of the cryogenic fluids which appear initially to be even more significant (and more favorable to LH_2) than the difference in boiling point temperatures. Those properties are the heat of vaporization, ΔH_v, the critical temperature, T_c, and the critical pressure, P_c, which are discussed in turn in the following paragraphs.

The heat of vaporization (ΔH_v) is the quantity of heat required to transform a unit quantity of liquid to its vapor form at the boiling point. (The heat is required to overcome the attractive forces between the molecules of the liquid).

Helium's value of ΔH_v, 8.92 BTU/lb, (20.8 J/g) is relatively low and can be satisfied with a modest heat input, whereas the 192 BTU/lb (447 J/g) value for LH_2 requires better than 20 times as much of a heat gain by the fluid, for equal masses of Cryogen. (The numerical values of ΔH_v cited here are those for the normal boiling points of the Cryogens, and are higher than the ΔH_v's for elevated boiling points).

It is tempting to look upon the heat of vaporization as a heat sink or sponge which could enhance low temperature maintenance (i.e., retard vent losses) by soaking up sizeable amounts of any incoming heat flux to satisfy the thermal energy requirements of the vaporization process. However, this view assumes the conventional picture of the system remaining at a constant temperature and pressure (e.g., the normal boiling point and 1 atmosphere) until the liquid changes over completely to vapor. Since we are attempting to estimate the amount of heat our confined, closed system may gain before venting becomes necessary, correct use of the ΔH_v property demands that we consider only that vaporization which occurs wholly within the limited space of the unvented tank. (This constraint immediately eliminates the example just given of sustained vaporization at the normal boiling point temperature and a pressure of one atm, where unlimited expansion space is available).

As previously indicated (para C3) vaporization is largely inhibited within the closed ALBS tank at temperatures below T_c, when only 10 percent ullage space is provided. However, in the larger "ideal" tank (40-50 percent ullage space) much more vaporization can be accommodated. The actual value is difficult to determine because of the non-ideal behaviour of gases in the vicinity of the critical point. (Refer to Para C3). A compressibility factor, Z, is incorporated in the ideal gas equation to account for this anomalous behaviour. In our Allowable Heat Gain calculations (Table C-2) we will use an arbitrary vaporization percentage of 40 percent in the case of LH_2, where venting will occur well below T_c. As will be explained, the temperature in the LHe tank will be allowed to rise above T_c prior to venting so that 100 percent vaporization is appropriate for the LHe computations.

The numerical values of ΔH_v are not constant over the range of temperatures from $T_{b.p.}$ to T_c. As shown in figures C-2 and C-3 they decrease towards zero at T_c. Because the vaporization in the ideal ALBS tank occurs principally at elevated boiling points we will use a value of ΔH_v which is equal to the average of the normal boiling point and vent temperature values.

From Table C-2, item 14 it can be concluded that the heat of vaporization heat sink plays an important role in the Allowable Heat Gain calculations and does indeed give LH_2 a substantial edge over LHe with respect to ease of storage.

The critical temperature T_c for LHe is only 9.36°R (5.2°K), compared to 59.74°R (33.0°K) for LH_2. Of great interest here is the difference between the boiling point and the critical temperature, $\Delta T(T_c - T_{b.p})$, for the two Cryogens. That difference, as shown on figure C-1, is a measure of the temperature range over which the liquid and gaseous phases can coexist in the closed ALBS system. Thus, the heat required to raise the system temperature from $T_{b.p.}$ to T_c represents another possible heat sink ($\Delta T(T_c - T_{b.p.}) \times C_v \times M$) to assist in the cold temperature maintenance problem. $\Delta T(T_c - T_{b.p.})$ values for LHe and LH_2 are 1.79°R (1°K) and 23.04°R (12.8°K) respectively. This order-of-magnitude difference in the liquid/gas phase-coexistence temperature range values for LHe

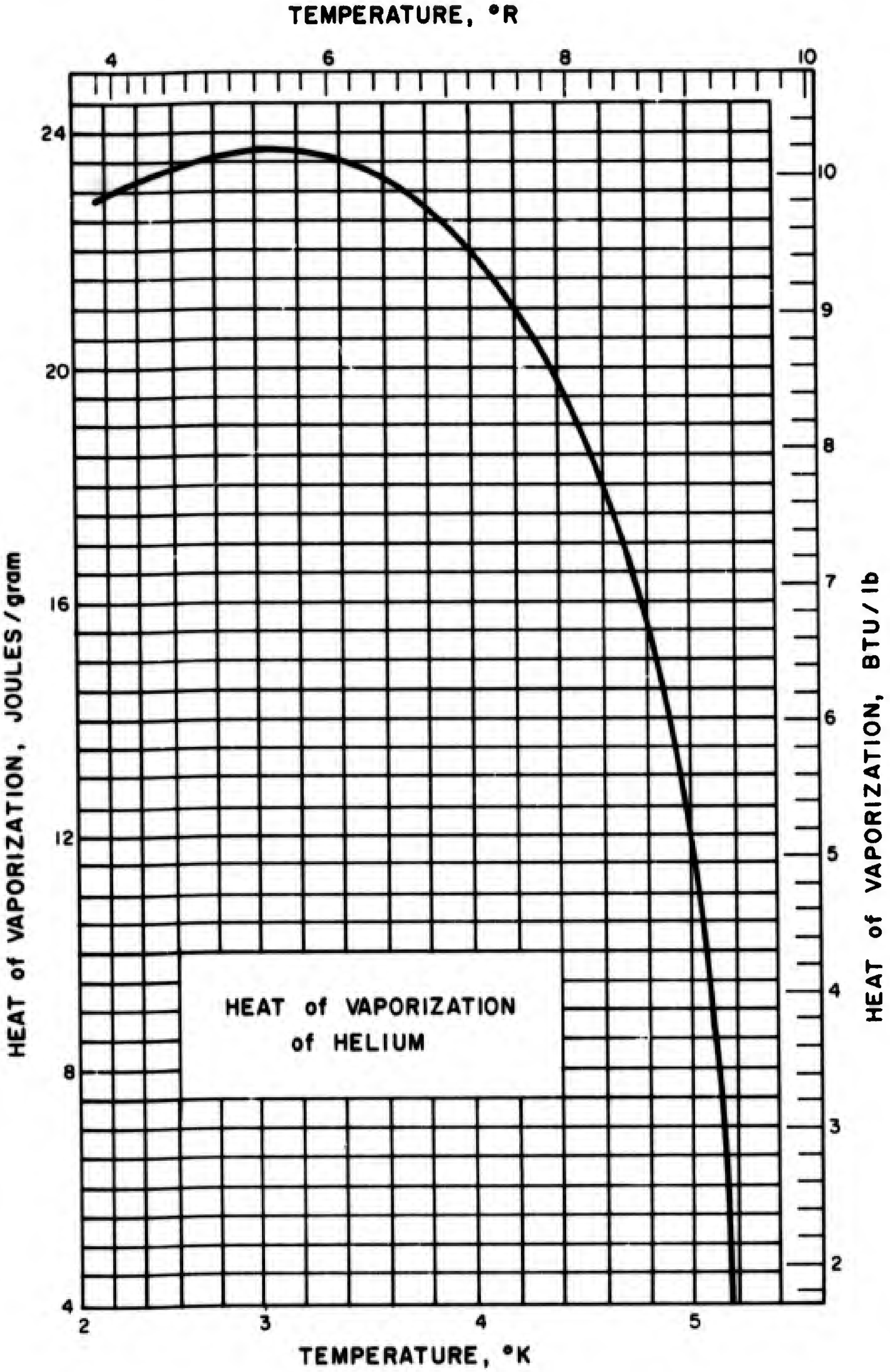

Figure C-2. Heat of Vaporization of Helium

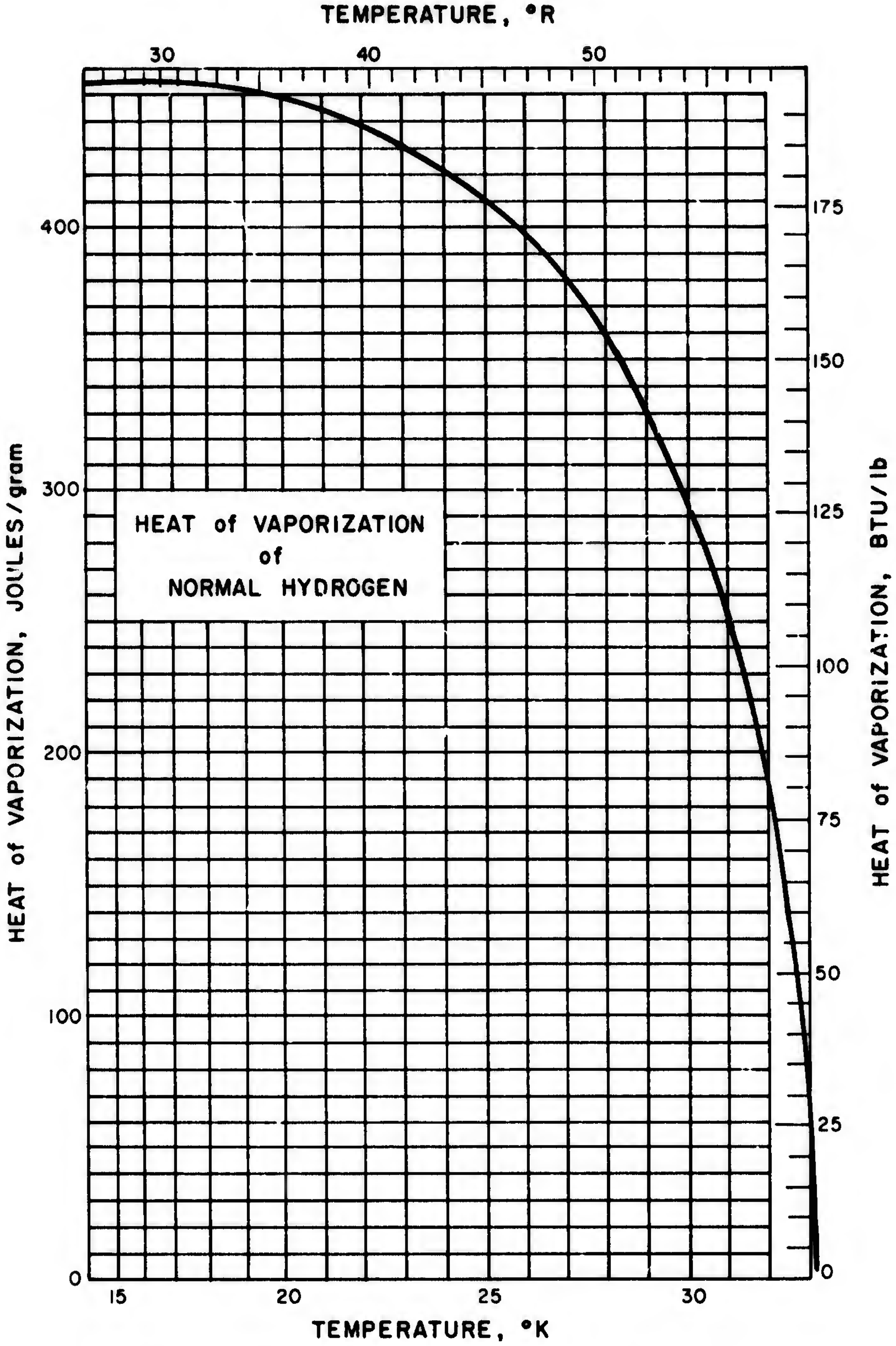

Figure C-3. Heat of Vaporization of Normal Hydrogen and LH_2 would seem to provide the LH_2 system with a $\Delta T(T_c - T_{b.p.})$ heat sink of much greater capacity than that of the LHe system. In the discussion of critical pressure in the next paragraph we will examine this point at greater length.

The critical pressure P_c is only 2.26 atm, (33.22 lb in^{-2}) for LHe, versus 12.98 atm (191 lb in^{-2}) for LH_2. The significance of the P_c in the ALBS situation is that it represents both the maximum possible internal system pressure while the two phases (liquid and gas) are in coexistence, and the exhaustion point of the $\Delta T(T_c - T_{bp})$ heat sink. Stated in another way, if the pressure at P_c does not exceed the safe limits of the "ideal" storage tank the system temperature can, conceivably, be allowed to rise to T_c, thus fully utilizing the $\Delta T(T_c - T_{b.p.})$ heat sink. Let us now examine the implication of venting LH_2 and LHe at various points along the liquid-vapor interface.

Recalling from figure C-1 that, for each intermediate value of system temperature, from $T_{b.p.}$ to T_c, there is a corresponding and specific intermediate value of saturated vapor pressure, we find from tables that a LH_2 system temperature of 52°R has an associated saturated vapor pressure of 100 lb. in^{-2} which happens to be the desired ALBS relief pressure setting. Therefore, if we vent LH_2 at 100 lb. in^{-2} we are venting at a pressure well below P_c (12.98 atm = 191 lb $in.^{-2}$) and at a temperature which is 7.7°R below T_c. From the standpoint of preventing loss of LH_2 mass this is a disadvantage since Cryogen vapor is being expended prior to the exhaustion of the $\Delta T(T_c - T_{b.p.})$ heat sink. However, to take full advantage of this heat sink, venting would have to be done at or slightly above P_c, 191 lb in^{-2}, which is almost double the preferred relief pressure and which can be considered only in the case where a heavier and stronger tank is allowable.

> Note: In this exercise, our "ideal" tank is inherently heavy because of the large (40-50 percent) ullage provided to accommodate expansion of the liquid. Because the venting pressure is only 100 lb in^{-2} abs LH_2 would have to be vented at subcritical pressures and temperatures in this tank. On the other hand, an ideal tank designed for venting LH_2 at temperatures and pressures above T_c and P_c would require thicker walls for the 200 lb in^{-2} abs working pressure. Such a tank would be considerably larger and heavier, both because of the higher stress design and also because of the greater ullage space needed to accommodate continued expansion of LH_2 between 52°R and T_c. (See Table C-1, line 7b, for LH_2). The weight and size penalties we would have to pay for not venting LH_2 until $T = T_c$ are too great, therefore, to justify going to a vent pressure equal to or higher than the critical pressures. Subcritical ($P < P_c$, $T < T_c$) venting at 100 lb in^{-2} abs seems much to be preferred even though we, thereby, leave part of the $\Delta T(T_c - T_{bp})$ sink unused.

The P_c for LHe is only 33.22 lb in^{-2} (2.26 atm). If we attempt to vent LHe in the subcritical state, as seems indicated for LH_2, we must set the relief vent at about 32 lb in^{-2}, a value which greatly underutilizes both tank strength and the heat capacity of the stored system. Here, we would be giving up stored mass prematurely, and unnecessarily, cutting down on the duration of the storage period theoretically available. As it turns out, it appears better in ideal unrefrigerated systems to allow the LHe temperature to exceed T_c slightly so that there is a complete changeover to the gaseous phase inside the tank. LHe venting is then done from the all vapor phase at the preset relief pressure. Because the densities of the gas and the liquid are equal at T_c, there is not a sharp, explosive expansion at the change of state. However, the density of the gas decreases fairly rapidly above T_c and the internal pressure of the tank will build up as the gas seeks to expand. If the tank is set to vent at 100 lb in^{-2} abs, venting will begin after a short temperature rise.

In para 6.7.2 (3) we calculated the volume occupied by 1/2 lb mol. of CO_2 at STP (0^oC, 1 atm). The answer (179 ft^3) agrees with the textbook value of 359 ft^3 per lb mol. of any gas at STP. Now, if we divide the mass of LHe in our tank, 100 lb, by the molecular weight of He in lb, 4, we see that we have 25 lb mol of LHe, which should occupy 25x359 ft^3 or 8, 975 ft^3 at STP. In accordance with the combined Boyle's and Charles' laws, assuming ideal gas behaviour for the moment,

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Thus, the volume of the gaseous helium, V_2, at the critical point ($P=P_c$, $T=T_c$) should be equal to the volume at STP multiplied by the ratio of the critical temperature to the standard temperature and by the inverse of the ratio of the critical pressure to the standard pressure:

$$V_2 = \frac{V_1T_2P_1}{T_1P_2}$$

or

$$V_2 = 8975 \times \frac{5.2}{273} \times \frac{1}{2.26} = 75.5\ ft^3$$

where:

$$\left\{\begin{array}{lcl} V_1 & = & \text{Volume at STP} \\ V_2 & = & \text{final volume} \\ P_1 & = & 1\ \text{atm} \\ P_2 & = & 2.26\ \text{atm} = P_c \\ T_1 & = & 0^oC = 273^oK \\ T_2 & = & 5.2^oK = T_c \end{array}\right.$$

The volume of 75.5 ft^3 which the ideal gas should theoretically occupy at 5.2^oK is roughly four times the volume of 20 ft^3 (Table C-1, line 7b) it actually occupies at T_c at the time of phase transformation, when the densities of the gas and liquid are equal. This indicates that the gas density at the critical point is a unique maximum value. If we multiply the 75.5 ft^3 by 0.27, which is the value of Z, the compressibility factor, for most gases at the critical point, we obtain a reduced volume of 20.4 ft^3 which is the approximate volume of line 7b, table C-1.

Above T_c, the value of Z climbs towards unity, eventually becoming large enough (e.g., 0.8) to permit quasi-ideal gas behaviour, that is expansion nearly to the theroetical volume. The problem is to determine the spread in degrees between T_c and the temperature at which the value of Z leads to a pressure of 100 lb in^{-2} abs. A rise of 1.8°R (1°K) has been chosen arbitrarily for this study (see Table C-2; item 10) and is subject to correction. Note that this has the effect of extending the $\Delta T(T_{vent}-T_{b.p.})$ heat sink for LHe to a point above T_c and requires that it be calculated in two increments.

C6. A CONCLUSION ON THE CHOICE OF VENTING PRESSURE

It appears from the foregoing that the 100 lb in^{-2} abs venting pressure is a reasonable choice in that it allows full use of the $\Delta T(T_c-T_{b.p.})$ heat sink for LHe, and avoids the need to maintain the liquid in a subcritical state for venting. The 100 lb setting is also more consistent with volume and weight limitations in sizing ideal LH_2 storage tanks, even though it means under-utilizing the $\Delta T(T_c-T_{b.p.})$ heat sink.

C7. ALLOWABLE HEAT GAINS IN STORAGE

Table C-2 shows calculations used to determine allowable heat gains per day for LHe and LH_2 in ideal storage if the Cryogen must be maintained without supplemental refrigeration or shielding, and without venting, for 10 days. Values are given for nominal pressure relief settings of 100 lb in^{-2} abs. Initial LHe and LH_2 temperatures are arbitrarily chosen as 7°R and 30.7°R, respectively. For liquids initially at or very near boiling points, the allowable heat gain is less, since the factor $\Delta H(T_{b.p.}-T_i)$ disappears. The calculated values obtained in Table C-2 must be treated as approximations only, because of the many arbitrary values of factors and temperature differentials employed.

C.7.1 Conclusions from Table C-2:

The approximate daily allowable heat gain figures for LHe and LH_2 are given in item 16 of Table C-2. Two facts emerge quickly from the figures.

First, the LHe value is small, 84.2 BTU/day (8.9×10^4 J/day), and, without supplemental refrigeration, or shielding, would require very carefully designed and applied insulation material, evauated separation spaces, etc. Even so, unvented storage beyond ten days under these conditions is highly unlikely.

Second, the non-vented storage of LH_2 is clearly an easier task, because of the higher (by a factor of six) daily allowable heat gain. This is attributable to the greater values, in the case of LH_2, of the ΔH_v heat sink and of the heat sink between the boiling point temperature and the selected vent temperature, and, also, to the higher value of C_v for LH_2 versus that for LHe.

It is to be emphasized, again, that the figures derived in Table C-2 are for ideal storage, that is, for tanks with 40-50 percent ullage space. With smaller (and more reasonably priced) tanks, daily heat gain allowances would be much smaller, and, expected storage times before venting would be much shorter.

C8. SOLID STATE CRYOGENICS

As a matter of related interest, NASA has been conducting research on the use of the solid (frozen) state and on the use of slush (a mixture of the solid and liquid states), plus slush-gel combinations, to improve the slosh, low gravity acquisition and heat capacity qualities of cryogenic systems. The solid state and, to a lesser extent, slush mixtures exhibit greater densities than the liquid state, thereby reducing storage volume. They possess greater heat capacity by virtue of the heat of fusion. Thus they are attractive for lengthy deep-space missions. (Such measures are not considered necessary for the ALBS, however).

Table C-2. Allowable Heat Gains Per Day for LHe and LH_2 in ALBS Tanks, to Permit 10 Days of Non-Vented Storage

(APPROXIMATE VALUES)

NOMINAL VENT PRESSURE = 100 lb in.$^{-2}$ abs (6.87 x 10^5 N/m^2)

Note: Gains for initial storage temperature indicated in item 2. Allowable gains are less if initial storage temperatures are higher.

Item		LHe	LH_2
1.	a. Boiling Point Temperature $T_{b.p.}$ (P = 1 atm) b. Critical Temperature, T_c c. Critical Pressure, P_c (Atmospheres)	7.57°R (4.2°K) 9.36°R (5.2°K) 2.26 (2.28 x 10^5N/m^2)	36.7°R (20.4°K) 59.74°R (33.0°K) 12.98 (13.1 x 10^5N/m^2)
2.	Initial Storage Temperature T_i	7°R (3.88°K)	30.7°R (17°K)
3.	Temperature Differential, $\Delta T(T_{b.p.} - T_i)$	0.57°R (0.32°K)	6°R (3.3°K)
4.	Specific Heat Capacity, C_p at n.b.p. (P = const)	1.09 BTU/lb/$^{\circ}$R (4.57 J/g/$^{\circ}$K)	2.34 BTU/lb/$^{\circ}$R (9.8 J/g/$^{\circ}$K)
5.	Mass of Cryogen in ALBS tank, M	100 lb (45.36 kg)	47 lb (21.2 kg)
6.	Heat Gain $\Delta H(T_{b.p.} - T_i)$ $= C_p x \Delta T(T_{b.p.} - T_i) \times M$	1.09 x 0.57 x 100 62.1 BTU (0.66 x 10^5 J)	2.34 x 6.0 x 47 = 660 BTU (6.96 x 10^5 J)
7.	Venting Temperature (Venting Pressure = 100 lb in^{-2})	11.16°R(T_c+1.8°R (6.2°K)	52.0°R(T_c-7.7°R) (28.8°K)
8.	Temperature Differential $\Delta T(T_{vent} - T_{b.p.})$	3.59°R (2°K)	15.3°R (8.5°K)
9.	Specific Heat Capacity, C_v, at vent temperature (Note a)	Note b(2)	1.52 BTU/lb/$^{\circ}$R (6.38 J/g/$^{\circ}$K)
10.	Heat Gain to Vent = $C_v x \Delta T(T_{vent} - T_{b.p.}) \times M$	Note b(1) = 246 BTU (2.59 x 10^5 J)	1.52 x 15.3°R x 47 = 1092 BTU (1.15 x 10^6 J)

Table C-2. Continued

Item		LHE	LH_2
11.	Heat of Vaporization ΔH_v (average) $\frac{\Delta H_v \text{ at } T_{b.p.} + \Delta H_v \text{ at } T_{vent}}{2}$	Note c(1) 5.34 BTU/lb (12.5 J/g)	Note c(2) 168 BTU/lb (392 J/g)
12	Heat Gain for Complete Vaporization, ΔH_v (average) xM	5.34 x 100 = 534 BTU (5.61×10^5 J)	168 x 47 =7896 BTU (8.3×10^6 J)
13.	Percentage of Vaporization at relief pressure of 100 lb in^{-2}	100 percent	40 percent
14.	ΔH_v (average) xM for 100 lb in^{-2} venting	534 BTU x 1.0 = 534 BTU (5.61×10^5 J)	7896 BTU x .4 =3158 BTU (3.32×10^6 J)
15.	Total Allowable Heat Gain (10 days) for 100 lb in^{-2} venting (Sum of items 6, 10, 14)	62.1 246.0 534.0 842.1 BTU (8.9×10^5 J)	660 1092 3158 4910 BTU (5.16×10^6 J)
16.	Daily Allowable Heat Gain (Item 15 divided by 10)	84.2 BTU (8.9×10^4 J)	491 BTU (5.16×10^5 J)

Note a. C_v, the specific heat capacity at constant volume was used here because of the closed, fixed-volume nature of the ALBS tank. C_v takes into account only changes in the system's internal energy as the temperature changes, $\frac{du}{dt}$. On the other hand, C_p, the specific heat capacity at constant pressure, allows for the changes (with temperature) of the system's internal energy and also for the work done in expanding against the atmosphere,

$$\frac{du}{dt} + \frac{Pdv}{dt}. \quad (P = \text{const.})$$

Since the ALBS tank is a variable-pressure, constant-volume system, C_p appears inappropriate for use in our calculations. The actual values of C_v for LHe and LH_2 are taken from the WADD TR 60-56, sections 4.001 and 4.002.

Note b(1). In the case of helium, $\Delta T(T_{vent}-T_{b.p.})$ has to be divided into two increments, $\Delta T(T_c-T_{b.p.})$ and $\Delta T(T_{vent}-T_c)$ because of the change of state that occurs at T_c.

$$\Delta T(T_c-T_{b.p.}) = 9.36^oR-7.57^oR = 1.79^oR$$

$$\Delta T(T_{vent}-T_c) = 11.16^oR-9.36^oR = 1.80^oR$$

Note b(2).

$$C_v \text{ (for LHe) } \times \Delta T(T_c-T_{b.p.}) \times M = 0.62 \times 1.79 \times 100 = 111 \text{ BTU}$$

$$C_v \text{ (for gaseous He) } \times \Delta T(T_{vent}-T_c) \times \text{ lb He (gas)} =$$

$$0.75 \times 1.80 \times 100 = 135 \text{ BTU}$$

The total heat gain above the boiling point, exclusive of the heat of vaporization, is the sum of the two increments:

$$\Delta H(T_{vent}-T_{b.p.}) = 111 + 135 = 246 \text{ BTU } (2.59 \times 10^5 \text{ J})$$

Note c. $$\frac{\Delta H_v \text{ at } T_{b.p.} + \Delta H_v \text{ at } T_{vent}}{2} = \Delta H_v \text{ (average)}$$

Note c(1). $$LHe = \frac{8.92 + 1.75^*}{2} = 5.34 \text{ BTU/lb } (12.5 \text{ J/g})$$

$^*1.75 = \Delta H_v$ at T_c for LHe

Note c(2). $$LH_2 = \frac{192 + 143}{2} = 168 \text{ BTU/lb } (392 \text{ J/g})$$