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FINAL REPORT
BUOYANT VENUS STATION
FEASIBILITY STUDY

Volume II - Mode Mobility Studies

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Prepared under Contract NAS1-6607 by
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FOREWORD

This final report on the Buoyant Venus Station Feasibility Study is submitted by the Martin Marietta Corporation, Denver Division, in accordance with Contract NAS1-6607.

The report is submitted in six volumes as follows:

Volume I - Summary and Problem Identification;

Volume II - Mode Mobility Studies;

Volume III - Instrumentation Study;

Volume IV - Communication and Power;

Volume V - Technical Analysis of a 200-lb BVS;

Volume VI - Technical Analysis of a 2000- and 5000-lb BVS.

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BUOYANT VENUS STATION FEASIBILITY STUDY

VOLUME II - MODE MOBILITY STUDIES

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MODE MOBILITY STUDIES - TASK 4.1

The contractor shall determine and investigate the mobility parameters for various station mission modes in the prescribed ranges of the Venusian atmosphere including both the dark and light side of the planet. The mission modes investigated shall include as a minimum single, multiple, and platform station modes. For each mode the contractor shall investigate various methods of obtaining vertical mobility of the station.

SUMMARY

Five deployment methods are defined for a buoyant station. The deployment sequence begins with subsonic conditions in all three model atmospheres. All of the methods defined use a parachute (either a two-parachute method with a drogue parachute or a single parachute) to produce low dynamic pressure conditions for the inflation of the balloon. Four of the methods shed the parachute during inflation or when the balloon is fully inflated. One method, integral paraballoon system, uses the parachute as the structural member of the balloon and retains the parachute throughout the mission. All methods drop the inflation gas tankage immediately upon completing balloon inflation.

Altitude cycling is feasible for stations in the 2000-lb class, but is not feasible for a 200-lb class station. Two methods of cycling appear promising for performing three complete cycles to a minimum altitude of 10 km from an equilibrium altitude above 50 km in the mean density model atmosphere. These two methods are gas dump and makeup and gas dump and ballast drop. Three cycles can be performed for approximately 60% of the initial suspended mass of the station. The ballast can be in the form of drop sondes.

A third method of cycling, pumping and dumping atmospheric gases into a balloonette, is feasible but requires a receiver of more than 2000 cu ft for a 2000-lb station. This method allows for a large number of cycles and would be limited only by the power available for the compressor.

The deployment of a station is especially critical based on balloon industry experience from air-deployed systems. Initial deployment conditions assumed for this study were subsonic velocity ($M = 0.90$) and a vertical flightpath angle for all three model atmospheres at an altitude of 70 km. A parachute was deployed before balloon deployment with the parachute sized to obtain a low dynamic pressure of approximately 1.0 lb/sq ft for balloon deployment. Typical parachute snatch forces and opening shock loads of 77 200 and 73 200 lb, respectively, were established with the 2000-lb class station.

It was determined that if the balloon reached altitudes below equilibrium altitude it must be inflated to produce sufficient buoyancy to reverse the downward velocity of the station and allow it to ascend to the equilibrium altitude. This resulted in approximately a 10% gas penalty by weight. The excess gas had to be vented as the station ascended to maintain proper superpressure limits.

A survey of government agencies and commercial suppliers of balloon materials was performed by Raven Industries, Incorporated. The conclusions of this survey are:

1) A material or composite exists or is in development that would be usable as a balloon envelope for a buoyant station;

2) The most promising materials of those studied are polyester film, polybenzimidazole (PBI) film, and PBI fiber;

3) Material properties under simulated mission conditions must be determined to make the final selection of the material(s) for this mission;

4) Fabrication materials and techniques compatible with end use of the balloon must be developed.

Three inflation gases should be considered for this mission -- hydrogen, helium, and decomposed hydrazine. Hydrogen is the lightest system and produces the greatest supported payload. It is followed by hydrazine and helium in that order. Hydrogen can be transported as either a cryogenic liquid or high-pressure gas. Hydrazine liquid is decomposed with a spontaneous catalyst into hydrogen, nitrogen, and trace amounts of ammonia. To produce a compatible inflation temperature (275°) a mixture of 24% by weight of ammonia has to be added to the decomposed hydrazine gas producing an average molecular weight of 12.6.

INTRODUCTION

The mode mobility task attempts to answer certain questions pertinent to a buoyant Venus station (BVS):

1) Is it feasible to deploy a buoyant station in the Venus atmsophere as defined by the three models of NASA SP-3016?
2) Is it feasible to vertically cycle (altitude-cycle) a station in the atmosphere?
3) What are the material requirements for the inflated device of this station and is such a material presently available?
4) What inflation gas or gases should be considered and how should they be transported?
5) What problems are associated with the inflatable device for this station?

This task was accomplished by performing the following studies:

1) Balloon material requirements - This exercise delineated the natural and induced environments that the material may be required to survive from assembly through the atmospheric mission above Venus;
2) Balloon material survey - Government agencies and commercial suppliers of films, fabrics, and fibers were surveyed to determine candidate materials for this type of mission;
3) BVS deployment concepts - Several concepts for deployment of a buoyant station were defined, primarily based on proven or tried techniques for air drops;

4) Inflation gas analysis - An investigation to determine the better gases for buoyancy and the various methods of transporting the gases to Venus;

5) Development of computer program for deployment of a BVS - A mathematical model was formulated, and two computer programs were derived from the model.

6) Development of computer program for altitude-cycling a BVS - A mathematical model was formulated, and four computer programs were produced to investigate four methods of cycling the station;

7) Deployment and altitude-cycling studies - This effort employed the computer programs mentioned above to investigate the pertinent parameters associated with these two mission phases.

SYMBOLS

A_o	area of uninflated parachute, m^2
B	ratio of average density of atmosphere adjacent to balloon to average density of contained gas
BD	ballast drop, %
BVS	buoyant Venus station, dimensionless
C_{ap}	drag coefficient for uninflated parachute, dimensionless
C_p	specific heat, constant pressure, Btu/lb-°R
C_v	specific heat, constant volume, Btu/lb-°R
D	diameter of balloon, m
F_B	buoyant force, n
F_m	manufacturing factor to account for weld efficiencies, material tolerances, etc, dimensionless
FS	safety factor based on ultimate strength of material, dimensionless

F_S	snatch force, n
F_s	shape factor, dimensionless
F_u	ullage volume factor, dimensionless
g	local acceleration of gravity, m/sec^2
h^*	overall heat transfer coefficient, Btu/hr-ft^2-°F
h_c	convective heat transfer coefficient, Btu/hr-ft^2-°F
h_1	heat transfer coefficient, balloon film to ambient
h_3	heat transfer coefficient, balloon gas to film
K	conversion factor, kg/lb$_m$
K_1	strength to weight ratio, lb$_f$/in./oz/yd^2
k	thermal conductivity, Btu/hr-ft-°F
ℓ_p	suspension line length, m
L_s	static lift of gas, kg/m^3
M_a	molecular weight of atmosphere, kg/kg-mole
m_b	balloon mass, kg
M_g	gas molecular weight, kg/kg-mole
m_g	gas mass, kg
m_{gs}	initial mass of gas system, kg
m_ℓ	gross lift mass, kg
m_{pf}	mass of folded parachute, kg
m_{ps}	mass of decelerator system, kg
m_{sus}	suspended mass, kg
m_t	tank mass, kg
$(N-D)/N$	elongation of suspension line, dimensionless
OTR	operating temperature range, °K
P_a	ambient pressure, mb

PBI	polybenzimidazole
P_d	design pressure, psia
P_g	gas pressure, mb
P_r	Prandtl number, dimensionless
Q_{in}	heat flow in, Btu/sec
Q_{out}	heat flow out, Btu/sec
q_p	dynamic pressure
R	Reynolds number; universal gas constant
r	radius of balloon
S_d	design stress level of tank material, psi
S_o	opening shock
S_p	frontal area of inflated parachute
T	internal temperature
t	time
T_a	ambient temperature
T_g	gas bulk temperature
T_w	outside wall temperature
U_e	design ultimate load on risers
V_b	volume of balloon, m^3
V_e	equilibrium velocity, ft/sec
v_g	specific volume of the gas, m^3/kg
V_R	relative velocity between station and parachute, m/sec
W_g	weight of gas required, lb_m

X	empirical factor
Z	compressibility factor
α_s/ϵ	solar absorptivity/infrared emissivity
ΔP	superpressure, mb
ΔT	temperature difference, °F
ϵ	emissivity, dimensionless
θ	(buoyancy - weight)/weight
ρ_a	atmospheric gas density, kg/m^3
ρ_g	gas density, kg/m^3
ρ_ℓ	density of liquid, lb_m/cu in.
ρ_t	density of tank material, lb/cu in.
σ	Stephen-Baltzmann constant; superpressure of balloon, %

SYSTEM CONCEPTS

Five deployment methods are defined. The deployment sequence begins with subsonic conditions for all three atmospheres. Four altitude cycling methods are described. These are gas dump and makeup, gas dump and ballast drop, and pumping and dumping atmospheric gases and heat cycling.

Deployment Methods

Five methods of deploying the buoyant station are:

1) Balloon/payload-apex mounted system;
2) Balloon-apex mounted system;
3) Balloon/payload-suspended system;
4) Integral paraballoon system;
5) Separable paraballoon system.

The basic operation and sequence of each method is described in the following paragraphs.

Balloon/payload-apex mounted system. - In this configuration, shown in figure 1, the balloon and payload are located at the apex of the main parachute. Support hardware including initial inflation gas tankage and controls are suspended from the main parachute.

The drogue parachute is used in the deployment of the main parachute. It serves both to extend the main parachute and assist in support of the load at the apex. After the main parachute has reached terminal velocity, the balloon is released from its container and the drogue is then used to extract the balloon from its container and extend it. After inflation is completed the balloon-supported payload is separated from the parachute and the buoyant system is free to seek its equilibrium altitude. The tankage and parachute descend to the surface.

This configuration represents the method commonly used for air drops on earth. The ratio of suspended weight on the main parachute to weight at the apex is an important consideration. With assistance gained from the drogue parachute, systems have been successfully deployed with a ratio of suspended weight to apex weight of approximately 2.5 to 1.

Balloon-apex mounted system. - This system, shown in figure 2, is similar to the previous system except that the payload is suspended from the parachute along with the balloon support hardware. The use of the drogue parachute and the balloon-inflation sequence remain the same.

Variations in separation can be considered. The main parachute can be retained with the buoyancy system with separation of only the support hardware or the entire parachute can be separated. The possibility exists of initially retaining the parachute for release at a later time carrying a scientific payload to the planet surface.

Balloon/payload-suspended system. - Figure 3 illustrates this configuration in which the balloon is deployed and extended below the main parachute. Suspended from the balloon, in addition to the payload, is the required support hardware. After inflation is completed the support hardware and parachute are released.

Again, variations in configuration exist such as the possibility of inflating the balloon within the parachute canopy.

Integral paraballoon system. - In the approach shown in figure 4, the final decelerator consists of a modified hot-air balloon, PARAVULCOON, that becomes the buoyant balloon. The balloon would initially be inflated with atmospheric gases by a scoop arrangement. Once the system is stabilized, a liner (gas barrier) would be deployed and inflated within the paraballoon. As the liner is inflated the atmospheric gases in the paraballoon are exhausted through the porous material or a valve arrangement. The liner will, when fully inflated, serve as the gas barrier while the paraballoon serves as the structureal member. Support and inflation hardware will then be released.

Separable paraballoon system. - This system, shown in figure 5, represents a variation on the previous system. In this system, the paraballoon serves as the final decelerator and then provides a quiescent environment in which to inflate the balloon. Once the inflation is complete the balloon and payload are released to seek equilibrium altitude.

Cyclic Methods

Four methods of altitude cycling a buoyant station are shown in figures 6 thru 9.

Gas release and makeup. - This method consists of dumping a sufficient amount of inflation gas to create a nonequilibrium condition. For the superpressure balloon, this would consist of dumping gas until the balloon is in pressure equilibrium with the atmosphere. The station will then descend at a rate dependent on the heat transfer characteristics of the balloon and contained gas. Once the desired minimum altitude is reached, the cycle gas supply is activated and the balloon reinflated. This creates sufficient lift to cause the station to ascend to its new equilibrium altitude. If empty and not required for further cycling, the cyclic gas supply tankage may be ejected.

Gas release and ballast drop. - The gas release sequence is identical to that of the previous method. Once the station reaches its minimum desired altitude, mechanical ballast is released, allowing the station to ascend to its new equilibrium altitude. The mechanical ballast may consist of a drop sonde or other instrumentation package. This cycle may be repeated more than once.

Pump and dump atmospheric gases. - This method uses a mechanical pumping system in conjunction with a ballonet or other reservoir to receive and expel the pumped atmospheric gases.

The primary balloon for this concept does not expel its gas. The ballonet may be external to the primary balloon (as shown) in fig. 8) or contained within the primary balloon. The principle involved is simply to add ballast, in the form of high-pressure atmospheric gases, and to dump the ballast when the minimum desired altitude is reached. This system will continue to return to its original equilibrium altitude and may be cycled as often as desired.

Heat cycling. This method employs a heat source, such as an isotope, that can be selectively used to heat or not heat the balloon gases. The station would be maintained at equilibrium altitude by using the heat source to hold the gas temperature at a value consistent with equilibrium.

The heat source is then switched off by a method that allows the buoyant gas to cool and, therefore, reduce its total volume.

This produces a net force downward and allows the station to descend to the desired minimum altitude. At this time, the heat source is again brought in contact with the buoyant gas, heating it and creating a lift on the station that returns the station to its original altitude.

BALLOON GASES

Five gases were analyzed -- hydrogen, helium, decomposed hydrazine, ammonia, and methane. Three methods of transporting and generating these gases were considered -- high-pressure gas storage, liquid, and cryogenic liquid.

For the 200-lb class station, hydrogen, transported as a high-pressure gas produces the largest payload, thus the highest efficiency. This is followed by decomposed hydrazine and helium.

Hydrogen, transported as a cryogenic fluid produces the most efficient gas system for the large (2000-lb) stations. This is followed by hydrogen transported as a gas, decomposed hydrazine, and helium in order of decreasing efficiency.

Ammonia is not attractive because of the high molecular weight and not having a spontaneous catalyst to dissociate it to a low molecular weight gas mixture. Methane has a high molecular weight and boiloff losses during transit that make it very unattractive.

Based on the above reasons, only hydrogen transported as a cryogen and gas, decomposed hydrazine, and helium should be further considered for this mission.

Analysis

For the case of the nonextensible balloon, the buoyant-force equation is

$$F_B = m_g \cdot g(B - 1) - m_\ell \cdot g \tag{1}$$

where F_B is the buoyant force, m_g is the mass of the gas, g is the local acceleration of gravity, B is the ratio of the average density of the atmosphere adjacent to the balloon to the average density of the contained gas,

$$B = \frac{\rho_a}{\rho_g} = \frac{P_a}{P_g} \cdot \frac{M_a}{M_g} \cdot \frac{T_g}{T_a} \tag{2}$$

and m_ℓ is the gross lift mass (mass aloft).

For the simple case of static equilibrium,

$$F_B = 0$$

$$m_g(B - 1) = m_\ell \tag{3}$$

where $m_g = V_b/v_g$, V_b is the volume of the balloon, and v_g is the specific volume of the gas. Assuming the inflation gas can be described by the perfect gas law,

$$v_g = \frac{RT_g}{M_g P_g} \tag{4}$$

where R is the universal gas constant, T_g, P_g, and M_g are the gas bulk temperature, pressure and molecular weight, respectively.

The capability of an inflation gas can be measured by several means, one being the lift capacity of the gas. Letting the static lift of the gas,

$$L_s = \frac{m_\ell}{V_b} \tag{5}$$

then

$$L_s = \frac{B - 1}{v_g} \tag{6}$$

$$= \frac{\left[(P_a M_a T_g)/(P_g M_g T_a)\right] - 1}{(RT_g)/(M_g P_g)}$$

$$= \frac{(P_a M_a T_g) - (P_g M_g T_a)}{RT_g T_a} \tag{7}$$

For the superpressure balloon system, the balloon is designed for a maximum pressure differential. When the bulk temperature of the inflation gas is equal to the average temperature of the surrounding atmosphere, $T_g = T_a$, then $P_g = \left(1 + \frac{\sigma}{100}\right)P_a$, where σ is the superpressure of the balloon in percent. Therefore, substituting the above expressions into equation (7),

$$L_s = \frac{P_a}{RT_a}\left[M_a - \left(1 + \frac{\sigma}{100}\right)M_g\right] \tag{8}$$

Since the model atmospheres of NASA SP-3016 are defined in millibars of pressure and temperatures in degrees Kelvin, it is best to express the universal gas constant R in units of

$$\frac{mb \cdot m^3}{Kgmole \cdot {}^\circ K} \tag{9}$$

This will produce L_s in units of kg/m^3.

$$R = 83.2173 \frac{mb \cdot m^3}{Kgmole \cdot {}^\circ K} \tag{10}$$

The static lift capabilities for three gases considered are shown in figures 10 thru 12 for the three model atmospheres. To determine the density of the gas within the balloon at any given altitude, assuming the gas can be defined by the perfect gas law,

$$\rho_g = \frac{P_g M_g}{RT_g} \tag{11}$$

Now, for any given gas,

$$\frac{M}{R} = \text{Constant} \tag{12}$$

so the density may be expressed by

$$\rho_g = \frac{P_g}{T_g} \cdot \text{Constant} \tag{13}$$

If we assume temperature equilibrium between the gas and the average atmospheric temperature surrounding the balloon, the density can be expressed as

$$\rho_g = \frac{P_a}{T_a} \cdot \text{Constant} \tag{14}$$

where the new constant includes the superpressure function.

$$\rho_g = \frac{P_a}{T_a} \cdot \frac{M_g}{R}\left(1 + \frac{\sigma}{100}\right) \tag{15}$$

Gas density as a function of altitude for the mean model atmosphere is shown in figure 13.

The gases that were considered for balloon inflation for this mission are shown in table 1. Various methods of transporting and generating the gases were considered.

TABLE 1. - INFLATION GASES

Gas	Method of transport		
	High-pressure gas	Liquid	Cryogenic liquid
Hydrogen	Yes	No	Yes
Helium	Yes	No	No
Hydrazine	No	Yes	No
Ammonia	No	Yes	No
Methane	No	No	Yes

The final selection of gas used as well as the method of transporting and generating depends on such criteria as the initial gas system mass required to produce a given amount of gas in the balloon. The initial mass is selected as the criterion as opposed to gas system mass at the time of deployment because cryogenic gas storage losses during transit to Venus should be considered to truly assess the efficiency of the cryogenic system in comparison to high-pressure storage methods. Also, the cryogenic tankage would have to be sized to include transit boiloff.

High-pressure gas storage vessels can be calculated in the following manner, assuming a spherical tank and nonoptimum considerations such as shape, manufacturing, and safety factors.

$$m_t = \frac{K\ P_d\ V_d\ \rho_t\ \cdot\ F_s\ \cdot\ FS\ ;\ F_m}{S_d} \tag{16}$$

where

m_t = Mass of tank, kg

K = Conversion factor, kg/lb_m

P_d = Design pressure, psia

V_d = Design volume, cu in.

ρ_t = Density of tank material, lb/cu in.

F_s = Shape factor, dimensionless

FS = Factor of safety based on ultimate strength of material

F_m = Manufacturing factor to account for weld efficiencies, material tolerances, etc

S_d = Design stress level of tank material, psi

For a spherical, titanium tank, letting:

K = 0.4536 kg/lb_m,

ρ_t = 0.162 lb_m/cu in.,

F_s = 1.20,

FS = 2.0,

F_m = 1.20,

S_d = 155,000 psi,

then

$$m_t = 1.365 \times 10^{-6} P_d V_d \tag{17}$$

For high-pressure gas storage of hydrogen and helium let

$$P_d = 4500 \text{ psia} \tag{18}$$

The results of this are plotted in figures 14 and 15 for m_t vs mass of gas $\left(m_g\right)$ for hydrogen and helium, respectively. For hydrazine and ammonia let:

$$P_d = 300 \text{ psia} \tag{19}$$

$$V_d = \frac{W_g F_u}{\rho_e}$$

where

W_g = weight of gas required, lb_m

ρ_e = density of liquid, $lb_m/\text{cu in.}$

F_u = ullage volume factor (15%)

= 1.15

Then,

$$m_t = \left(1.365 \times 10^{-6}\right) (300) \frac{1.15}{(0.036)} W_g$$

$$m_t = 1.308 \times 10^{-2} W_g \text{ for hydrazine} \tag{20}$$

$$m_t = 2.140 \times 10^{-2} W_g \text{ for ammonia}$$

The results are plotted in figure 16 for m_t vs mass of gas for hydrazine.

CRYOGENIC TANKAGE ANALYSIS

This analysis is based on the following assumptions:

1) Liquid hydrogen stored at 2.0 atm;
2) Spherical, titanium tank with a wall thickness of 0.25 cm;
3) Tank is insulated with multilayer Mylar aluminized on both sides, separated by nylon netting;
4) Tank environment of 20°C throughout 145-day transit period;
5) Heat flux through tank supports of 126 cal/hr;
6) Penetration heat leakage of 5% of total heat leakage;
7) Thermal conductivity for the insulation of 8.28×10^{-8} cal/sec-cm-°K $\left(2 \times 10^{-5}\ \text{Btu/hr-ft-°R}\right)$.

This conservative number is used to include manufacturing and assembly nonoptimum factors.

The tank wall thickness is predicated on the extreme loads experienced on entry into the Venus atmosphere; this deceleration is on the order of 200 to 500 times the acceleration of gravity on earth for several seconds.

The results of this analysis are shown in figures 17 and 18. To transport 35 kg of liquid hydrogen an initial mass of 212 kg of liquid and tankage is required.

A method must be devised to vaporize the liquid for balloon inflation. This inflation must take place within a period of a few minutes to minimize the undershoot of the balloon. One method has been investigated for vaporizing cryogenic hydrogen: A finned tube, counter-flow-type heat exchanger with decomposed hydrazine as the heat source.

A 2000-lb station balloon with 6 mb superpressure, and an equilibrium floatation altitude of 57 km in the mean density atmosphere requires 31.5 kg of hydrogen at 225°K. The following assumptions were made for this analysis:

1) Required hydrogen flow rate of 0.1135 kg/sec;

2) Decomposed hydrazine inlet gas temperature of 1145°K;

3) 60% ammonia dissociation in the decomposed hydrazine;

4) Spontaneous catalyst used to decompose the hydrazine;

5) Fin-tube-type, two-phase, counter-flow heat exchanger of multiple pass design;

6) Regulated, pressure-fed hydrazine system with nitrogen pressurization.

The results of this analysis indicates that a three-pass heat exchanger weighing approximately 60 kg requires a flow rate of 0.159 kg/sec of hydrazine. This results in a hydrazine storage, control and reactor subsystem of approximately 61.5 kg for a total heat source and heat exchanger system weight of 121.5 kg.

This analysis indicates a total gas production system, including cryogenic storage and a method of vaporizing the liquid for a 2000-lb station, of 334 kg.

To calculate gas system efficiency as a function of initial gas system mass and equilibrium altitude the following steps are required:

1) From the plots of static lift calculate balloon volume, V_b, as a function of the mass aloft, m_ℓ. The results of these calculations are shown in figures 19 thru 21;

2) Plots of gas density vs altitude, are used to calculate the mass of the gas, m_g, required as a function of altitude and mass aloft. The relationship of m_g to m_ℓ is shown in figures 22 thru 24;

3) Based upon tank mass, m_t, required to transport the inflation gas to Venus, the initial mass of a gas system, M_{gs}, is calculated as a function of the gas mass required to inflate a balloon of volume V_b. The M_{gs} is then plotted as a function of m_ℓ. These plots are shown in figures 25 thru 27;

4) Considering a total undeployed station mass of 908 kg, an m_ℓ is selected based on

$$m_\ell = m_s - m_{ps} - m_{gs} \tag{21}$$

where m_{ps} is the mass of the decelerator system. Letting $m_{ps} = 48$ kg for all cases, m_ℓ can be determined. The mass lofted is the sum of the balloon mass and the suspended mass

$$m_\ell = m_b + m_{sus} \tag{22}$$

where the mass of the balloon, m_b, can be described by

$$m_b = \frac{C}{K_1} \Delta P \ V_b \tag{23}$$

where ΔP is the amount of superpressure in millibars and V_b is the balloon volume in cubic meters. The constants are

$$C = 3/8$$

$$K_1 = lb_f/in./oz/yd^2 \tag{24}$$

The constant K_1 is the strength to weight ratio used throughout the balloon industry. The range of K required for this study appears to be 7 to 20 lb_f/in./oz/yd^2. Consideration has to be given to minimum practical thickness of material.

The above-generated data, from steps 1) thru 4), are cross-plotted over a range of altitudes thus deriving a plot similar to figure 28.

Gas system volume required for high-pressure gas storage is a function of both gas temperature and pressure. Hydrogen and helium can be expressed as a perfect gas modified to include a compressibility factor Z:

$$PV = ZRT \tag{25}$$

at 4500-psia storage pressure at 293°K,

$$Z = 1.160 \text{ for hydrogen}$$
$$Z = 1.145 \text{ for helium} \tag{26}$$

Figures 29 and 30 indicate system volume requirements for the above two gases. Tankage volume requirements for liquid hydrazine are shown in figure 31.

The balloon size varies for a given m_{ℓ} depending on the L_s of the inflation gas. This is shown in figures 32 thru 34.

The amount of superpressure must be closely controlled since it will directly affect the suspended mass of the station. The sensitivity of this effect is shown in figure 35.

Since balloon systems are to some extent porous to the inflation gases, a vernier system must be considered to offset the gas leakage for the long-duration missions desired.

MATERIAL REQUIREMENTS

A simplified analysis of the functions of the total mission and the environment surrounding each function was performed as related to defining the required characteristics of a "fabric" for inflatable devices for the Venus mission. From this, a tentative description of the desired performance characteristics for balloon/decelerator material was developed.

Functional Analysis

Figures 36 thru 43 constitute a first indenture functional analysis of the Venus mission. For each diagram, the important environmental factors are indicated.

Performance Characteristics

The functional analysis must be interpreted in terms of the performance required of the balloon material, the environment under which it must perform, and the total history of environment that the material must withstand. Table 2 is an expression of these requirements.

TABLE 2. - MISSION PERFORMANCE REQUIREMENT

Strength	6 lb/in. at continuous temperatures (194 to 373°K) and transient temperature extremes[a thru d]
Permeability	1×10^{-7} cc/cm^2/sec/cm of Hg for all temperature ranges and gases[e]
RF transparency	The material shall be RF transparent[f]
Conductivity	The material shall be conductive to electricity
Thermal conductivity	The thermal conductivity must be known[g]
IR transmission	The IR transmission must be known[g]
Storage	The material shall have the capability of being packed with a packing factor of 2.0[b] storage for 18 months at temperatures of 110 to 373°K will be required
Fold endurance	The material shall have the capability of withstanding 10,000 cycles before failure (cracking)[h]
Radiation	Must withstand normal deep space and RTG radiation for 6 months while in stored condition[i]
Sterilization	Must meet NASA sterilization requirements[c]

[a]Temperatures of 50°K may be encountered if cryogenic liquid transport is used. Temperatures of 1000°K may be encountered if decomposed hydrazine is used. These temperatures will be relatively short (time will be determined). Temperatures of 675°K will be reached three times in cycles from the continuous temperature range to 675°K and back in a 20-hr period or less. The tensile strength must not deteriorate on exposure to CO_2, N_2, N_2H_4, H_2, and either He, H_2, CH_4, or NH_3.

[b]The balloon will be pressure/vacuum packed and stored for 12 months at 273 to 373°K and six months at 110 to 420°K. It will be exposed to hard vacuum and direct solar radiation. Compatibility with ethylene oxide at the above temperatures is required.

[c]Present sterilization requirements are 408°K temperatures for 16.2 hr repeated six times while in a stored condition exposed to an ethylene oxide atmosphere.

[d]The balloon must withstand impact with 10-μ ice crystals at a velocity of 100 fps for up to 1 hr in either a partially (while fluttering) or fully inflated condition. Impact of micrometeoroids, per NASA SP-3016, shall also be withstood.

[e]In view of the required strength and temperatures, the gas barrier may not be the structural member. The structural member required by (a) may be a woven metal cloth or other such exotic material. The gas barrier will be required to maintain its impermeability to He, H_2, CH_4, or NH_3 for the temperature ranges listed in (a) while not being attacked by CO_2, N_2H_4, or H_2.

[f]RF transparency requirement will appear only if antenna design dictates, as an alternative, a conducting ground plane might be desired.

[g]Thermal conductivity and IR transmission must be known to predict balloon performance parameters. Materials that change characteristics with time may not be usable because of their effect on performance.

[h]The material must withstand manufacturing, handling, and storage without fatigue. The most severe requirement will be the flutter encountered in the deployment and inflation phases. During these phases transient and equilibrium temperature conditions as listed in (a) and possible high-frequency vibrations (flutter) will be encountered. Accelerations of 300 g (earth) for 5 sec will be encountered on Venus entry while stored at temperatures of 110 to 420°K. Saturn V launch environment will be encountered.

[i]RTG radiation will be maximum of 3 rad/hr.

MATERIAL SURVEY

Government agencies and industrial suppliers were surveyed by Raven Industries, Incorporated. Mechanical, thermal, electrical, and chemical properties of some of the more promising materials are listed. Only limited data are available on newly developed fibers and films. Several materials exist that appear compatible with this mission. However, fabrication of these materials into a balloon is an unknown. Mylar may be considered for the noncyclic mission.

Materials Description

Tables 3 and 4 list some of the mechanical, thermal, electrical and chemical properties of barrier and fibers, respectively. The materials that appear in these tables are those whose properties are such that use in a severe environment may be possible. A number of materials investigated are not listed because of obvious insurmountable deficiencies.

The determination of listed properties was based on providing adequate information to make a meaningful comparison with mission requirements. Certain properties have a great influence on the suitability of a material for the Venusian application. These properties are the operating temperature range, tensile or breaking strength, and strength to weight ratio. The remaining properties have varying degrees of importance to the mission. Inadequate performance by a material in some areas (e.g., tear resistance, seam strength, permeability, and molecular stability) requires careful design consideration. Other values (e.g., specific heat, resistivity, and dielectric strength) must be known to fully define the system.

Materials Selection

The selection of material for any application follows the following general sequence:

1) Identify the major requirement of the application;
2) Search for the material that most nearly meets the requirement;
3) Test for additional information on properties;
4) Select the material most nearly meeting the requirement, and develop methods of correcting the material limitations or modifying the application requirements.

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TABLE 3. - GAS BARRIERS FOR BALLOONS

Material identification trade name and/or generic name	Manufacturer or cognizant agency	K factor ratio of strength in lb/in. to weight in oz/yd^2	Tensile strength, psi	Specific gravity	Tear resistance	Flexibility (folding endurance cycles)
Viton® fluoroelastomer (c)	E. I. du Pont de Nemours & Co	1.49 @ 298°K 0.44 @ 422°K	2000 @ 298°K 600 @ 422°K	1.8		
Perfluoronated elastomer (d)	E. I. du Pont de Nemours & Co					
Pyre-M. L.® polyimide coating (e)	E. I. du Pont de Nemours & Co	18.2 @ 298°K 8.5 @ 523°K	15 000 @ 298°K 7 000 @ 523°K	1.1		
Kapton® polyimide film (f)	E. I. du Pont de Nemours & Co	32.9 @ 78°K 23.5 @ 298°K 16.0 @ 473°K	35 000 @ 78°K 25 000 @ 298°K 17 000 @ 473°K Yield: 10 000 @ 298°K 5 000 @ 473°K	1.42	Initial: 510 g/mil ASTM D-1004-59T Propagating: 8 g/mil ASTM D-1922-61T	10 000 cycles ASTM D-643-43
Mylar® polyester (g)	E. I. du Pont de Nemours & Co	24 @ 298°K	25 000 @ 298°K Yield: 12 000 @ 298°K	1.395	Initial: 600 g/mil ASTM D-1004-61 Propagating: 15 g/mil ASTM-1922-61T	14 000 cycles ASTM D-2176-63T
Bakelite® parylene polyparaxylene (h)	Union Carbide Corp	10.7 @ 298 K	9000 @ 298°K	1.12 max		
Polysulfones	Union Carbide Corp	10.9 @ 298 K	10 200 @ 298°K (yield, ultimate is lower)	1.24		
Perfluoroalkyltriazine elastometer (i)	AFML Wright-Patterson AFB					
PPO® polyphenylene oxide (j)	General Electric Co	12.6 @ 298°K 6.9 @ 398°K	10 000 @ 298°K 5 500 @ 398°K Yield: 11 000 @ 298°K 6 500 @ 398°K	1.06		
Silastic 1410 HST® silicone rubber (k)	Dow Corning Corp					
Pyrrones polyimidazopyrrolones (l)	NASA/Langley		15 000 to 22 000 @ 298°K			
PBI Film (m)	Celanese Corp	23 @ 298 K	22 400 @ 298°K 14 700 @ 573°K Note: 25 800 @ 398°K	1.3	Initial: 390 g/mil Propagating: 10 g/mil	1139 cycles

[a]All permeability measurements are quoted for a temperature of 298°K except where noted.

[b]Thermal characteristics include the following items with their abbreviations:

OTR = Operating temperature range
C_p = Specific heat
k = Thermal conductivity, cal/sec cm^2 °C/cm
α_s/ϵ = Solar absorptivity/infrared emissivity.

[c]Viton must be used in conjunction with a fabric base. No data are available on uv attack in an inert $(no\ O_2)$ atmosphere or vacuum. Cold brittle temperature = 227°K. Resistant to abrasion (Taber abrasion test).

[d]Compound has been prepared. Will be a good gas barrier. Presently is not curable. Most useful as a coating for fabric in this application.

[e]Figures quoted are for varnish or enamel of this polyimide. Must be used with a suitable substrate. Zero strength temperature is 1073°K. Material is crease sensitive. Compound loses 8.3% of weight during 1000 hr soak at 523°K.

[f]Seal strength of 80% of parent will be achieved soon. Improvement in this figure is anticipated as development continues. Zero strength temperature is 1088°K. Not heat sealable. Packagability, 40 to 50 lb/cu ft.

TABLE 3. - GAS BARRIERS FOR BALLOONS - Concluded

Permeability, cm^3/cm^2 sec cmHg/mil (a)	Elongation	Molecular stability	Resistance to penetrating radiation	Thermal characteristics (b)	Resistivity, ohm-cm, and dielectric strength, V/mil
Helium: 4.621×10^{-7} 347×10^{-7} @422°K Nitrogen: $.028 \times 10^{-7}$	150 to 300% @ 298°K 75 to 150% @ 422°K	Severely attacked by ethylene oxide Resistant to ozone attack $(UV + O_2)$	Should not be exposed to gamma radiation exceeding 1×10^7 rad	OTR = 250 to 422°K C_p = .395 cal/g k = 5.44×10^{-4} @ 395°K	2×10^{13} ohm/cm 500 V/mil
	25% @ 298°K 25% @ 298°K		Resistant to electron exposure up to 3×10^9 rad	OTR = 250 to 616°K OTR = up to 523°K k = 3 to 7.5×10^{-4}	3400 V/mil
Helium: $.980 \times 10^{-7}$ Hydrogen: $.590 \times 10^{-7}$	2% @ 78°K 70% @ 298°K 90% @ 473°K	Excellent resistance to UV, slightly moisture sensitive	Elongation reduced @: gamma = 3.65×10^9 R electron = 6×10^9 rad neutron = 1×10^{10} rad (film darkened)	OTR = 4 to 675°K k = 3.7×10^{-4}	1×10^{18} ohm-cm 7000 V/mil
Hydrogen: $.236 \times 10^{-7}$	130% @ 298°K	Type A (balloon grade) film degraded by UV in presence of O_2 and vacuum. Attacked by strong bases.		OTR = 213 to 423°K C_p = .315 cal/g k = 8.96×10^{-5} IR transmission = 90 to 60%	1×10^{18} ohm-cm 7500 V/mil
Nitrogen: $.035 \times 10^{-7}$ Oxygen: $.130 \times 10^{-7}$	200% @ 298°K			OTR = 2 to 494°K	1.4×10^{17} ohm-cm 6000 V/mil
Helium: 4.626×10^{-7} Hydrogen: 4.249×10^{-7} Methane: $.088 \times 10^{-7}$	50 to 100% @ 298°K			OTR = up to 444°K k = 6.2×10^{-4}	5×10^{16} ohm-cm 425 V/mil
				OTR = up to 703°K	
	50 to 80% @ 298°K			OTR = 103 to 398°K k = 11.5×10^{-4}	1×10^{17} ohm-cm 500 V/mil
	500% @ 298°K		Upper limit: gamma = 1.76×10^7 R neutron = $3.3 \times 10^{14}/cm^2$ @ 2.9 MeV		
	3 to 7% @ 298°K		Unchanged by levels of 1×10^{10} rad		3-5 x 10^{12} ohm/cm
	3.6% @ 298°K 5% @ 573°K			OTR = Up to 723°K	

[g]Mylar is not heat sealable. UV effects in inert atmosphere not available. Seam strength, 95 to 100% of parent. Packagability, 40 to 50 lb/cu ft.

[h]A fluorinated parylene film has been experimentally formed with a melting point above 773°K. Usable strength exists as high as 673°K.

[i]Compound has been prepared. It is a temperature stable molecule with no apparent strength loss 703°K (although it loses 18% of its weight after 5 hr @ 703°K). The compound evaporates in 30 minutes @ 753°K.

[j]An experimental PPO film has been prepared. Low abrasion loss (Taber abrasion test).

[k]Silastic 1410 HST is one of a large number of silicone compounds. A great variety of characteristics are available Would be most useful as a coating on a fabric substrate.

An experimental polymer developed as a high temperature, radiation resistant material for aerospace applications.

[m]An experimental PBI film has been formed. PBI loses 10% of its weight after 600 hr @ 590°K.

TABLE 4. - FIBERS FOR BALLOONS

Material identification	Manufacturer or cognizant agency	Filament strength	Specific gravity	k factor	Breaking strength	Weight
trade name and/ or generic name		(tenacity)		ratio of strength in lb/in. to weight in oz/yd^2		
Carbon fiber carbon filament and graphite (Thornel^R) filament (b)(c) (23 mil thick)	Union Carbide Corp Aerospace Materials Dept	Filament = 10.0 g/denier Yarn = 3.0 to 3.9 g/denier Filament tensile = 400 000 psi	1.49	For grade WCL cloth, k = 11.8	For grade WCL cloth Warp = 85 lb/in. Fill = 75 lb/in.	For grade WCL cloth 7.2 oz/yd^2
Glass fiber (d) (6.0 mil thick)		Filament = 6.0 to 7.3 g/denier Yarn = 4.2 to 5.8 g/denier Filament tensile = 200 000 psi	2.54	For cloth at 298°K, k = 42.7	Warp = 225 lb/in. Fill = 195 lb/in. @ T = 298°K	5.27 oz/yd^2
Metal fiber titanium alloy (B-120 DCA)(e)	Alloy produced by Crucible Steel Co	Filament tensile = 120 000 psi @ 298°K 100 000 psi @ 700°K	4.5	For theoretical cloth: k = 16.0	For theoretical cloth: Warp = 189 lb/in. Fill = 157 lb/in. @ T = 700°K	Theoretical cloth: 11.8 oz/yd^2
Metal fiber 305 stainless steel (MF A-1) (f)	Brunswick Corporation	Yarn = 2.67 g/denier Filament tensile = 275 000 psi @ 298°K yield occurs @ 220 000 psi	7.9			
Polyimide fiber (filament flexibility: 2 x 10^6 cycles)	E. I. du Pont de Nemours & Co	Filament tensile: 98 000 psi @ 298°K 58 000 psi @ 473°K 42 000 psi @ 573°K 28 000 psi @ 673°K	1.42			
BBB fiber (g)	AFML Wright-Patterson AFB	1.40 g/denier to 1.67 g/denier				
PBI fiber (h)	AFML	4.9 g/denier @ 298°K 3.5 g/denier @ 573°K 1 g/denier @ 723°K	≈1.4	For experimental cloth: k = 35.2	For experimental cloth: Warp = 140 lb/in. Fill = 167 lb/in.	For experimental cloth: 4.75 oz/yd^2

[a] Thermal characteristics include the following items with their abbreviations:

OTR = Operating temperature range
C_p = Specific heat
k = Thermal conductivity
α_s/ϵ = Solar absorptivity/infrared emmissivity

[b] Conversion efficiency, ratio of yarn strength to clogh strength, .95 for given patterns of weave in heavy fabric.

[c] Thornel fibers now in development will exceed existing filaments in modulus $\left(50 \times 10^6\right)$. Has poor properties in small radius bends and abrades easily.

[d] There are many producers of glass cloth. Those values quoted for cloth in the table are typical of a cloth produced by the Owens-Corning Fiberglas Corporation.

TABLE 4. - FIBERS FOR BALLOONS - Concluded

Thread count	Weave	Elongation	Molecular stability	Thermal characteristics	Electrical characteristics
				(a)	
Warp = 51 Fill = 49	Eight - harness satin weave	Filament: 1% Cloth grade WCL: 3 to 5%	Oxidizes rapidly in presence of O_2	OTR = up to 2300°K C_p = 0.17 g-cal/g @ 298°K k = 7.58×10^{-3} g-cal/sec cm^2 °C/cm α_s/ϵ = 0.9	Resistivity = .0042 ohm-cm
Warp = 34 Fill = 32	Plain weave	Filament 3 to 4%		OTR = up to 743°K C_p = 0.19 g-cal/g k = 2.48×10^{-3} g-cal/sec cm^2 °C/cm	Resistivity = 2 to 5×10^{12} ohm-cm Dielectric strength = 2800 V/mil
For theoretical cloth: Warp = 24 Fill = 20	For theoretical cloth: Plain weave			OTR = above 1000°K C_p = 0.11 g-cal/g	Resistivity = 3.2×10^{-6} ohm-cm
		Filament 2%		OTR = up to 811°K for short periods C_p = 0.12 g-cal/g k = 1.1×10^{-1} g-cal/sec cm^2 °C/cm	Resistivity = 29×10^{-6} ohm-cm
		Filament: 13% @ 298°K		OTR = up to 673°K 0 strength @ 823°K	
Warp = 39 Fill = 39	Plain weave	23% @ 298°K	Early development fibers affected by UV. Moisture sensitive	OTR = up to 723°K	

[e] Titanium wire is available in diameters as small as .01 in. A diameter of .0005 in. is required for flexible cloth. The calculation of a cloth is based on .01 in. diameter wire. Note that such a cloth would not be flexible and could not be packed. Development studies are attempting to hot form (melt spinning) titanium wire.

[f] Yarn is available with filament diameters of 4 to 50μ with 90 to 300 filaments/yarn.

[g] BBB identifies poly-bisbenzimidazobenzophenanthroline. An experimental yarn has been spun. The yarn has good high temperature strength retention. Because BBB is in early development status, values for tenacity are approximate and may vary greatly in final form.

[h] PBI identifies polybenzimidayole. Pilot production of this material has been achieved. This material is to be a high-temperature resistant substitute for Nomex ®. Therefore, several characteristics of the fabric (including packability) may be assumed to approach nylon. Packed density, approximately 40 lb/cu ft. Seam strength: warp = 88% of parent, fill = 86% of parent. Porosity = 65 $ft^3/min/ft^2$ at .5 in. H_2O.

The above steps have been considered in the rating of materials in Table 5. In the supplementary discussion that follows, a brief listing of the reasons for a particular rating of a material will be given. These ratings are applicable to a balloon used as a buoyant Venus station and are not intended to reflect the merits of the material in any other use.

TABLE 5. - MATERIALS SELECTION SUMMARY

Material trade name and/or general name	Usable	Needs study	Not usable
Polyester film	X		
Viton® elastomer			X
Perfluoronated elastomer		X	
Pyre-M.L.® polyimide			X
Kapton® polyimide	X		
Parylene® polyparaxylylene		X	
Polysulfone			X
Perfluoroalkyl triazine-elastomer			X
PPO® polyphenyleneoxide			X
Silicone rubber		X	
PBI film	X		
Carbon and graphite			X
Glass			X
Titanium wire		X	
304 stainless wire		X	
Polyimide fiber		X	
BBB fiber		X	
PBI fiber	X		

The material characteristics that had the greatest influence on this selection are operating temperature range, strength to weight ratio, and tensile strength. Final determination of a material must be made relative to specific mission requirements.

Polyester film appears to meet all of the requirements for the trip to Venus. The material characteristics of polyester film are generally very good relative to other balloon films. Although the operating temperature range of polyester film is limited, the experience that exists in fabrication and operations with this film makes it desirable for certain limited missions.

The operating temperature range of Viton elastomer is more limited than the operating temperature range of polyester film. In addition, this elastomer is limited by relatively high permeability and complex fabrication requirements.

The perfluoronated elastomer is a recent development with reportedly good barrier characteristics and an extended operating temperature range. Although this material cannot presently be cured into a usable form, future work in this area may result in an applicable material.

The polyimides, Pyre-M.L. varnish and enamel and Kapton film, exhibit very desirable characteristics. The usability of Pyre-M.L. is questionable because of its physical form. However, Kapton has as good or better properties than most films. Its most outstanding property is the operating temperature range of 4 to 675°K. In addition, the permeability characteristics are nearly as good as polyester film. Seal characteristics of Kapton do not yet match the parent material performance.

Development of materials in the parylene (polyparaxylylene) family is continuing. Some future members of this group show promise of operating temperature ranges of up to 673°K. However, there is a lack of information on material characteristics under conditions that will be experienced in a Venusian application of this group of films.

Polysulfone cannot be used in the maximum temperatures that could be experienced. Additionally, other properties of this film are not comparable with those of some other films.

Perfluoroalkyl triazine elastomer is in the developmental stage as a sealing compound for SST fuel tanks. This material does not appear to be applicable to the Venus program.

PPO (polyphenylene oxide) has an operating temperature range that extends only to 398°K. This property makes PPO much less desirable than other films with superior characteristics.

The gas barrier properties and continuous-use temperatures of current silicone rubber compounds are lower than may be achievable. Research is being directed toward improved inorganic polymers. Because of the variety of properties achievable with silicone rubber compounds, a usable material may be developed in this group.

PBI (polybenzimidazole) film has been produced in the laboratory. Although this film is not commercially available, the known properties appear to place it in the same category as polyester and polyimide films.

Carbon and graphite fibers have many attractive characteristics. However, the conversion of fiber to yarn results in a loss of 60% of the single-fiber strength. Additionally, the high modulus of these materials presents problems in packing the material.

Glass fiber, although very desirable from a strength-to-weight ratio standpoint, is severely weakened by creasing. Since creasing the material will almost certainly result from the packing of the balloon, this material is not considered usable.

Cloth woven from metal yarn is an attractive solution to the operating temperature range problem encountered in the Venusian atmosphere. Titanium wire is the most promising of the metals because of its relatively low density and high strength. However, this wire is presently available in diameters only as small as 0.01 in. Research is not presently directed toward lowering this diameter, although industry sources indicate that the required 0.0005-in. diameter could be achieved.

Stainless steel (304) is also attractive, although its density will require a loose weave to keep the envelope mass to a minimum. This requirement will result in lower seam strengths than are desirable. This material is presently available in diameters as low as 7.5μ.

Polyimide fiber has strength and temperature resistance comparable to the polyimide film. The fiber has been produced in pilot quantities although test information on the fiber and the resulting cloth is limited.

PBI fiber has good high-temperature properties and has been woven into cloth. Although the material is not yet commercially produced, its properties are applicable to this mission.

Mission Limitations

Figures 44 thru 48 illustrate the degradation of material strength with an increase in temperature. This degradation imposes the most serious limitation on a mission into the Venusian atmosphere. Balloon system design must be based on the highest temperatures to be encountered. The information in these figures may be used to determine the actual mission limitations imposed by each material. Figures 49 thru 51 illustrate the mission limits for each material and atmosphere model based on temperature. Metal fiber is not included in the figures because no temperature limit for metal cloth exists within the atmosphere of Venus.

Additional limitations may be imposed by the molecular stability of a material. For example, Viton is attacked by ethylene oxide while Mylar is degraded by ultraviolet radiation. Since ethylene oxide is used as a sterilization medium, Viton could not be used unless a different sterilization requirement was approved. The ultraviolet sensitivity of Mylar could limit its use to areas where the radiation is least or to short-duration missions.

Determination of mission limits from properties other than temperature sensitivity is generally limited by lack of data under the conditions expected. Also, the specific system configuration coupled with the use and location of a given material within the system will be a factor in determining the limitations.

Problem Areas

Table 6 summarizes the major problem areas that exist relative to balloon materials and balloon fabrication. The relative importance of specific problems within these general areas will depend on the details of the mission requirements.

TABLE 6. - PROBLEM AREA SUMMARY

Problem area	Impact on program	Work needed
1. Physical property data at mission condition are not available	Extrapolations from existing data are certainly inaccurate; designs are therefore approximations that may not be adequate	Material properties must be determined under simulated Venusian mission requirements
2. Full capabilities of some materials are not yet realized	Optimum balloon design cannot be achieved	Research required to optimize material properties
3. Fabrication techniques and materials are not optimized for mission conditions	Potential of materials cannot be used resulting in less than optimum designs	Development of techniques and materials for maximum use of balloon materials
4. Reliability of balloon and components is not adequate	The required reliability to justify a mission to Venus is not available in existing balloon technology	Development of inspection methods and testing systems as well as fabrication materials and techniques (see Item 3 above)

The lack of physical property data at mission conditions prevents a confident selection of balloon materials. Almost no engineering data exist in the temperature range from 200 to 400°C. For example, permeability data are almost universally gathered at room temperature. An example of the effect of temperature on permeability may be found in Table 3 for Viton elastomer. In this case the permeability increases 7.5 times as the temperature is increased from 25 to 204°C. If this increase is representative, existing design data may well be invalid.

The least critical of the general problem areas listed is that dealing with the stage of development of promising materials. Of the five materials listed as usable in Table 5, the PBI materials are the only ones that might fall in this area. However, it is conceivable that a member of the parylene, silicone rubber, or BBB fiber groups could become the most optimum material for the Venusian application. It is felt, however, that an improvement in this area will have a minimum effect on the mission.

The lack of adequate fabrication materials and techniques is a serious problem. For example, Kapton film is a promising material for the balloon envelope. However, the strength of seals presently attainable is only 80% of parent material strength. For full use of this material, seals must be developed with strengths of at least 95% of parent strength throughout the operating temperature range required by the mission. Very little, if any, work has been done with PBI film.

Reliability required of a balloon system for this application exceeds the state of the art. Present inspection and test methods are not adequate to ensure sufficiently high reliability to justify a Venus mission. Development of techniques and machines to test fabrication quality is required. Fabrication methods must be studied to determine methods of improving existing reliability.

COMPUTER PROGRAMS

The deployment of a buoyant station logically falls into two phases. The first phase involves the dynamics of parachute opening and reaching terminal velocity. Important factors are the snatch force and opening shock of the parachute. This demands very small calculation intervals and both analytical and empirical formulas using a two-body system with the station and parachute connected by a harness (connecting cable and risers). The second phase lends itself to the larger calculation intervals associated with the inflation and floatation of the balloon.

A computer program was developed for each of the four cycling methods. Each method had significant differences in control logic and functions and required different input data.

Parachute Deployment

The parachute deployment computer program uses a single body with its attendant aerodynamic loads initially. At the time of parachute release, the program becomes a two-body problem with an interconnecting spring. The aft body dynamics depend on the external aerodynamic loads and the interconnecting force between the two bodies. The dynamics of the forebody, which is the undeployed station, also depend on the aerodynamic loads and the interconnecting force. The interconnecting force must be solved simultaneoulsy through matrix solution or the previously calculated value used for describing the dynamics of the two bodies. The computer program used the later method.

Table 7 lists the input data and typical values used for deployment of a 200- and 2000-lb station in the mean density atmosphere. The assumptions and formulas used for the snatch force and opening shock are as follows:

TABLE 7. - BUOYANT VENUS STATION PARACHUTE DEPLOYMENT INPUT DATA

Description	Typical input values: 200-lb station	Typical input values: 2000-lb station
Mass of folded chute, kg m_{pf}	4.58	48
Chute enclosed airmass, kg	.86	71.4
Chute apparent mass, kg	.43	35.7
Station normal velocity at T = 0, m/sec	0	0
Station axial velocity at T = 0, m/sec	263.5	263.5
Station angular velocity at T = 0, m/sec	0	0
Station pitch attitude at T = 0, m/sec	0	0
Chute reference diameter, m	7	23
Station reference diameter, m	1.525	3
Length, suspension line, m ℓ_p	8.6	8.6
Length, chute cg to moment center, m	10.43	10.43
Unstretched length of connecting cable, m	7.62	7.62
Station moment of inertia, kg-m	16.25	16.25
Gravitational acceleration, m sec^2	8.86	8.86
Opening shock factor	1.20	1.20
Connecting cable ultimate load, N U_ℓ	44 400	96 000
Uninflated chute reference area, m^2 A_o	.1	.5
Initial altitude, km	70.1	70.1
Chute deployment altitude, km	70.0	70.0
Computing interval, sec	.1	.1
Print interval, sec	.2	.2
Connector cable spring constant	4 000	90 000
Chute geometric porosity	.40	.40
Gondola mass, kg	51.6	360
Weight of gas in inflation tank, N	35	300
Mass of inflation tank, dk	53.0	451
Drag coefficient, normal C_{ap}	.67	.67
Frontal area of the inflated chute, m^2 S_p	38.4	415

1) Snatch force - The sum of the drag force on the folded parachute and the kinetic energy of the parachute with respect to the station. It is described by (ref. 1)

$$F_S = C_{ap} \cdot q_p \cdot A_o + P \tag{27}$$

where

$$P = \frac{m_{pf} \cdot V_R^2 \cdot U_\ell}{\ell_p \cdot e} \tag{27A}$$

C_{ap} = Drag coefficient for uninflated parachute.

q_p = Dynamic pressure

A_o = Area of uninflated parachute

m_{pf} = Mass of folded parachute

V_R = Relative velocity between station and parachute

U_ℓ = Design ultimate load on risers

ℓ_p = Suspension line length

e = Elongation of suspension line under ultimate load per unit length;

2) Opening shock - This force caused by initial inflation of the parachute, is described by (ref. 1)

$$S_o = C_{ap} \cdot q_p \cdot S_p \cdot X \tag{28}$$

where

S_p = Frontal area of the inflated parachute

X = Empirical factor

The value of X has been noted to lie between 1.2 and 1.5 from wind tunnel test data and actual flights. A value of 1.2 was used for this analysis.

Balloon deployment. - This phase of the station deployment was analyzed with a second computer program. The problem was started with the parachute deployed and the flight conditions determined from the final conditions of the first program.

This computer program calculates the aerodynamic loads on the parachute and balloon but assumes no drag from the inflation tankage and station payload. The flow fields of the parachute and balloon are assumed to be mutually independent, and the tankage and payload do not affect the flow field of either.

The balloon internal pressure during inflation is assumed to be equal to the dynamic pressure of the atmosphere. Flutter of the slack balloon fabric was not included. The shape of the balloon was assumed to be an expanding sphere throughout the period of inflation. For the high-pressure gas inflation, an adiabatic expansion process was assumed for the gas flow. For decomposing hydrazine, a constant flow rate was assumed. The parachute and tankage were released simultaneously when the balloon became fully inflated or the proper amount of gas was released into the balloon.

Table 8 lists input data for the program and typical input values for a 200- and 2000-lb class station.

TABLE 8. - BUOYANT VENUS STATION BALLOON DEPLOYMENT INPUT DATA

Description	Typical input values	
	200-lb station	2000-lb station
Mass of chute, kg	5.90	48
Chute enclosed airmass, kg	.74	71.4
Chute apparent mass, kg	.43	35.7
Mass of folded balloon, kg	9.30	12.8
Rate of balloon venting, N/sec	.044	.044
Station horizontal velocity, m/sec	10	10
Station vertical velocity, m/sec	40.0	25.0
Starting time, sec	0	0
Parachute reference diameter, m	5 0	23.0
Gravitational acceleration, m/sec^2	8.86	8.86
Balloon drag coefficient	.44	.44
Maximum balloon radius, m	4.42	8.41
Initial altitude, km	59.84	58.0
Balloon inflative altitude, km	58.50	56.0
Balloon suspended mass, kg	45.0	36.0
Balloon fill-line area, m^2	7.86×10^{-6}	3.14×10^{-5}
Ratio of specific heats	1.40	1.40
Initial tank pressure, N/m^2	310 000	310 000
Initial tank temperature, °K	294	294
Maximum balloon fabric strength, N/m	353	353
Weight of inflation gas, N	42.1	300.0
Mass of inflation tank, kg	63.9	451

This program allowed the balloon inflation altitude, the inflation rate, and the amount of gas dumped into the balloon to be varied.

Altitude Cycling - Gas Dump and Makeup

This computer program was developed using certain assumptions and approximations that are shown to be sufficiently accurate for this study. The basic assumptions are discussed in the following paragraphs.

Balloon gases. - It is assumed that the gas in the balloon is a perfect gas, with a specified molecular weight. The mass of the gas is constant. The viscosity of the gas is assumed to vary as the square root of the bulk temperatures.

Balloon geometry. - As long as the volume of the gas is less than a specified maximum, the gas pressure is assumed to be equal to the ambient pressure, and the volume of the balloon may vary with time. As soon as the volume has reached a specified maximum, the volume cannot be increased (it may be decreased). An overpressure in the balloon may occur. The shape of the balloon is assumed to be a sphere.

Velocity. - The velocity of the balloon is always assumed to be such that the drag force is equal to the difference between gravity and buoyancy. If buoyancy is greater than weight, the motion is up.

The assumption that the forces caused by acceleration can be ignored is perfectly acceptable when the flight times are long compared to the time it would take to establish equilibrium. The tendency toward equilibrium $(D = |B-W|)$ is approximately exponential, with a time constant $r/(1 + \theta)V_e$ where θ = (buoyancy - weight)/weight, V_e = equilibrium velocity, and r = radius of balloon.

For the balloons under consideration,

$$\frac{r}{V_e\ (1+\theta)} \approx 1 \text{ sec} \tag{29}$$

However, we are interested in rising or falling times on the order of an hour or more. Consequently, the assumption of equilibrium is acceptable.

Heat transfer. - One of the major considerations in the motion of a balloon is the bulk temperature of the buoyant gases. To simulate the heat flow, the conduction path is broken into three regions:

1) Outside skin of balloon to ambient atmosphere - According to several standard texts, the Nusselt number for a sphere is a function of the Reynolds number, and can be approximated by

$$\frac{h_c D}{k} = 0.33\ (R)^{.6} \tag{30}$$

where

R = Reynolds number, based on diameter $\frac{v\ D}{Y}$

D = Diameter of balloon

k = Conductivity of atmosphere

h_c = Convective heat transfer coefficient;

2) Inside skin of balloon to outside skin - This portion of the heat transfer is assumed to be pure conduction;

3) Inside of balloon to inside skin - According to various standard texts, this portion of the heat transfer is governed by the Grashof and Prandtl number (P_r). A reasonable approximation for the Nusselt number $\left(\text{in the equilibrium of interest, } N_{gr} \cdot P_r\ 10^9\right)$ is given by

$$\frac{h_3 D}{\text{cond } g} = 0.55 \left[\frac{D^3 p^2 g}{\mu^2} \frac{\Delta T}{T}\right]^{\frac{1}{4}} (P_r)^{\frac{1}{4}} \tag{31}$$

Since, for the gases considered, $(P_r)^{\frac{1}{4}} \sim 1$, the latter term is neglected. The temperature difference, ΔT is measured between fabric and the bulk of the gas;

4) Radiation - The only radiative heat transfer considered was between the fabric and the ambient air. The heat transfer coefficient, from the skin to the ambient, is therefore given by

$$h_1 = h_c + \epsilon\sigma \frac{\left(T_a^{\ 4} - T_w^{\ 4}\right)}{T_a - T_w} \tag{32}$$

where

T_a = ambient temperature

T_w = outside wall temperature

ϵ = emissivity (~.4)

σ = Stephen-Boltzmann constant

Assuming that $\frac{T_a - T_w}{T_a} \ll 1$, we have

$$h_1 = h_c + 4\ \sigma T_a^{\ 3} \tag{33}$$

5) Total heat transfer coefficient - The total heat transfer coefficient is given by

$$h^* = \left[\frac{1}{h_1} + \frac{1}{h_3}\right]^{-1} \tag{34}$$

Venus atmosphere. - The atmosphere temperature, pressure, and viscosity are specified as functions of the altitude. The density is computed assuming a perfect gas and specified (constant) molecular weight. It is further assumed that there are no winds or updrafts, that there is no condensation on the balloon, and there are no time-dependent changes in the atmosphere.

The following general equations are used to describe the motion of the balloon.

Heat transfer. - There is one differential equation for the internal temperature. It is given by

$$\left.\begin{aligned} \frac{dT}{dt} &= \frac{1}{C_p m_g}\left[Q_{in} - Q_{out} + V\frac{dp}{dh}\cdot v\right] && \text{if } V < V_{max} \\ \frac{dT}{dt} &= \frac{1}{C_v m_g}\left[Q_{in} - Q_{out}\right] && \text{if } V \geq V_{max} \end{aligned}\right\} \tag{35}$$

where

V = instantaneous volume of balloon

V_{max} = maximum volume of balloon

T = internal temperature

t = time

m_g = mass of gas

C_p = specific heat, constant pressure

C_v = specific heat, constant volume

Q_{in} = heat flow in

Q_{out} = heat flow out

$\frac{dp}{dh}$ = pressure gradient

v = velocity

Care must be taken so that all quantities are measured in compatible units.

We have also that

$$Q_{out} = 4\pi r^2 \,(T - T_a)\, h^* \tag{36}$$

where

h^* = overall heat transfer coefficient

T_a = ambient temperature

r = radius of balloon

Since h^* is a function of at least T, T_a, H_1, and H_2, it is necessary to solve, by iteration, for h^*. Since r is a function of V, and V it self depends on the pressure, temperatures, etc, we also have to continuously solve for r.

<u>Altitude</u>. -

$$\frac{dh}{dt} = v \tag{37}$$

<u>Geometry</u>. - The volume is given by

$$v = \frac{m_g r T}{P} \tag{38}$$

where

P = internal pressure

R = gas constant

As long as $V < V_{max}$, P = ambient pressure, P_a. When $\frac{m_g RT}{V_{max}} > V_{max}$, we have

$$P = \frac{m_g RT}{V_{max}} \tag{39}$$

The radius is given by

$$r = \left[\frac{3V}{4}\right]^{1/3} \tag{40}$$

The buoyancy is given by

$$B = VP_a g \tag{41}$$

Velocity. - The velocity is computed by

$$V = + \left[\frac{2\left(B - m_g\right)}{\pi C_D \; r^2 \; P_a} \right]^{\frac{1}{2}} \quad \text{if } B > M_g$$

$$- \left[\frac{2\left(m_g - B\right)}{\pi C_D \; r^2 \; P_a} \right]^{\frac{1}{2}} \quad \text{if } B \leq M_g \tag{42}$$

Mass. - The gas mass is instantly changed to account for a gas dump. The initial mass of gas is changed by a fraction to allow for descent. The mass of the payload is decreased by a fraction when the minimum desired altitude is reached and this change in mass is added to the gas mass to establish ascent.

The input data for this program is shown in Table 9 along with typical values.

TABLE 9. - BUOYANT VENUS STATION ALTITUDE CYCLING GAS DUMP AND MAKEUP INPUT DATA

Description	Typical input value for 2000-lb station
Final time, hr	20
Print interval, hr	0.20
Calculation interval, sec	60
Initial altitude, km	57
Minimum altitude, km	10
Maximum balloon volume, cu ft	87 700
Initial balloon gas temperature, °R	405
Balloon emissivity	.40
Radius of planet, km	6 045
Surface gravity, ft/sec^2	29.1
Atmosphere molecular weight	32
Atmosphere conductivity, Btu/sec-°R-ft	8.3×10^{-6}
Mass of balloon gas, slugs	2.02
Molecular weight of balloon gas	2.0
Conductivity of balloon gas, Btu/sec.-°R-ft.	2.8×10^{-5}
Gas viscosity, slub/ft-sec.	2×10^{-7}
Gas ratio of specific heats	1.40
Initial station mass, slugs	27.43
Fraction of gas dumped	.20
Fraction of gas makeup	.0147

Altitude Cycling - Gas Dump and Ballast Drop

This computer program uses the same basic equations and assumptions as previously described except for the logic on mass changes. In this program, the change in mass to the payload is dropped and not added to the gas mass.

Altitude Cycling - Pump and Dump Atmospheric Gases

This program adds a ballonet (pumped gas receiver) that is collapsible. A compressor ratio establishes, in conjunction with the ballonet volume, the mass of gas that is added to the station. The pump is assumed to operate throughout the descent phase of the cycle. The added gas mass is dropped instantly when the cycle minimum altitude is reached. The compressor is again operated when the station reaches equilibrium altitude.

Altitude Cycling - Heat Source

This program does not have any mass changes but allows for an internal heat to be generated at equilibrium altitude, shut off during descent, and turned on at minimum altitude to produce ascent.

DEPLOYMENT

The deployment of a BVS has been investigated for the three model atmospheres of NASA SP-3016. The deployment phase was initiated at 70 km, subsonic ($M = 0.9$) velocity and a 90° flight-path angle. The parachute loads do not present any major problems nor does this mission appear to dictate new parachute technology beyond that of withstanding sterilization. The deployment sequence consisted of deployment of a parachute, subsequent deployment and inflation of the balloon, release of the inflation tankage and parachute, and establishing equilibrium floatation. Two computer programs were developed to analyze the deployment phase. The first program was used to determine the dynamic loads resulting from parachute deployment. The second was used to analyze the balloon deployment and inflation characteristics through establishment of equilibrium floatation. The balloon has to be inflated with sufficient gas to produce sufficient "free lift" (buoyancy) to reverse the station downward velocity. This inflation requires approximately a 10% gas weight over that required for the balloon after equilibrium has been established. The excess gas is vented off as the balloon rises to its altitude. Inflation above the equilibrium altitude presents a control problem because of the excess differential pressure that must be controlled.

Parachute

Parachute deployment for 200- and 2000-lb stations was analyzed for the three model atmospheres. The most important factors were snatch force, opening shock loads, dynamic pressure peaks, and maximum deceleration of the stations.

The 200-lb station was deployed with a 16.4-ft diameter (measured over the canopy) guide surface parachute at the initial conditions previously stated. The snatch force was 7000 lb and the opening shock was 8300 lb. These are shown in figure 52. The parachute was sized to produce a dynamic pressure of approximately 1.0 psf for deployment of the balloon. The maximum deceleration was 1000 ft/sec^2 and the maximum dynamic pressure was 40.5 psf.

Deployment of the 200-lb station in the upper and lower atmospheres at the same altitude, Mach number, and flightpath angle results in a snatch force of 10 200 lbs and 1900 lb, and opening shock loads of 8900 lb and 2600 lbs in the upper and lower atmospheres, respectively.

The 2000-lb class station was deployed with the use of a 75.5 ft (measured over the canopy) guide surface parachute, again sized to produce approximately a 1.0 psf dynamic pressure field for the inflation of the balloon. The terminal velocity at 57 km is approximately 82 ft/sec. The deployment was made at 70 km in all three model atmospheres. Table 10 shows the results of the computer runs. The magnitude of the snatch force and opening shock is strongly influenced by the spring constant of the risers and connecting cable (bridle). If a spring constant of 1000 lb/in. is used, rather than the 500 lb/in. used for the above cases, the snatch force and opening shock are 134 000 and 101 200 lb. A spring constant of 200 lb/in. will decrease the snatch force and opening shock to 35 200 and 42 000 lb, respectively, in the mean density atmosphere. Figure 53 reflects the bridle loads as a function of time in the mean atmosphere.

Table 10. - PARACHUTE DEPLOYMENT, 2000-LB STATION

Model atmosphere	Deployment altitude, km	Max dynamic pressure, psf	Maximum deceleration, g	Snatch force, lb	Opening shock, lb
Mean	70	17	22	77 200	73 200
Upper	70	49	156	112 200	78 000
Lower	70	.70	6.2	20 700	22 800

Balloon

Balloon deployment for 200- and 2000-lb stations was investigated for the three model atmospheres. The parameters of primary interest are:

1) Magnitude of altitude undershoot;

2) Inflation altitude;

3) Inflation rate;

4) Time to establish equilibrium;

5) Amount of gas required in balloon.

The computer runs established bounds for these parameters.

The fundamental problem associated with deployment of a balloon from a descending station is the means of detecting when the inflation should take place. If the balloon is inflated in one operation at an altitude above the equilibrium altitude, the superpressure may be prohibitive from a design standpoint. For example, if the balloon were inflated with the amount of gas designed for floatation at 57 km with a superpressure of 6 mb, but the balloon was at 58 km in the mean atmosphere, the superpressure would be 20 mb. This could result in a balloon weight penalty of approximately 300 lb for the 2000-lb hydrogen gas station. If the balloon is inflated at 56 km, sufficient gas must be injected to produce a margin of buoyancy resulting in a gas system weight penalty. A method to minimize these problems of inflation is to initiate the inflation at an altitude above equilibrium altitude and control inflation with time maintaining a maximum differential pressure in the balloon.

Inflation was initiated by altitude for the analyses to date. However, the uncertainty of the atmospheres dictates use of measurements such as density, dynamic pressure, and static pressure for deployment. This will impose stringent accuracy requirements on the sensors.

Typical altitude profiles for the deployment phase are shown in figure 54 for the three atmospheres with a 2000-lb station. A typical gas inflation profile is shown in figure 55, which shows the 10% weight penalty caused by the undershoot, in this case approximately 1 km in the mean density atmosphere.

ALTITUDE CYCLING

Altitude cycling was studied with four methods of accomplishing the cycling. These were (1) gas dump and makeup, (2) gas dump and ballast release, (3) pumping and dumping atmospheric gases, and (4) heat cycling. A computer program was developed for each method and established that the first three methods are feasible but heat cyling is prohibitive because of the high heating rate required. It takes from 50 to 100 Btu/sec heat input to cycle a 2000-lb class station. This would require approximately a 1500- to 3000-lb isotope heater.

Gas Dump and Makeup

Cycling by dumping sufficient inflation gases to descend and adding gas to the balloon when the minimum desired altitude is reached is feasible, but does have a limit in the number of cycles that can be performed.

A 2000-lb class station inflated with hydrogen gas has been studied in the three model atmospheres. A range of percentages of dump and makeup show that 3 cycles to 10 km are feasible. The gas makeup system requires approximately 60% of the original suspended weight. This station can support 800 lb at equilibrium. The 3 cycles allow for a suspended weight of 370 lb for the payload. This is sufficient to allow the largest science payload identified to date that is considered for this mission.

A typical trajectory for each atmosphere is shown in figure 56. The cycle period ranges from 3 hr in the lower density atmosphere to over 10 hr in the upper density atmosphere. This requires that the payload be subjected to an ambient environment above 160°F for approximately 7 hr. The cycle period is decreased if the percentage of dump and makeup is increased. Figure 57 shows three trajectories in the mean atmosphere for a range of amounts of dump and makeup. The relationship between percentage dumped and cycle time is shown in figure 58. Also shown is the resulting time when the station is subjected to an ambient temperature above 160°F. The minimum cycle altitude is also a factor in the cycle time. This effect is shown in figure 59. A typical ambient temperature profile is shown in figure 60 for a cycle between 57 and 10 km in the mean atmosphere.

The amount of superpressure in the balloon has an effect on the amount of gas required to be dumped and, therefore, gas to be added. The superpressure has to be vented and the balloon has to become slackened to initiate and sustain descent. When the venting is initiated, the station will rise a small increment because of the loss of mass of vented gas. This allows even more gas to be vented because of the reduced ambient pressure. This continues until the balloon becomes slack, which then produces decent of the station. The 20% dump could be decreased to 15% by decreasing the initial superpressure from 10 to 5 mb.

The amount of gas makeup is critical as shown in figure 61. The 9% makeup initiated ascent but could not sustain it. The station slowly descended again to the 10 km, which triggered another incremental addition of gas (total of 12%), which was sufficient to allow return of the station to equilibrium altitude.

Gas Dump and Ballast Drop

Altitude cycling by dumping gas and dropping ballast (when minimum altitude is reached) is very close in efficiency to that of gas dump and makeup. Three cycles with the 2000-lb station allows for a 350-lb payload. The ballast dropped for these 3 cycles was between 40 and 80 lbs, which can be allocated to large drop sondes identified in the instrumentation study. As in the gas dump and makeup mode, initial superpressure does affect the amount of gas required to be dumped. The amount of ballast dropped produces the largest effect in this mode. Figure 62 shows the trajectories for a range of percentages dropped in the upper density atmosphere. A typical ambient temperature profile for the upper density atmosphere is shown in figure 63. This indicates that as many as 6.7 hr may be spent in an environment above 160°F. The relationship between this time and percentage of gas dumped and ballast dropped is shown in figure 64. The effect of percentage of gas dumped and ballast dropped on cycle time is shown in figure 65. This indicates that a 20% dump and ballast drop will produce a cycle time of approximately 6 hr in the mean atmosphere.

Pump and Dump Atmospheric Gases

Altitude cycling a balloon by use of pumping and dumping atmospheric gases into a receiver (ballonet) is shown to be feasible, but results in an initial weight requirement of several hundred pounds.

A 2000-lb station inflated with hydrogen gas at a superpressure of 10 mb at 57 km in the mean density atmosphere has been investigated with cycling through this mode. To achieve a desirable descent velocity, a ballonet of over 2000 cu ft is required. This could be located within the adapter cone between balloon and payload gondola. A construction of fine titanium wire mesh with PBI film as the gas barrier would weigh approximately 366 lbs. This would be used with a single-stage, centrifugal compressor with a pressure ratio of 4.5 and approximate weight of 3 lb. The power source would consist of a radioisotope thermal generator allowing the pump a small flow rate of 72 lb/hr at altitude. A gas ballast of 134 lbs is required so approximately 2 hrs of pumping is required to obtain this ballast. The pump does not have to continue pumping throughout the descent phase. If it does pump continuously the velocity is increased significantly and allows a complete altitude cycle to be completed in less than 2 hr as shown in figure 66.

The relationship between ballonet volume and cycle time, with continuous pump operation during the descent phase is shown in figure 67. A ballonet volume of 2000 cu ft does not allow the station to cycle. The station settled out at a lower altitude of approximately 56 km.

A more acceptable method with minimum power consumption is to just operate the pump until sufficient ballast is obtained. This will increase the cycle time by several hours, but may present a temperature problem for the payload.

The amount of superpressure initially in the balloon influences the size of ballonet required. For example, if the balloon were essentially at zero superpressure, the above ballonet volume is decreased to 1110 cu ft (diameter of 12.85 ft). So the lower the superpressure the less the ballast required. The superpressure controls must be considered to establish a minimum acceptable limit on superpressure.

The lower the initial altitude of the station, the smaller the ballonet volume required. At 45 km, the 10-mb superpressure balloon requires a ballast of 92 lbs or a volume of 600 cu ft (10.5 ft diameter). However, the pressure requirement for the ballonet is much greater, so a weight savings cannot be realized.

The important parameters associated with the pump and dump concept are: (1) unlimited number of cycles are available, and (2) lower equilibrium altitudes are possible to maintain.

Heat Cycling

Altitude cycling by use of a heat source is not feasible for this mission. To be practical, from a weight standpoint, the heat input would have to be less than 20 Btu/sec, which results in an isotope heat source of 600 lbs. This mode was investigated because it would allow for an unlimited number of cycles. It was realized from the start that design problems would be a major drawback to this scheme.

A range of heating rates have been investigated for a 2000-lb class station using hydrogen and helium gases. The upper density atmosphere required the highest heating rates because of its lowest molecular weight (29.6). This required that the heat source be able to establish a temperature differential of approximately 150°K above that of the ambient temperature to create sufficient buoyancy to reverse the direction of the falling station. For an uninsulated balloon containing hydrogen, the heat required to cycle between 79 and 25 km is approximately 100 Btu/sec. Helium gas requires approximately 75 Btu/sec. If the mean or lower density atmosphere were encountered, the heating requirement would be decreased to 50 Btu/sec.

An isotope heat source, using Plutonium 238, would weigh more than 2000 lbs to supply 75 Btu/sec. Figure 68 is a typical trajectory for the 2000-lb station, hydrogen gas inflated in the upper density atmosphere. The period when the payload is subjected to an ambient environment about 160°F is approximately 3.5 hr. The relationship between heating rate and cycle period is shown in figure 69 for the 2000-lb station in the mean density atmosphere.

Using an insulated balloon did not reduce the heating rate to an acceptable rate. A double-walled balloon with thermofelt insulation was investigated. Insulation thicknesses of 1 to 6 in. (6 in. is not practical for a balloon that has to be packed for this type mission) with heating rates up to 20 Btu/sec did not allow the station to cycle in the upper density atmosphere.

Comparison

The three feasible methods of cycling have been compared for their efficiencies, sensitivity to atmospheres, limitations, complexity, and number of cycles feasible. The comparisons are shown in figure 70 and Table 11.

TABLE 11. - ALTITUDE CYCLE METHOD SUMMARY

Method	Practical limitations	Number of cycles feasible	Number of functions required	Sensitivity to extreme atmospheres
Gas dump and makeup	Amount of makeup gas carried as payload	3	6	Insensitive except for ascent and descent rates
Gas dump and ballast	Ballast should be usable instrumentation	3	6	Insensitive except for ascent and descent rates
Pump and dump atmosphere gases	Ballonet volume and compressor ratio	Limited by available power	9	Sensitive - molecular weight and temperature determine ballast added
Heat cycling	6 kcal/sec (300 kg)	Limited by available power	8	Sensitive - molecular weight at atmosphere determines rate of heat input required

STATION CLASSES

Three classes of stations have been identified for this mission. A 200-lb class appears to be the minimum weight station that can perform a noncyclic mission with an acceptable scientific payload. The 2000-lb class supports the total complement of science identified in the instrumentation task and also will allow for the cyclic mode to be used. The 5000-lb station is the maximum allowed for this study.

200-lb Station

A weight breakdown for this station is shown in figure 71. This station is designed to float at an altitude of 57 km in the mean density atmosphere. This will ensure floating between 40 and 80 km in the lower and upper density atmospheres, respectively.

Mylar film in bilaminate form of 0.5 mil by 0.5 mil sheets can be used for this altitude range. The design of 6 mb superpressure produces a stress of less than 7000 psi, which allows for a safety factor on yield of approximately 2.0.

2000-lb Station (Noncyclic)

This class station is shown in figure 72. Again, this weight statement is shown for a Mylar balloon, 6-mb superpressure of hydrogen. The hydrogen is transported as a high-pressure gas. The station shown floats between 40 and 80 km in the extreme atmospheres. This station does not cycle, but can carry a large complement of drop sondes.

2000-lb Station (Cyclic)

The cyclic station demands use of a high-temperature material. For the station shown in figure 73, PBI film is assumed. This new material has an operating range above 675°K (10 km in the upper density atmosphere).

Three cycles from 57 km (in the mean atmosphere) to 10 km are assumed by use of the dump and gas makeup method. Hydrogen gas is stored in individual tanks for each cycle and released when emptied.

5000-lb Station

Figure 74 indicates a weight breakdown for this size station. Hydrogen gas is used for initial inflation and for each of the cycles. Three-cycle capability is shown. However, the large payload indicates that five or six cycles could be considered.

CONCLUSIONS

Altitude cycling is feasible for stations in the 2000 and 5000-lb class. It is not feasible to cycle a 200 pound class station. Two methods of cycling are attractive for performing three complete cycles to a minimum altitude of 10 km from an altitude above 50 km in the mean density model atmosphere. These two methods are gas dump and makeup and gas dump and ballast drop. Three cycles can be performed for approximately 50% of the initial suspended mass of the station. The ballast can be in the form of scientific payloads (drop sondes).

A third method of cycling, pumping and dumping atmospheric gases, is feasible and attractive for producing a large number of cycles. This method is limited only by the available power for compressor. This can be performed for approximately 60% of the suspended mass of the station.

Deployment of the station by a parachute to produce a low-dynamic pressure field for the balloon appears feasible. Deployment was limited to subsonic initiation for this study.

A survey for balloon materials indicates that a material or composite exists, or is in development that can be used for this mission. The most promising materials are polyester film (Mylar), polyimide (Kapton), and polybenzimidazole film and fiber (PBI). Several physical properties of these materials are missing or limited and require further testing or determination. Development of fabrication techniques and controls demanded by this mission is necessary.

Three inflation gases should be considered for this mission -- hydrogen, helium, and decomposed hydrazine. Hydrogen transported as a cryogenic fluid produces the lightest gas system for the 2000-lb or larger stations. Carried as a high-pressure gas, hydrogen produces the largest payload for the 200-lb class station. Hydrazine, decomposed with a spontaneous catalyst and cooled with ammonia vapor is next in system efficiency. Helium is slightly less efficient than hydrazine.

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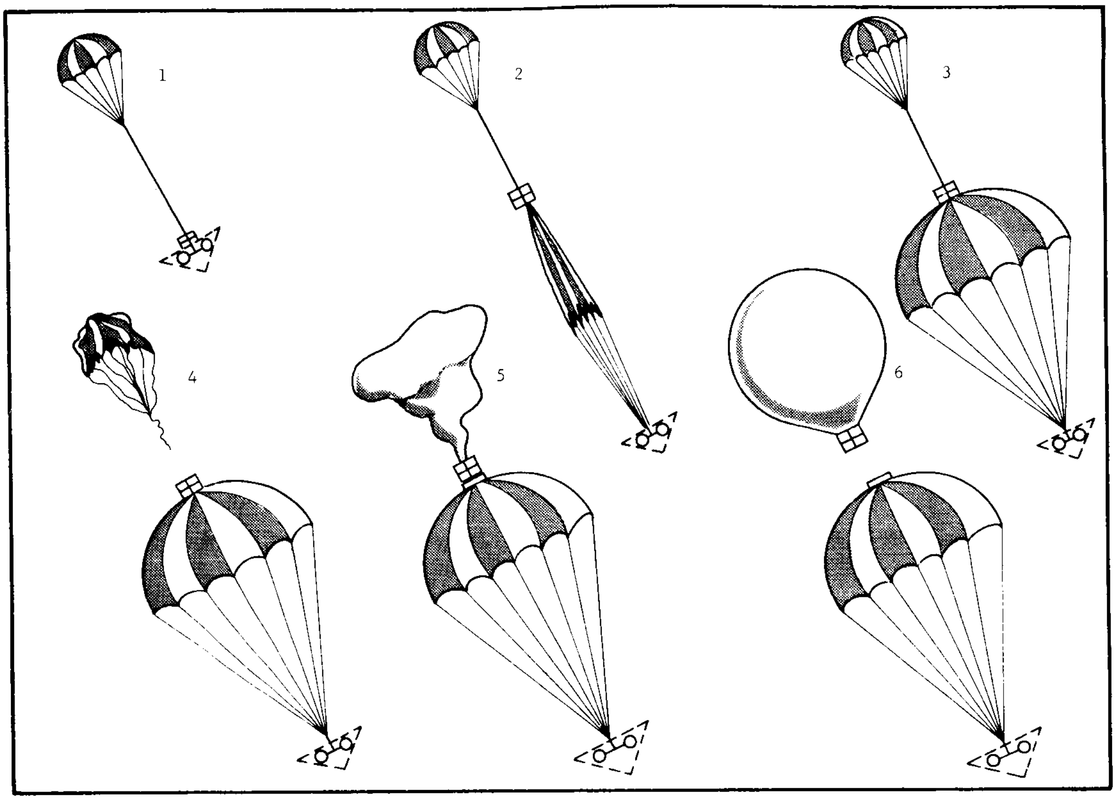


Figure 1. - Balloon/Payload-Apex Mounted System

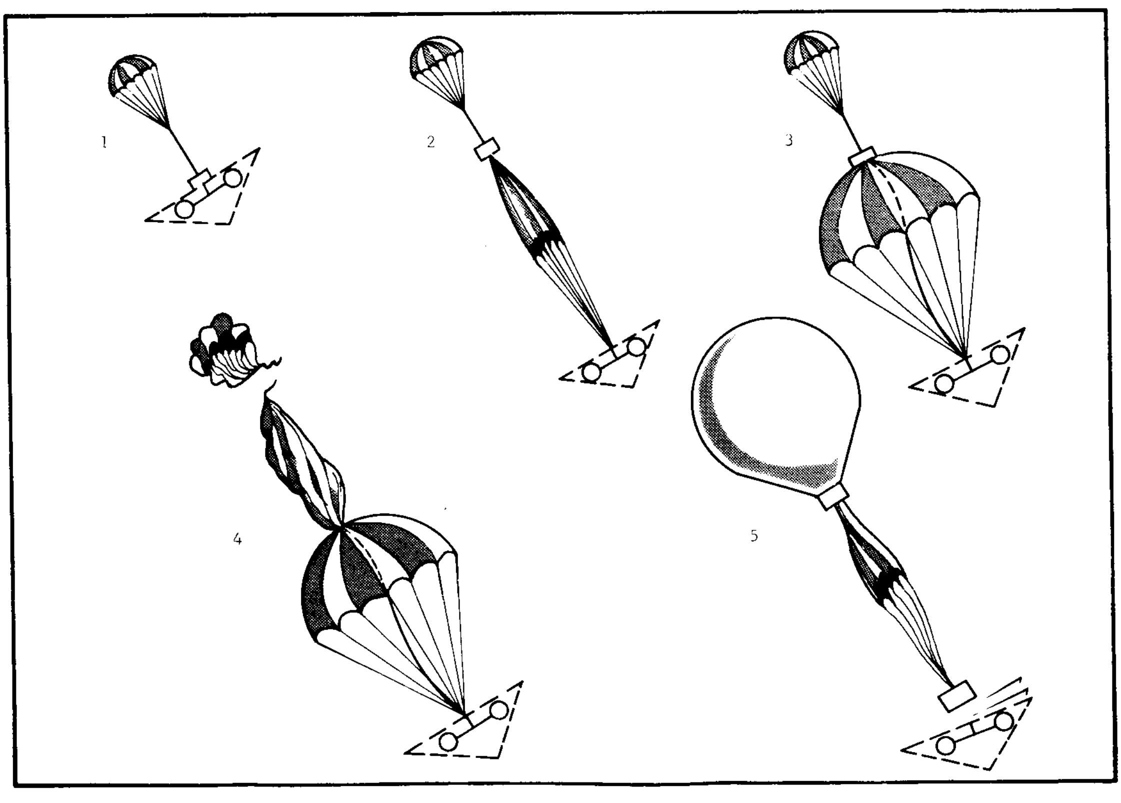


Figure 2. - Balloon-Apex Mounted System

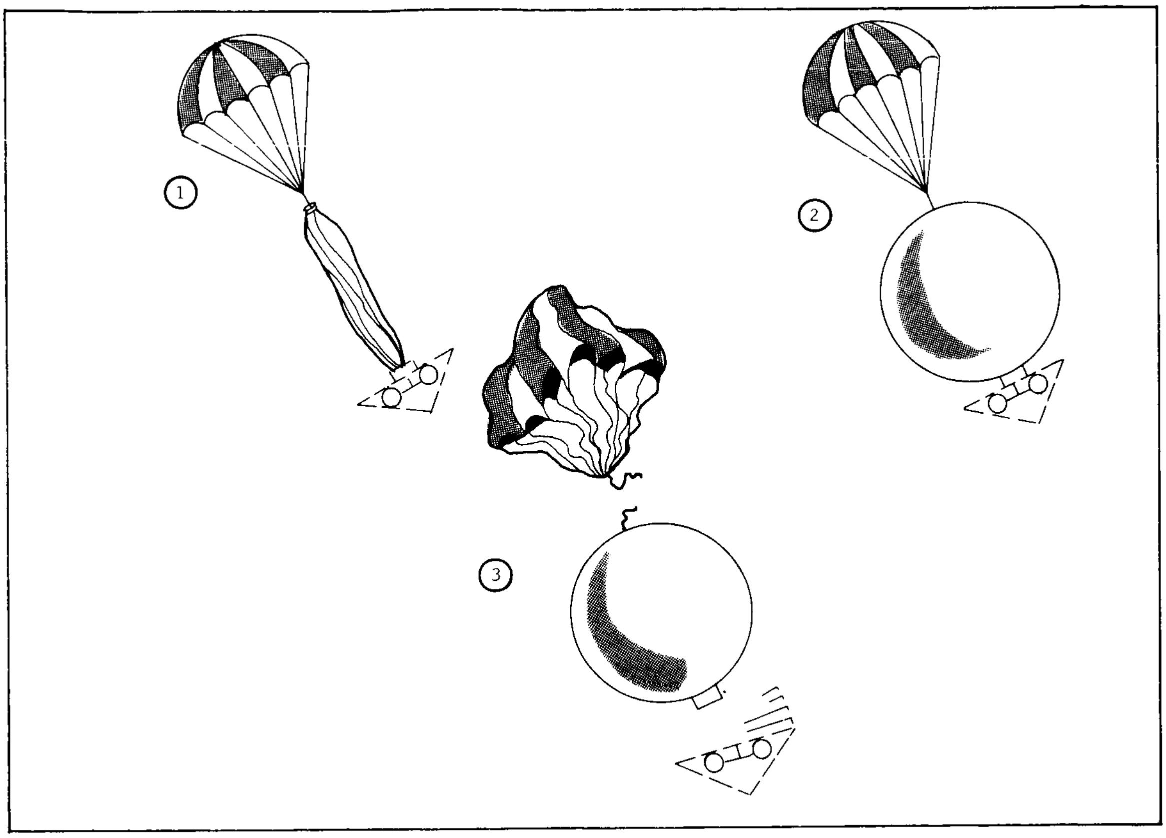


Figure 3. - Balloon/Payload-Suspended System

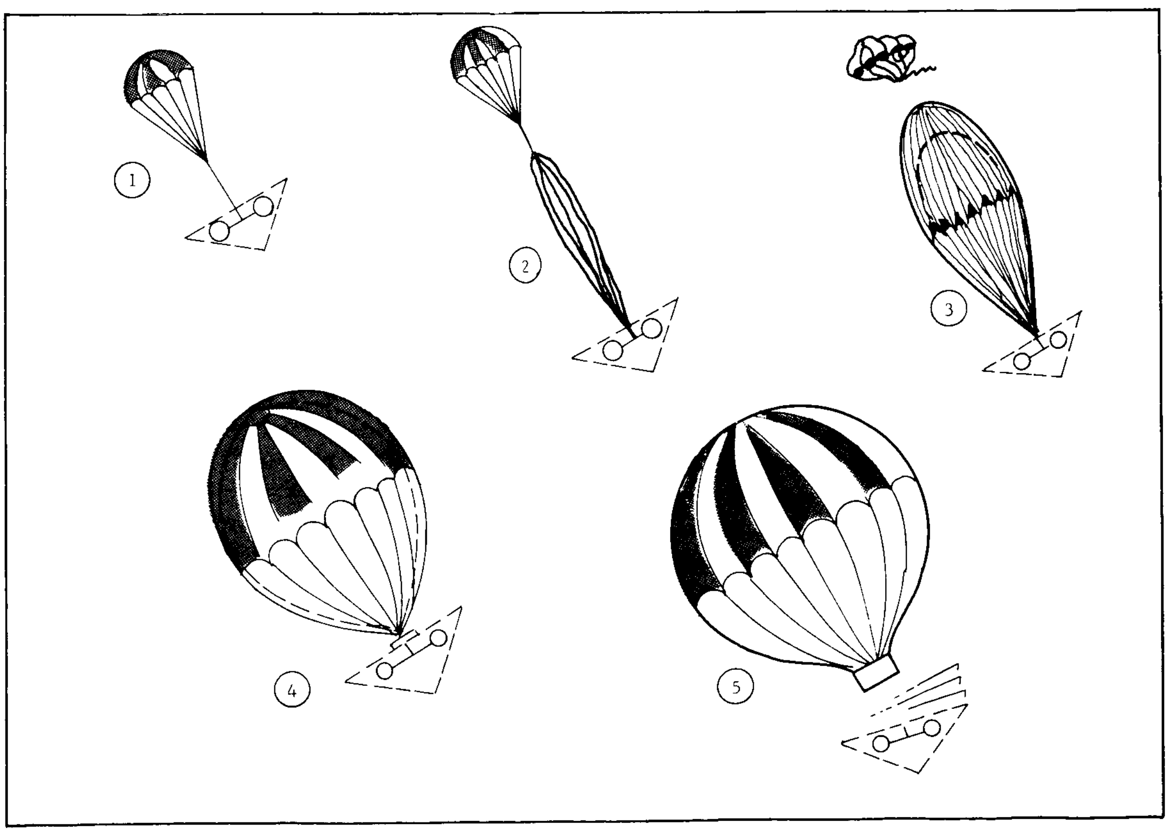


Figure 4. - Integral Paraballoon System

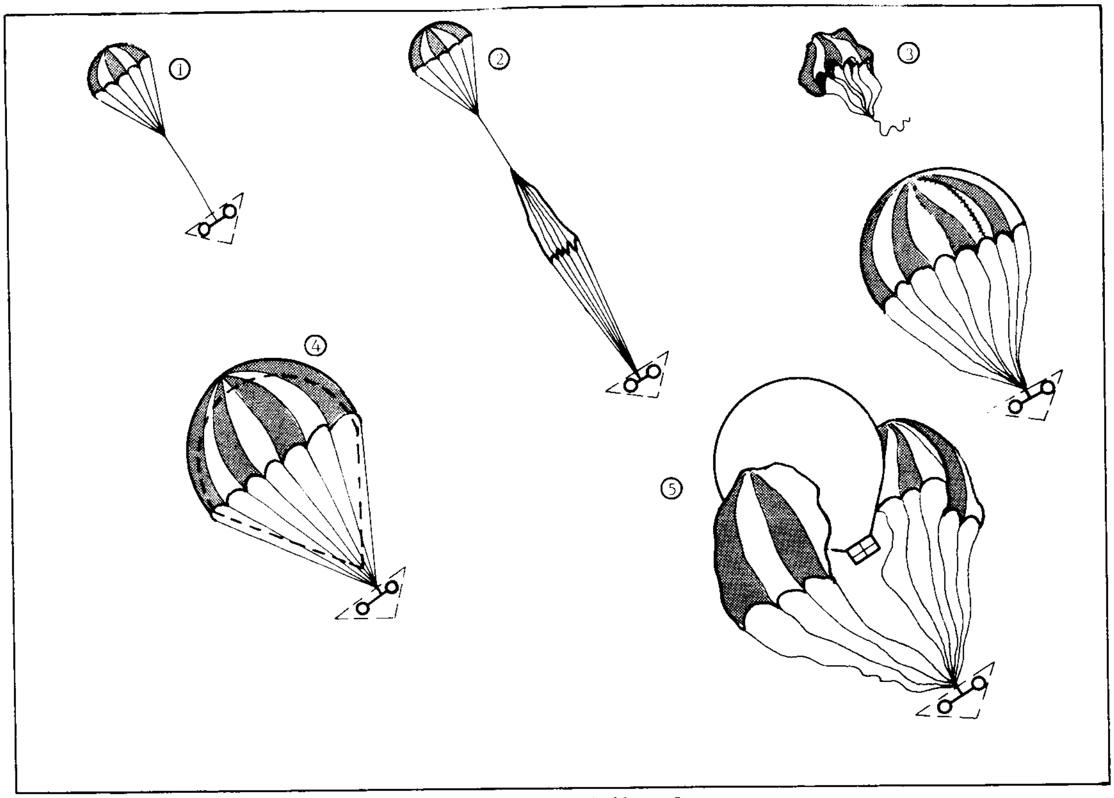


Figure 5. - Separable Paraballoon System

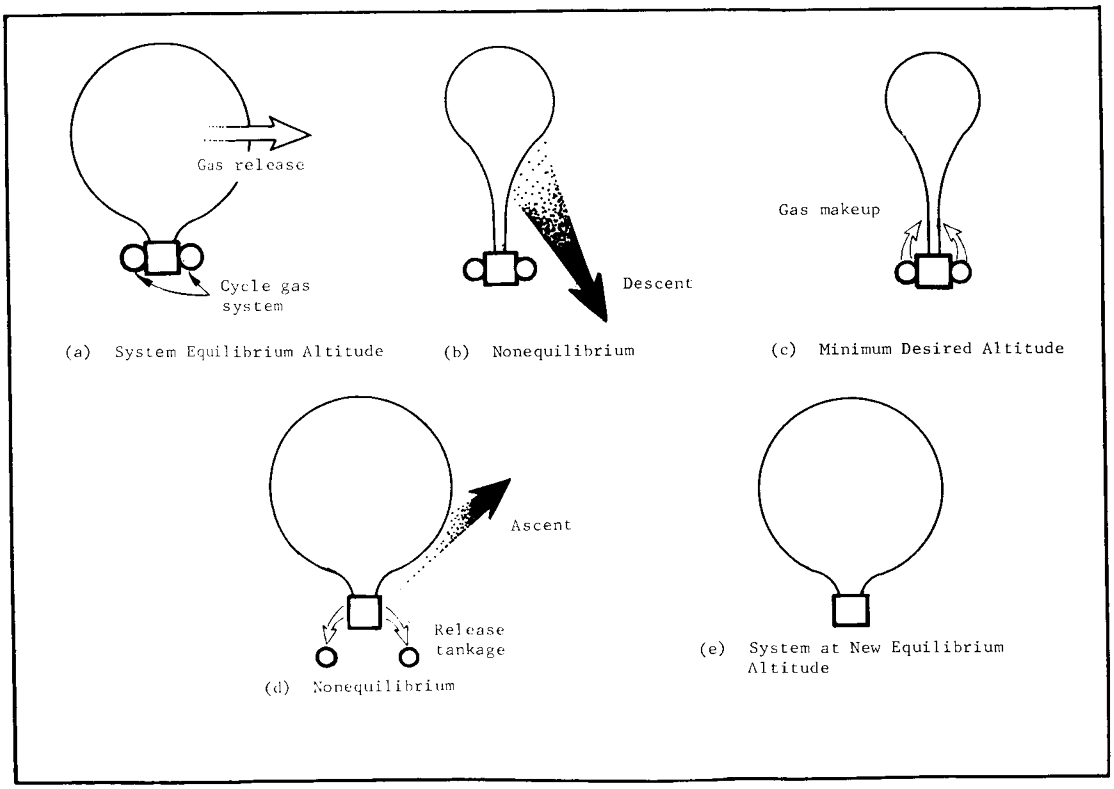


Figure 6. - Gas Release and Makeup

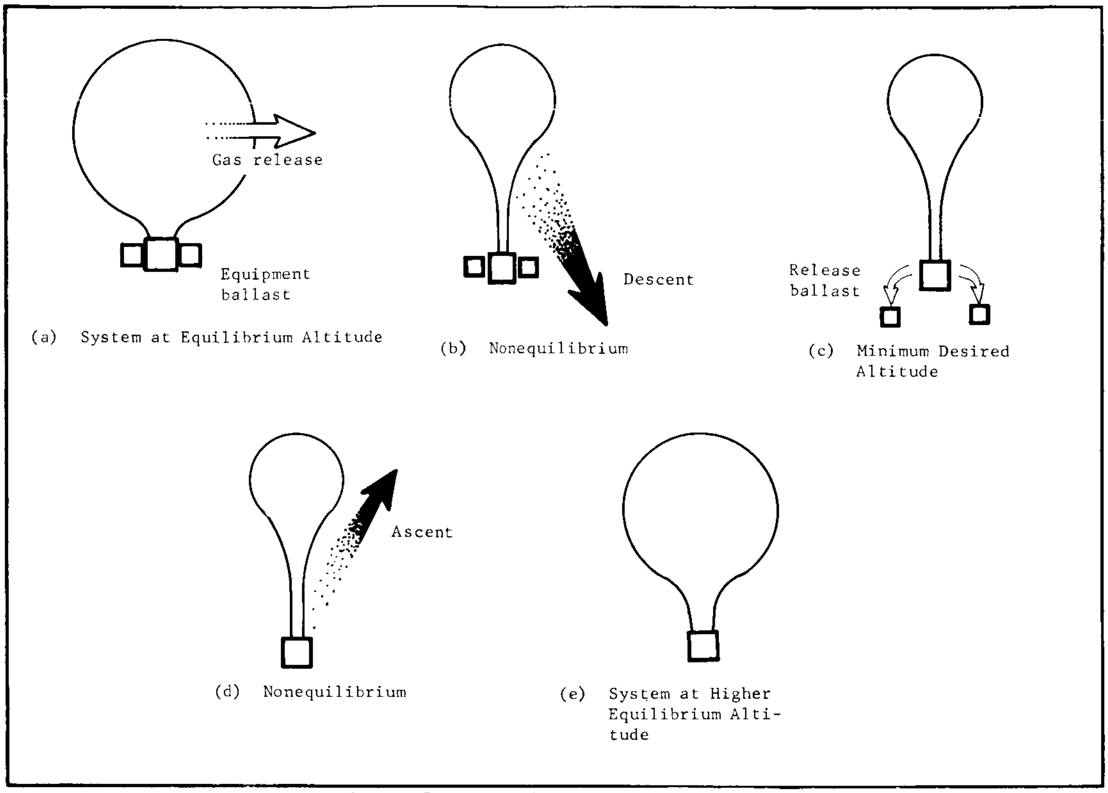


Figure 7. - Gas Release and Ballast Drop

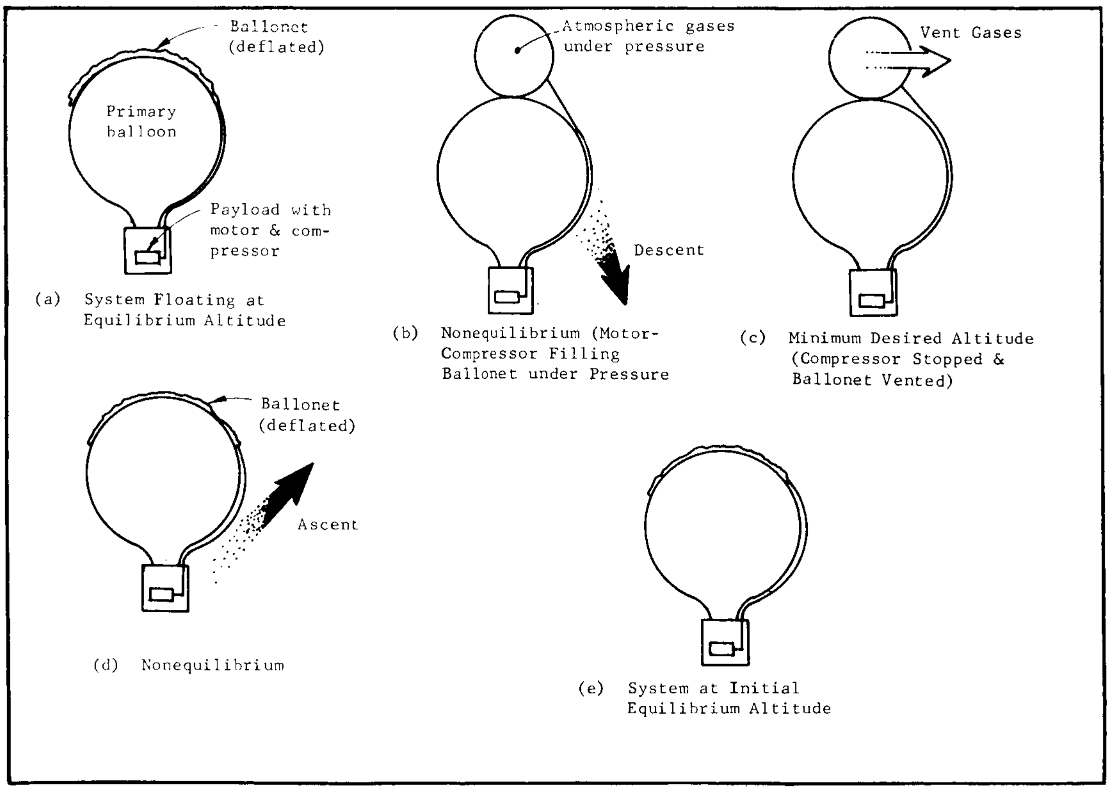


Figure 8. - Pump and Dump Atmospheric Gases

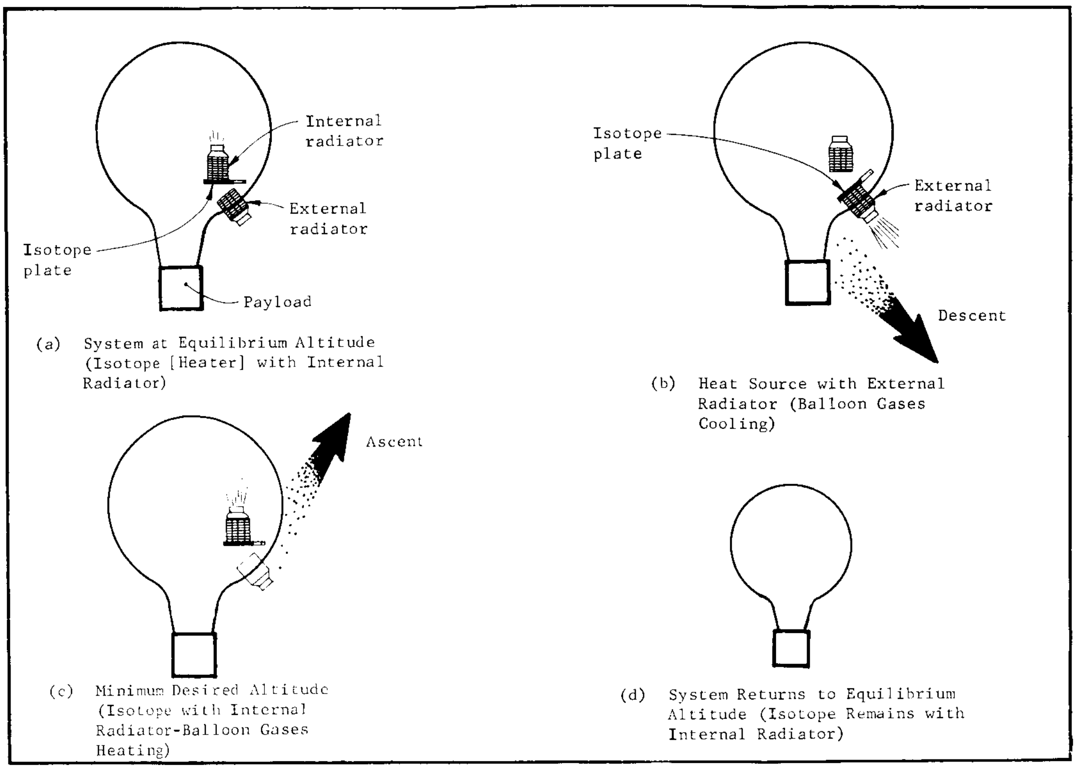


Figure 9. - Heat Cycling

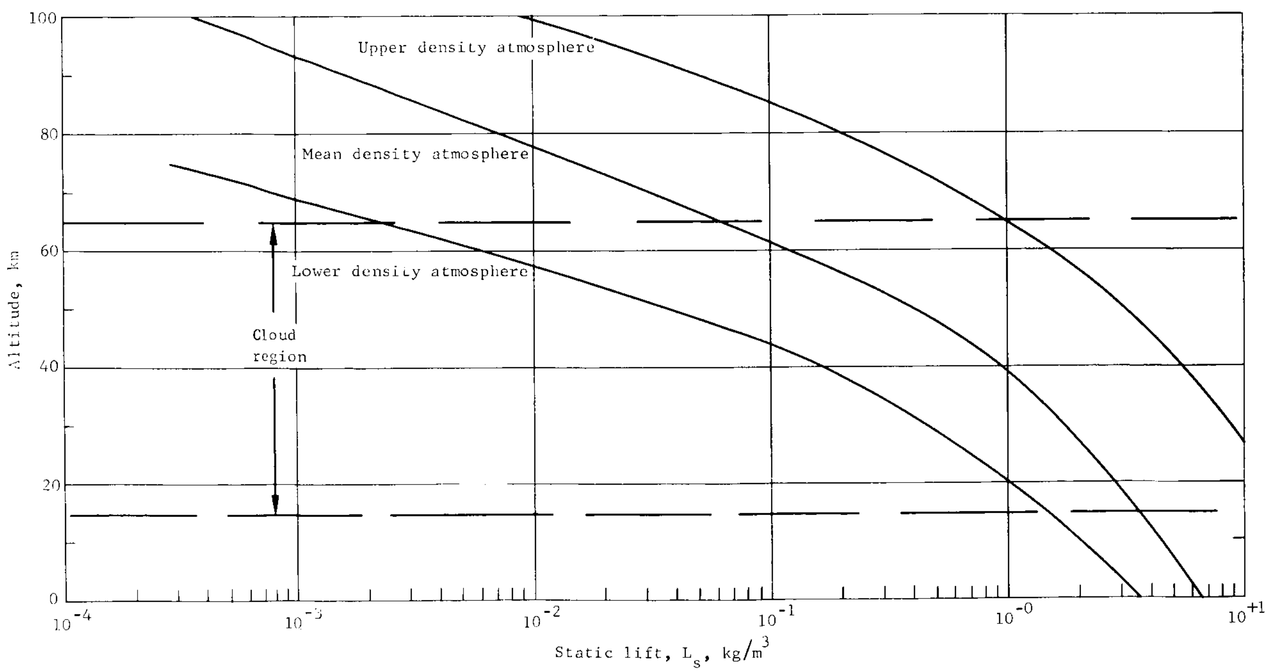


Figure 10. - Static Lift Capacity for Hydrogen in Temperature Equilibrium with Atmosphere - 10% Superpressure

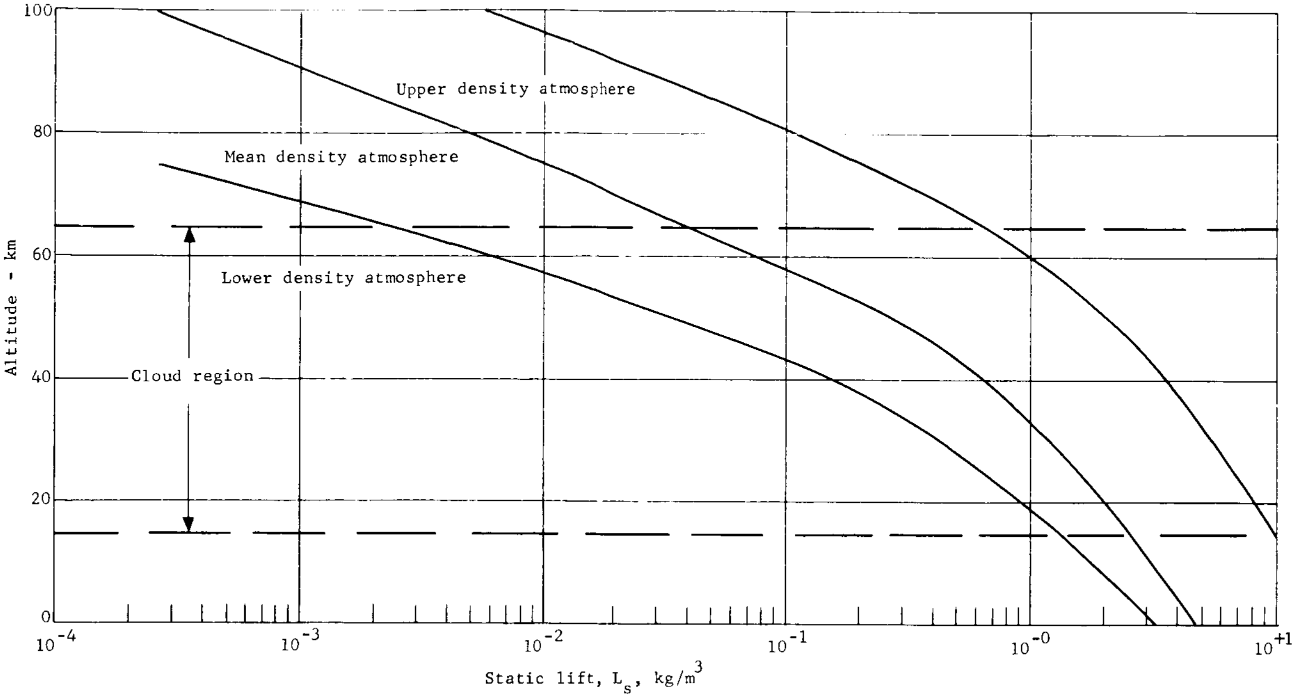


Figure 11. - Static Lift Capacity for Helium in Temperature Equilibrium with Atmosphere - 10% Superpressure

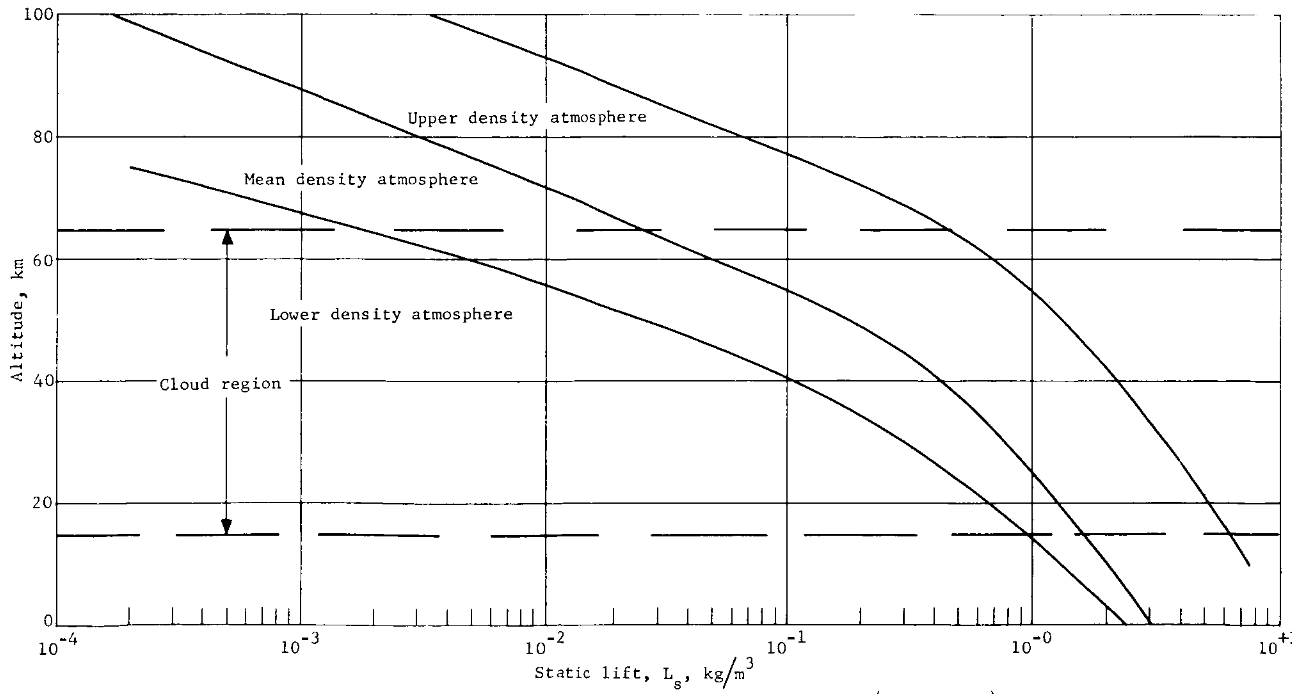


Figure 12. - Static Lift Capacity for Decomposed Hydrazine $\left(m_g = 12.60\right)$ in Temperature Equilibrium with Atmosphere - 10% Superpressure

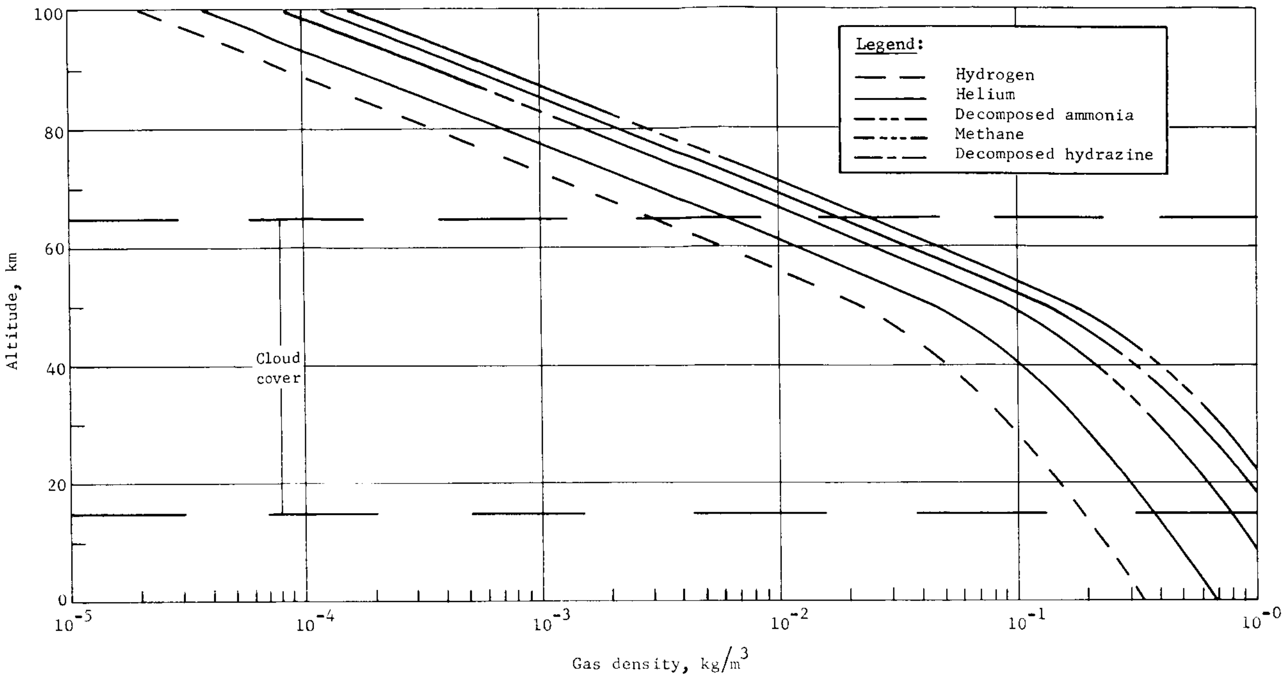


Figure 13. - Density of Five Gases in Temperature Equilibrium with Mean Density Atmosphere

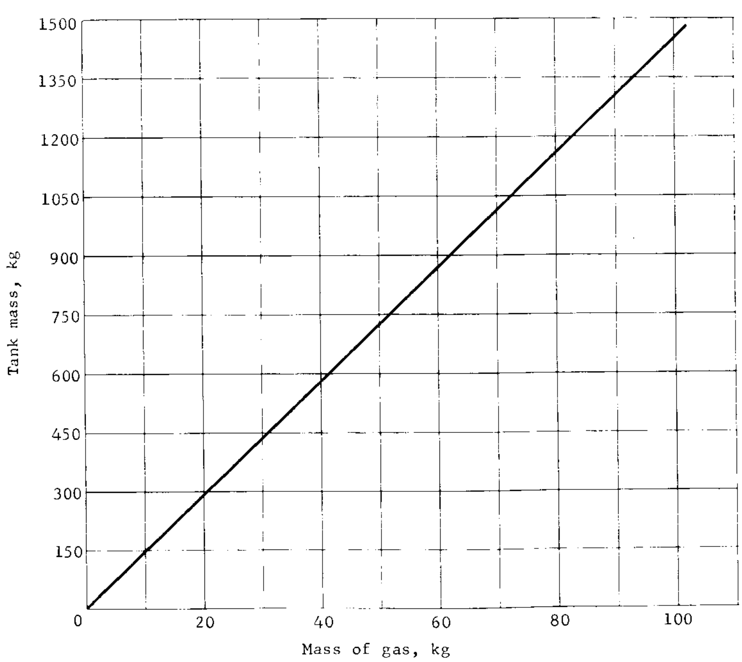


Figure 14. - Tank Mass for Transporting Hydrogen Gas at 4500 psia

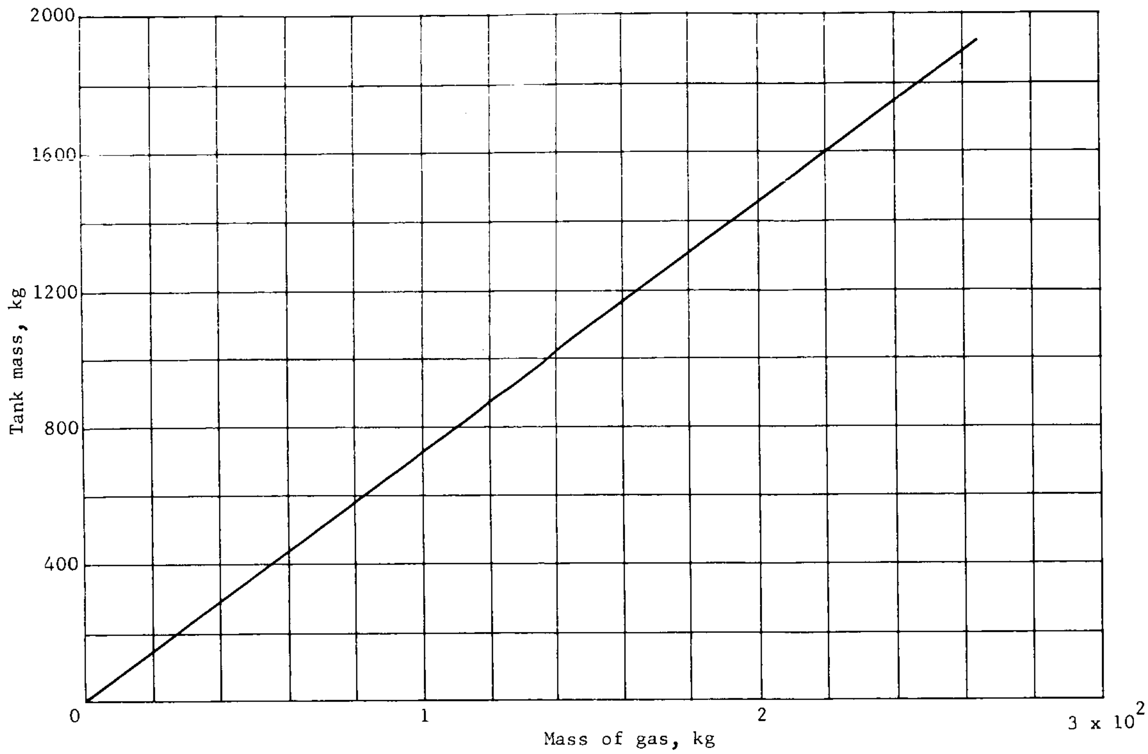


Figure 15. - Tank Mass for Transporting Helium Gas at 4500 psia

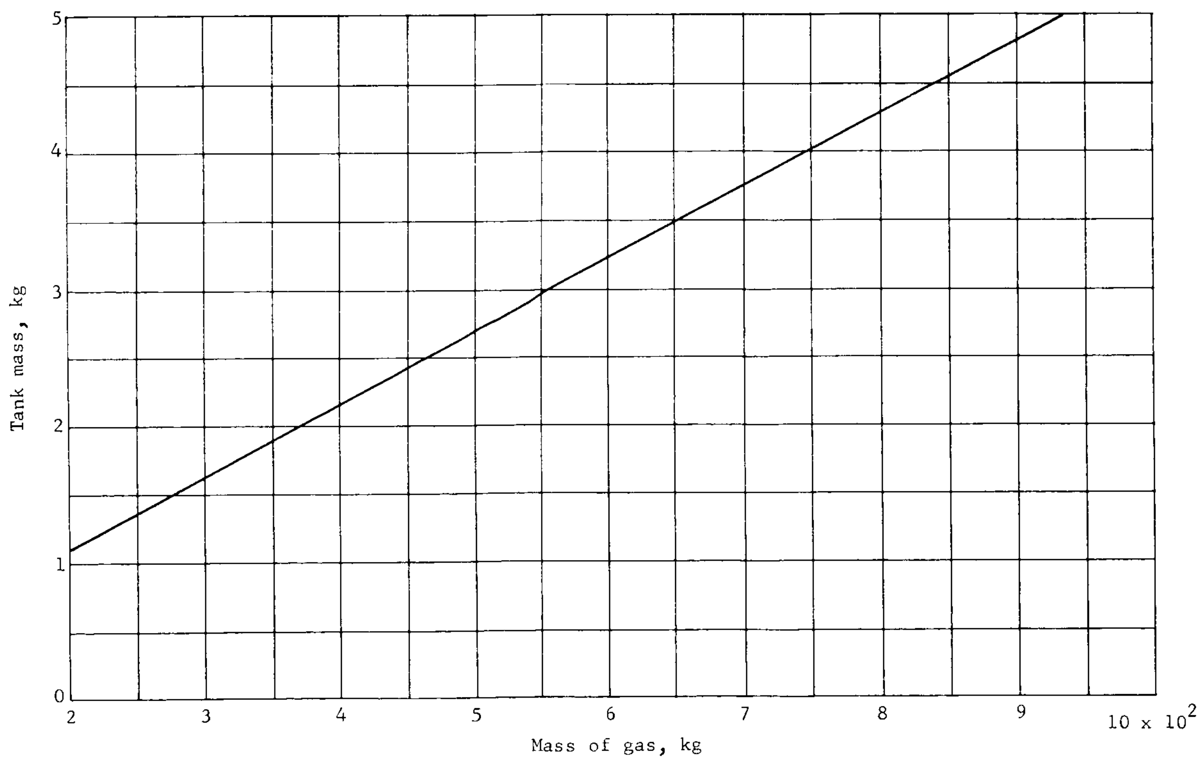


Figure 16. - Tank Mass for Transporting Hydrazine (with 23% Ammonia Addition) at 300 psia (M = 12.60)

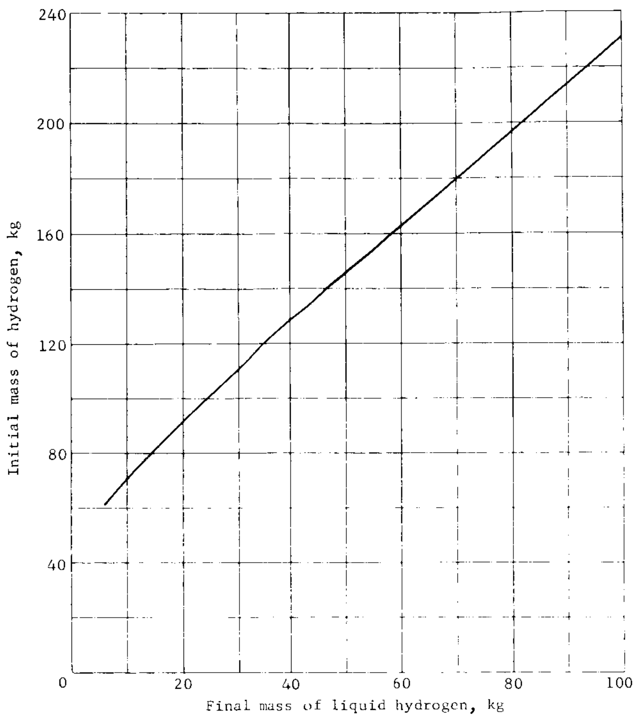


Figure 17. - Transit Losses for Liquid Hydrogen, 145-Day Transit, 20°C Ambient Temperature for Titanium Tank with Multilayer, Aluminized Mylar

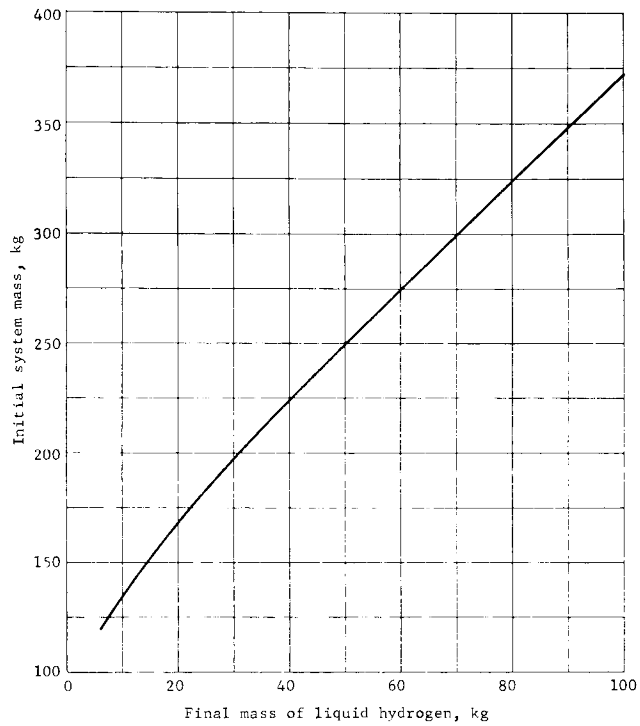


Figure 18. - Initial Mass of Cryogenic Hydrogen System to Deliver Liquid Hydrogen to Venus with 145-Day Mission

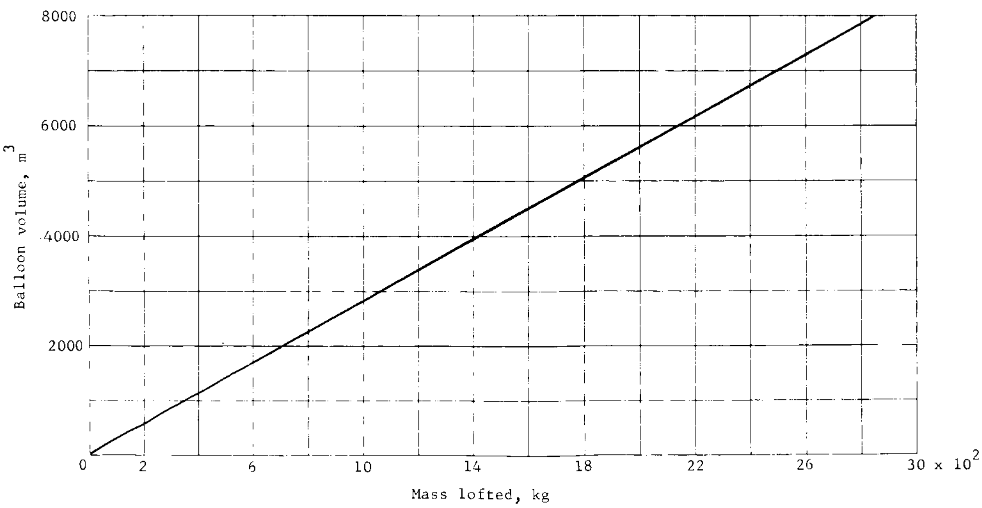


Figure 19. - Volume of Hydrogen Superpressure (0.3%) Balloon in Upper Density Atmosphere at 75 km

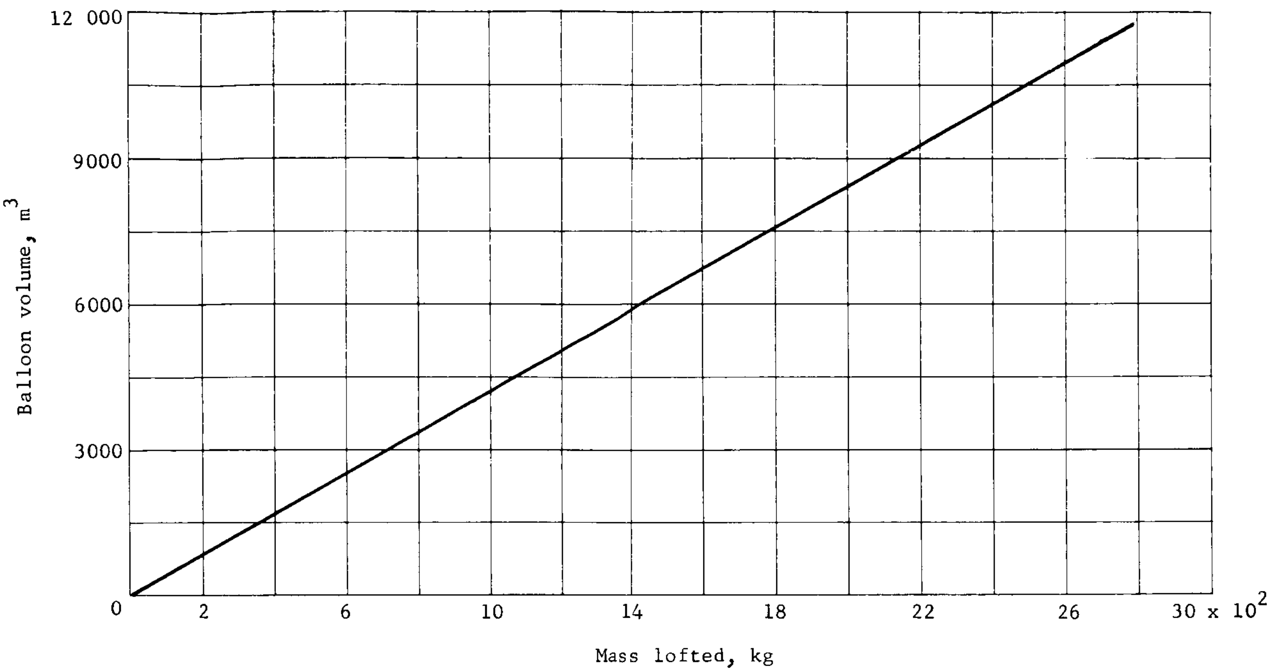


Figure 20. - Volume of Helium Superpressure (0.3%) Balloon in Upper Density Atmosphere at 75 km

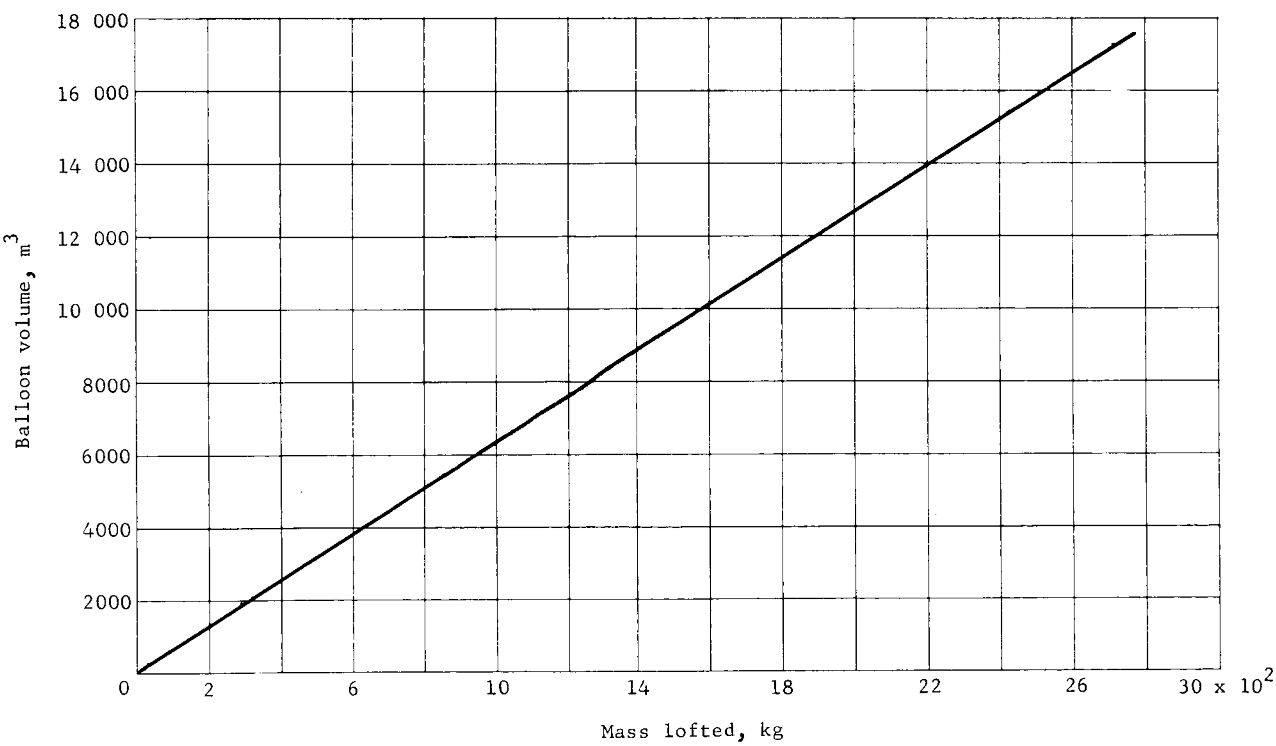


Figure 21. - Volume of Hydrazine Superpressure (0.3%) Balloon in Upper Density Atmosphere at 75 km

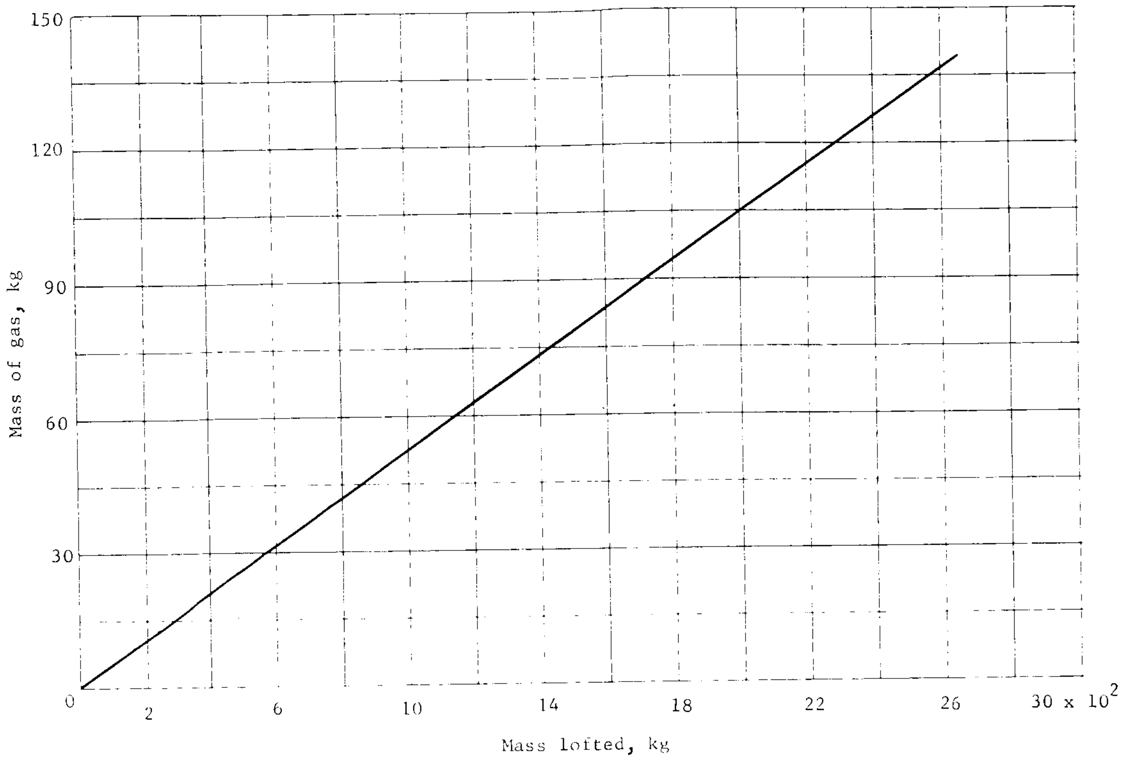


Figure 22. - Mass of Hydrogen Gas Required to Loft Various Masses to 75 km in Upper Density Atmosphere (0.3% Superpressure)

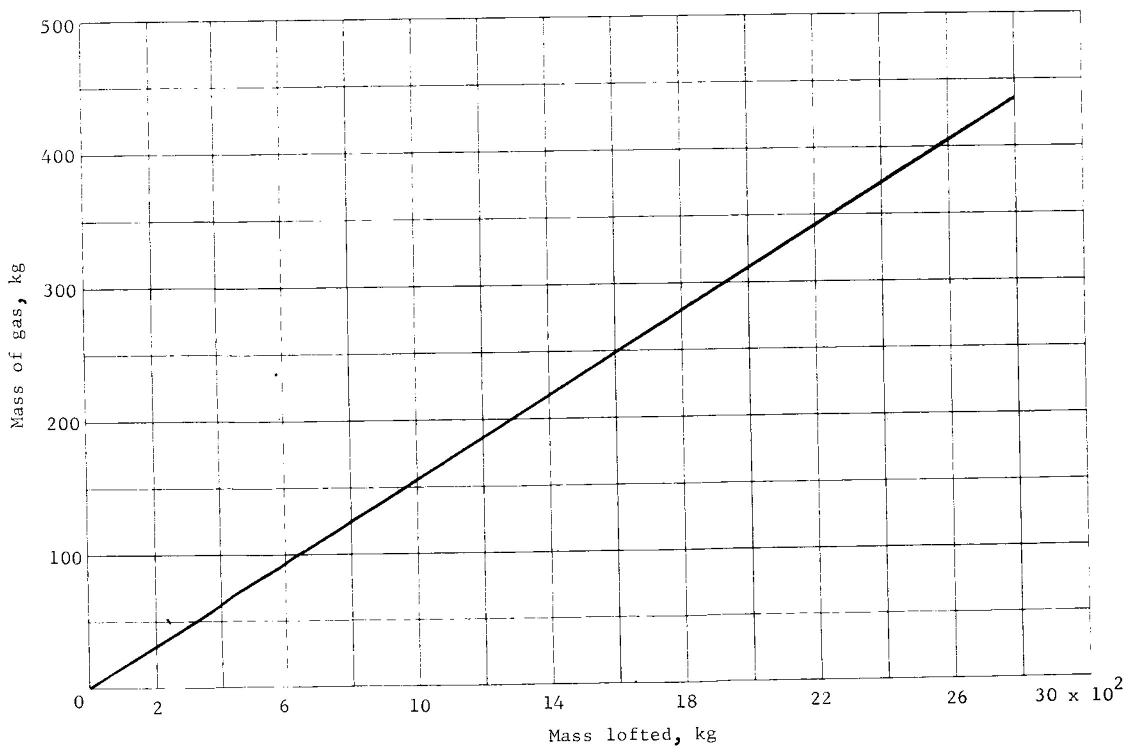


Figure 23. - Mass of Helium Gas Required to Loft Various Masses to 75 km in Upper Density Atmosphere (0.3% Superpressure)

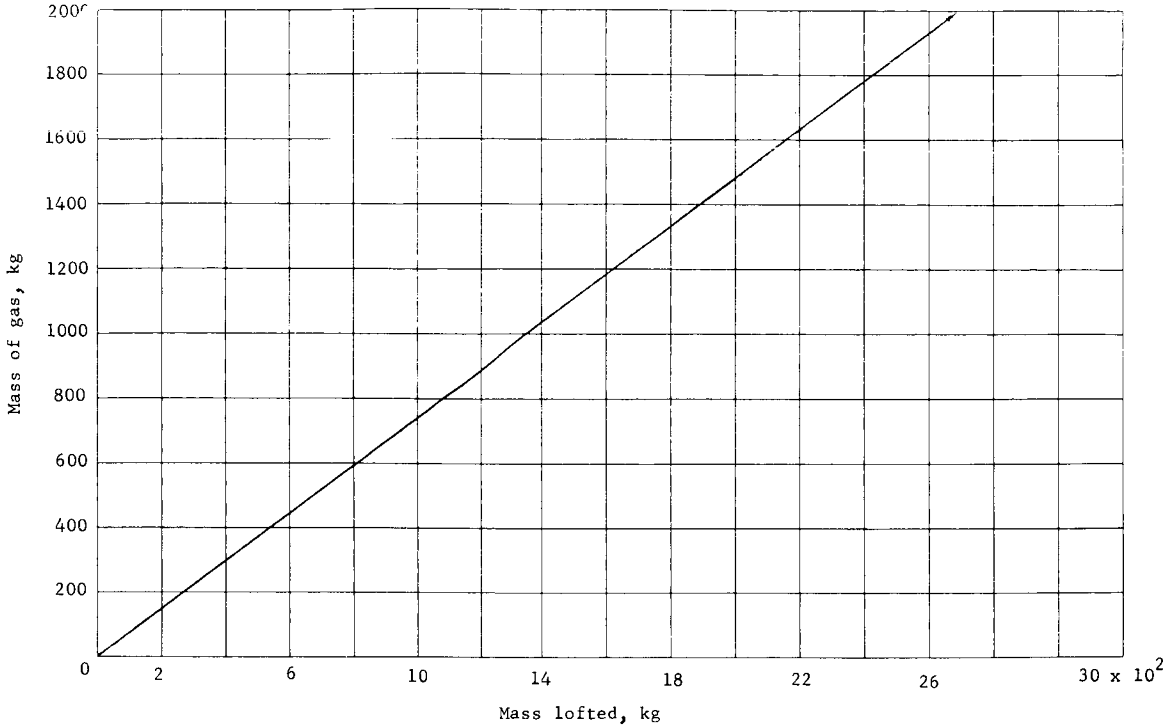


Figure 24. - Mass of Hydrazine Gas Required to Loft Various Masses to 75 km in Upper Density Atmosphere (0.3% Superpressure)

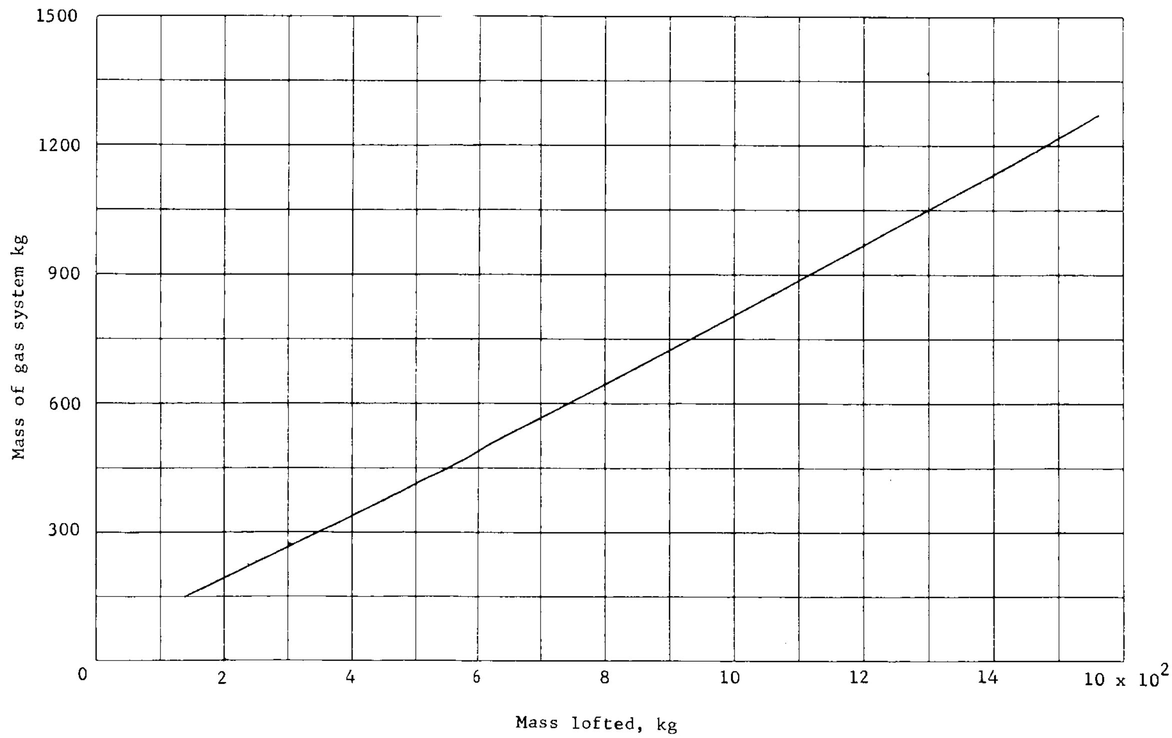


Figure 25. - Mass of Hydrogen Gas System Required to Loft Various Masses to 75 km in Upper Density Atmosphere (0.3% Superpressure)

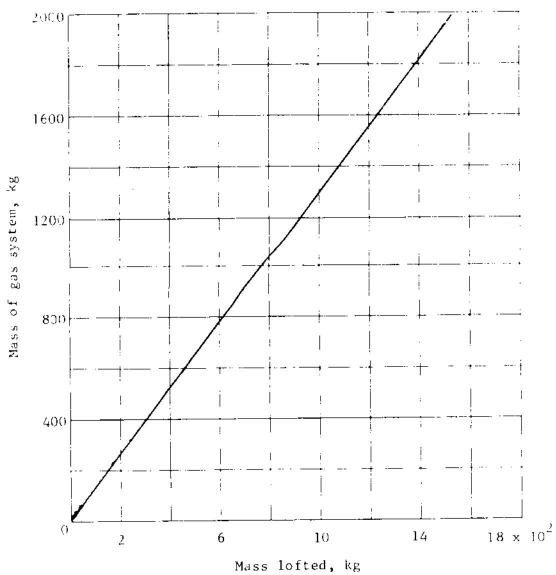


Figure 26. - Mass of Helium Gas System Required to Loft Various Masses to 75 km in Upper Density Atmosphere (0.3% Superpressure)

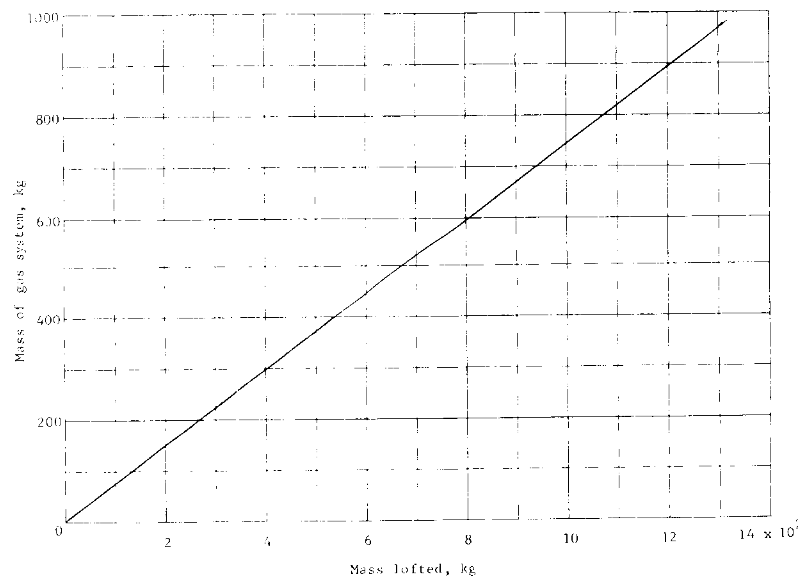


Figure 27. - Mass of Hydrazine Gas System Required to Loft Various Masses to 75 km in Upper Density Atmosphere (0.3% Superpressure)

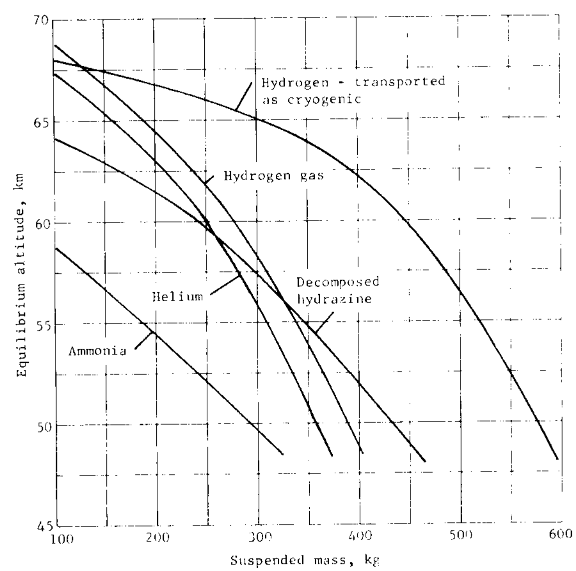


Figure 28. - System Efficiencies for Four Gases at Various Altitudes in Mean Density Atmosphere

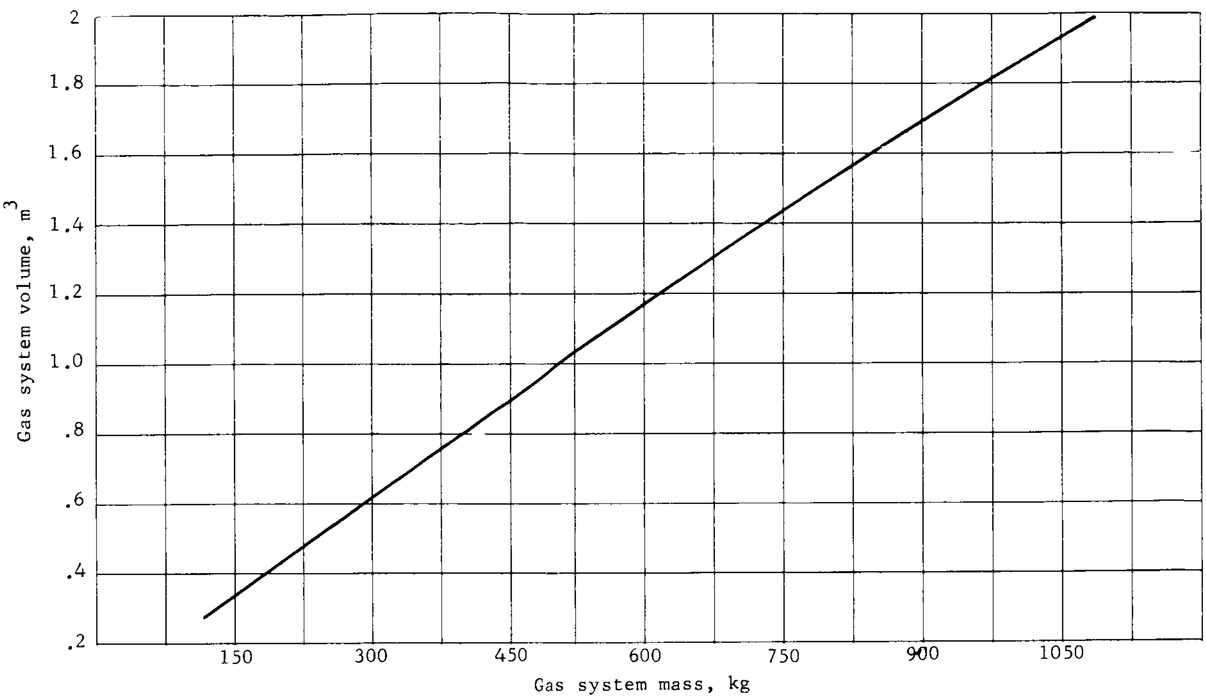


Figure 29. - Hydrogen Gas System Volume for Various Gas System Masses (Hydrogen Gas at 4500 psia)

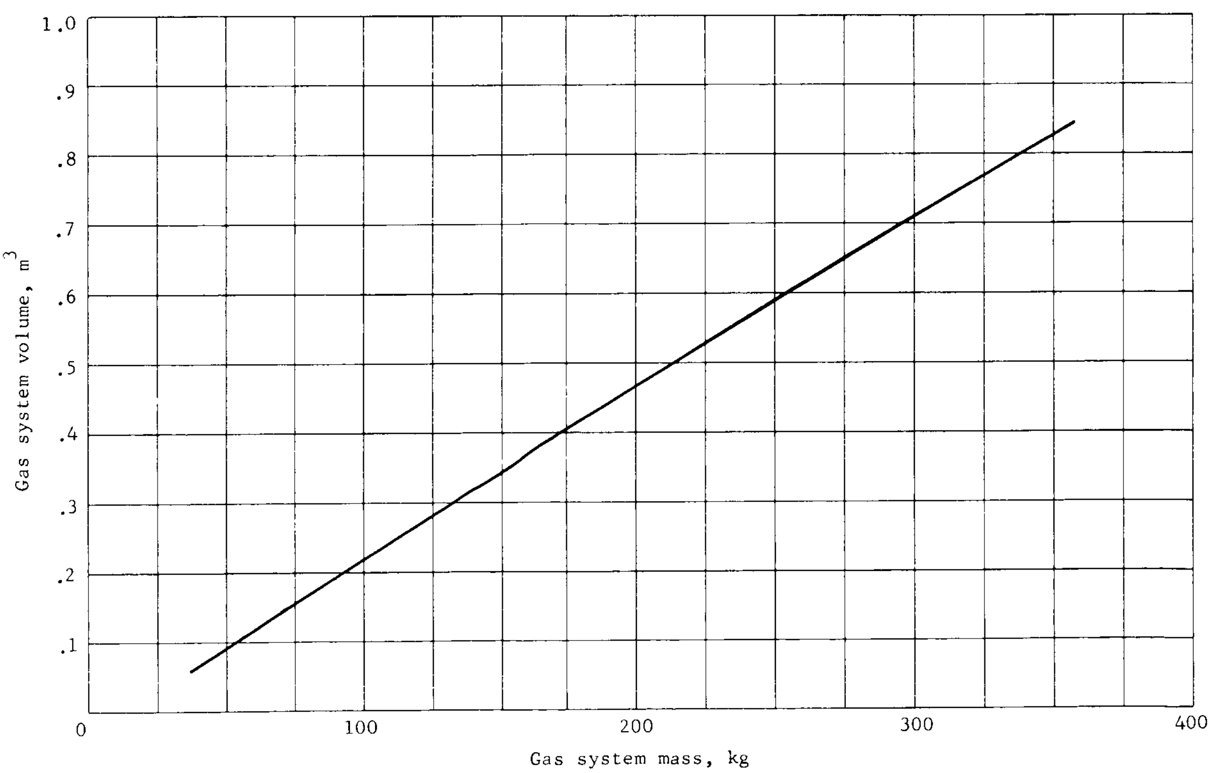


Figure 30. - Helium Gas System Volume for Various Gas System Masses (Helium at 4500 psia)

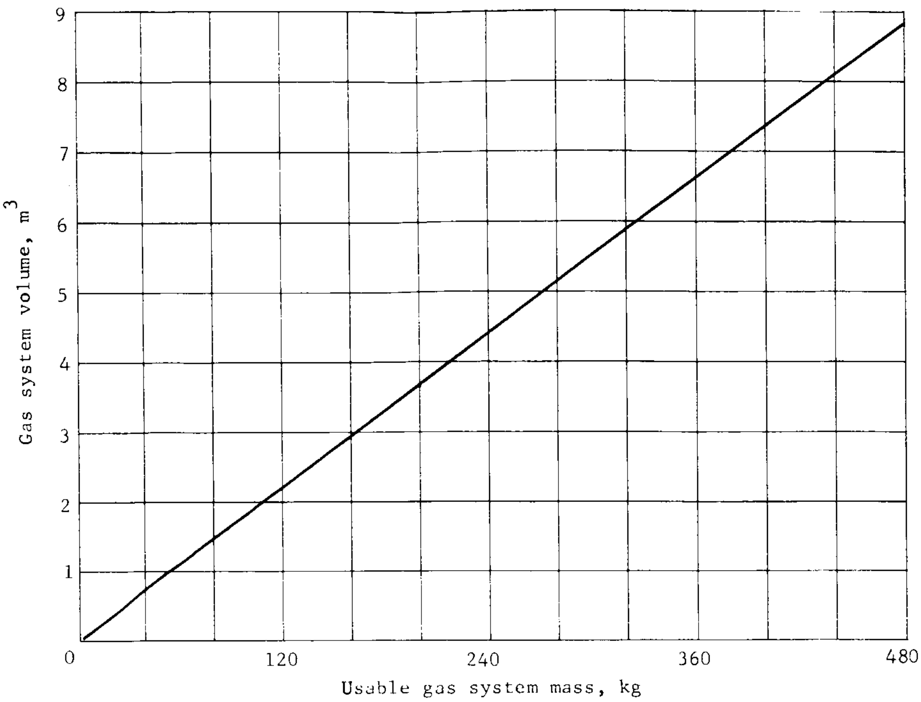


Figure 31. - Hydrazine/Ammonia System Volume for Various Gas System Masses

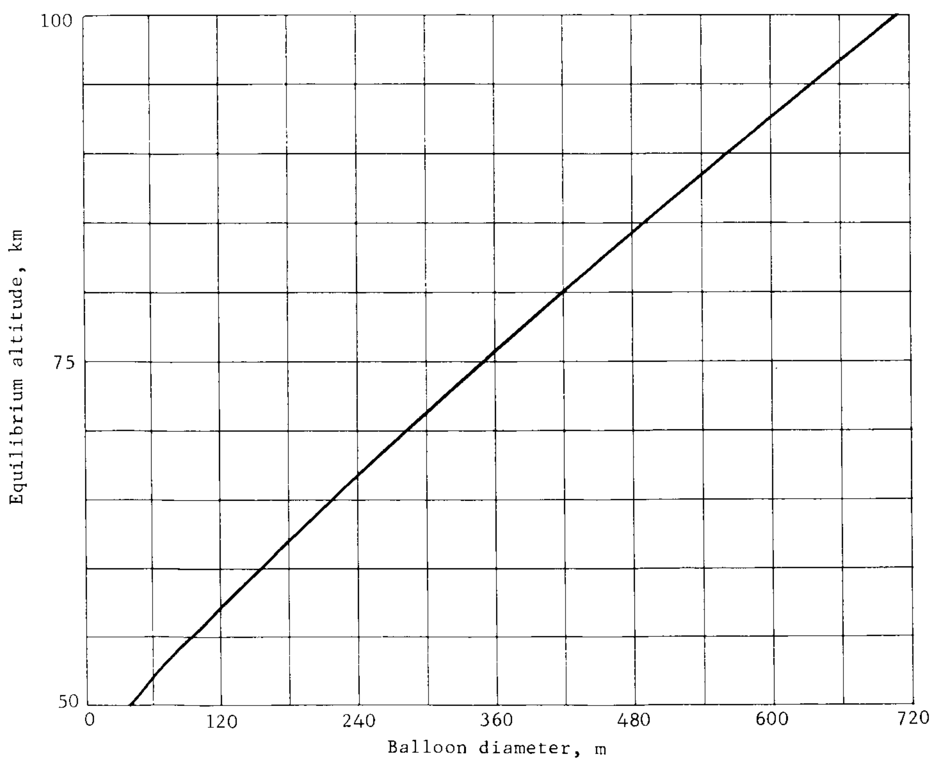


Figure 32. - Hydrogen Superpressure Balloon Sizes for Various Altitudes in Upper Density Atmosphere (0.3% Superpressure)

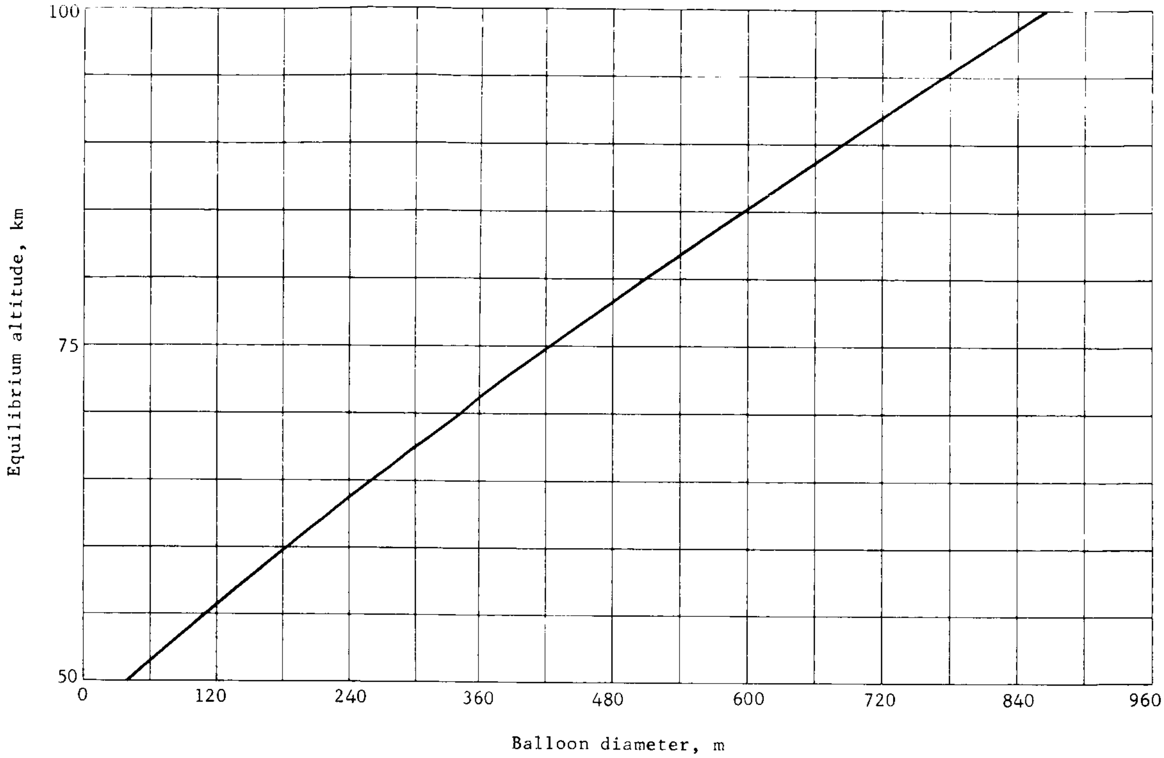


Figure 33. - Helium Superpressure Balloon Sizes for Various Altitudes in Upper Density Atmosphere (0.3% Superpressure)

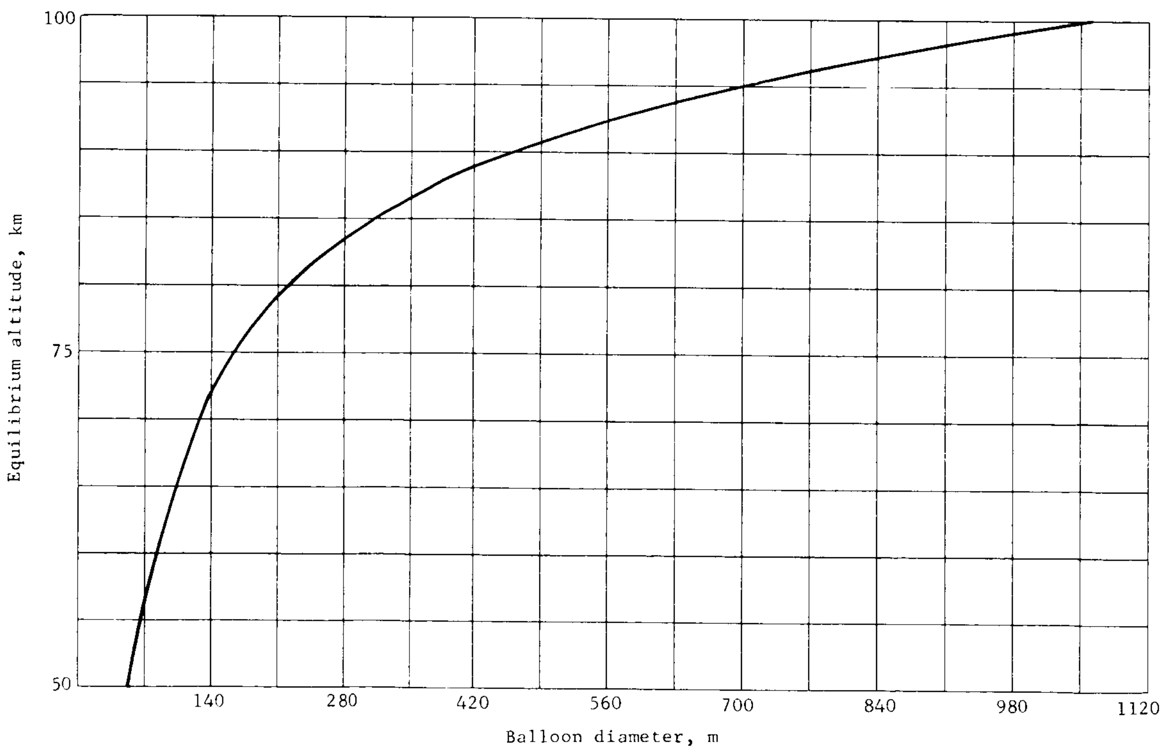


Figure 34. - Hydrazine Superpressure Balloon Sizes for Various Altitudes in Upper Density Atmosphere (0.3% Superpressure)

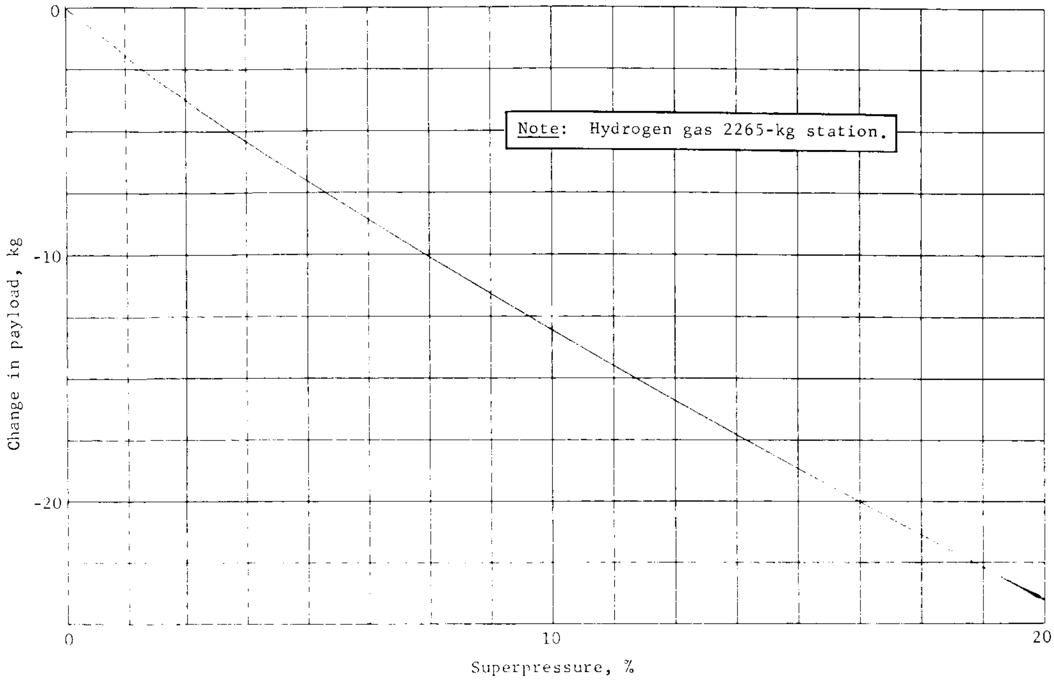


Figure 35. - Effect of Superpressure on Payload for Model Atmospheres at 75 km

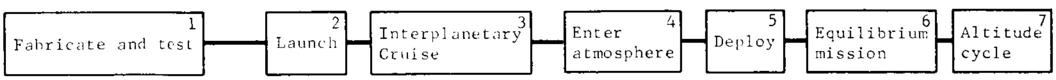
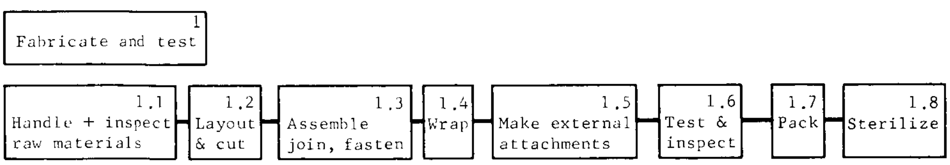


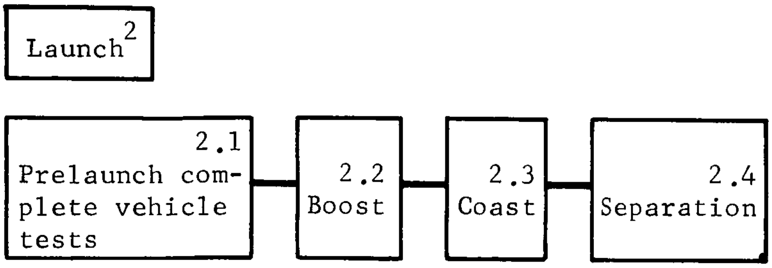
Figure 36. - Complete Mission Sequence



Environmental factors

1) Handling - rolling, unrolling, spreading, marking, cutting;
2) Mechanical handling of empty balloon;
3) Inflation;
4) Leak detection - leakage, access for leak detection;
5) Deflation and packing - handling of empty balloon;
6) Compression - remove all gas, temperature, local stresses, allowable packing pressure, allowable packing density;
7) Sterilization temperature (135°C + hot spots);
8) Gas compatibility - helium, hydrogen, ammonia, hydrazine, methane, ethylene oxide.

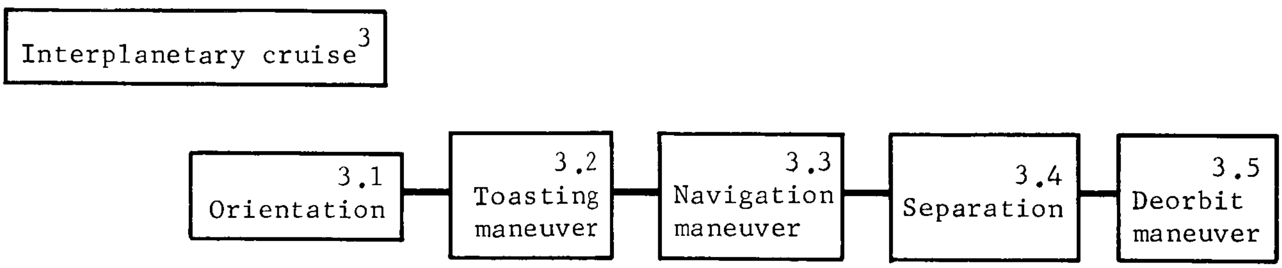
Figure 37. - Fabrication and Test Factors



<u>Environmental factors</u>

1) Storage in packed (compressed) condition during miscellaneous functional and environmental tests and terminal sterilization;
2) Launch acceleration and vibration;
3) Heat - solar radiation, enclosed RTG;
4) Coast environment in earth orbit;
5) Separation acceleration;
6) Leakage of air from packed condition (pressure change);
7) Temperature change;

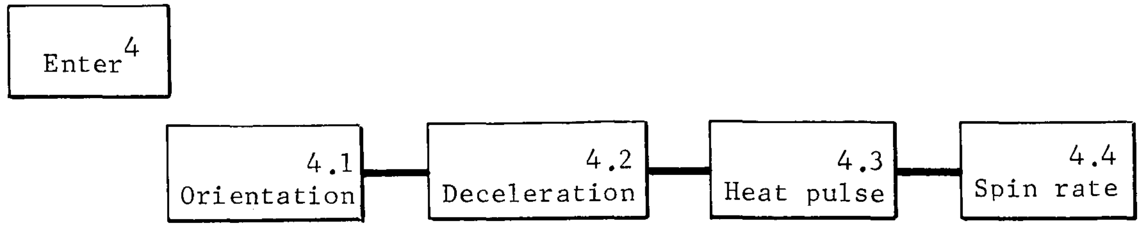
Figure 38. - Launch Factors



<u>Environmental factors</u>

1) Hard vacuum;
2) Cycling temperature - deep space to solar radiation;
3) Life 6 to 8 months - hard vacuum, packing stress;
4) RTG radiation;
5) Solar radiation;
6) Micrometeoroids;
7) Ethylene oxide;
8) Separation accelerations;
9) Retro propulsion exhaust.

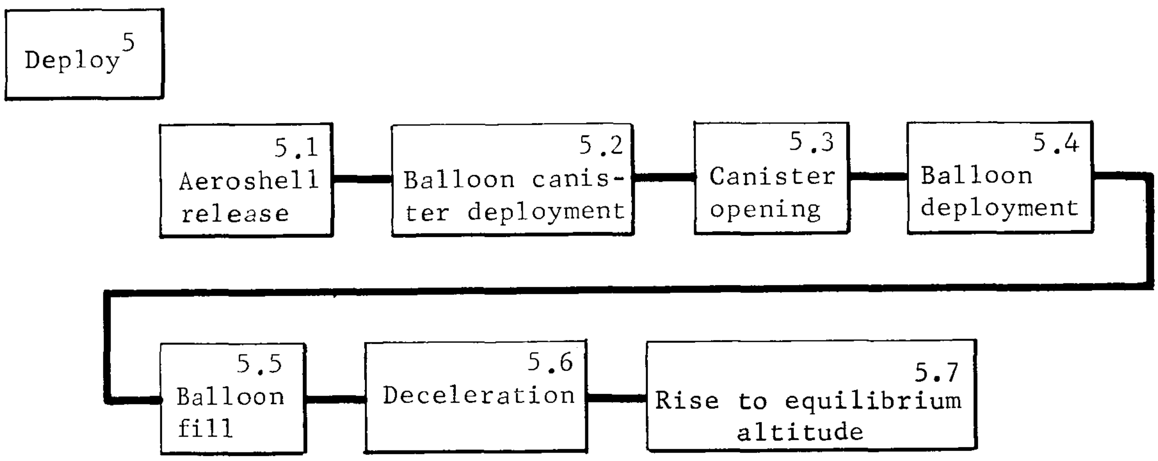
Figure 39. - Interplanetary Cruise Factors



Environmental factors

1) Decleration;
2) Temperature change;
3) Acceleration due to spin;
4) Atmospheric repressurization.

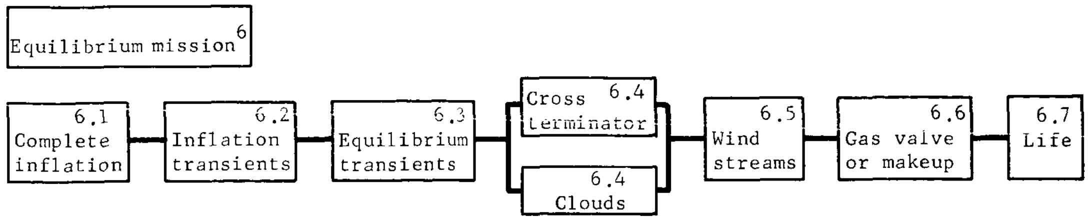
Figure 40. - Entry Factors



Environmental factors

1) Acceleration at aeroshell separation;
2) Acceleration at canister deployment;
3) Acceleration during balloon deployment and fill;
4) Local stresses as balloon unfolds and fills (balloon cold);
5) Local stresses as balloon flutters in airstream;
6) Impact with ice crystals
7) Stress due to wind streams;
8) Fill gas temperature near cryogenic;
9) Fill gas temperature high (gas generator);
10) Over temperature due to undershoot of equilibrium altitude;
11) Compatibility with exotic Venus atmospheres;
12) Temperature transients due to all of above;
13) Overpressure (excess superpressure) due to overshoots, imperfect fill control, etc.

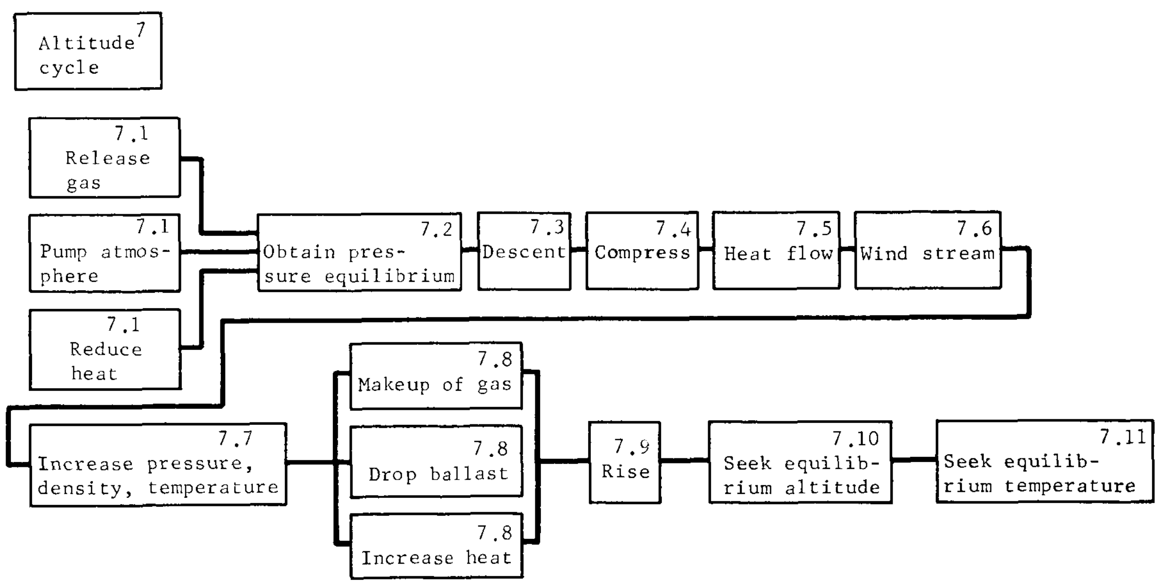
Figure 41. - Deployment Factors



Environmental Factors

1) Stress of unfolding and pressurizing cold, wrinkled fabric;
2) Overpressure before temperature stabilizes;
3) Excess temperature - due to unknown, transient effects;
4) Temperature transients;
5) Pressure transients;
6) Wind streams on unfolded device;
7) Micrometeorites;
8) Ice crystals;
9) Exotic Venus atmosphere;
10) Hot or cold makeup gas into balloon;
11) Solar radiation;
12) RTG radiation;
13) Inflation gas compatibility for 6 months (more than one gas);
14) Leakage over 6 months;
15) Local stresses to support payload.

Figure 42. - Equilibrium Mission Factors



Environmental factors

1) Heat transients;
2) Wind streams;
3) Low-altitude temperature environment;
4) Local stress to support payload;
5) Stress due to superpressure.

Figure 43. - Cyclic Mission Factors

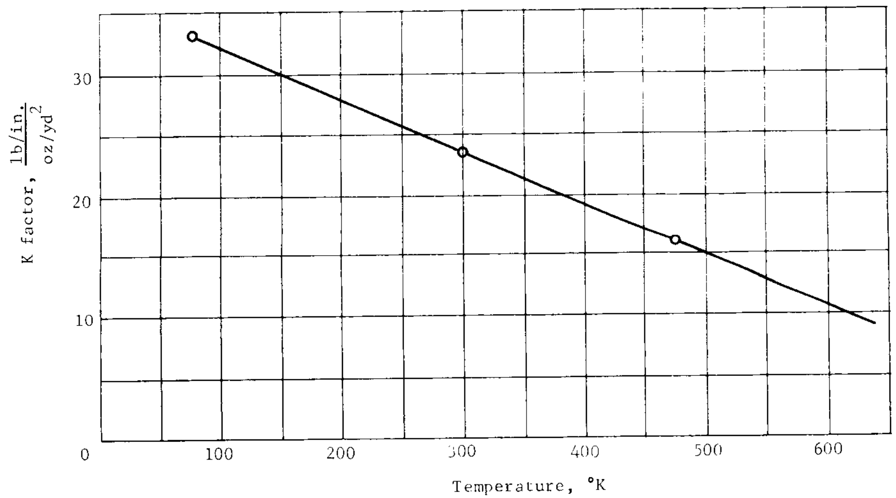


Figure 44. - Strength to Weight Ratio vs Temperature for Kapton

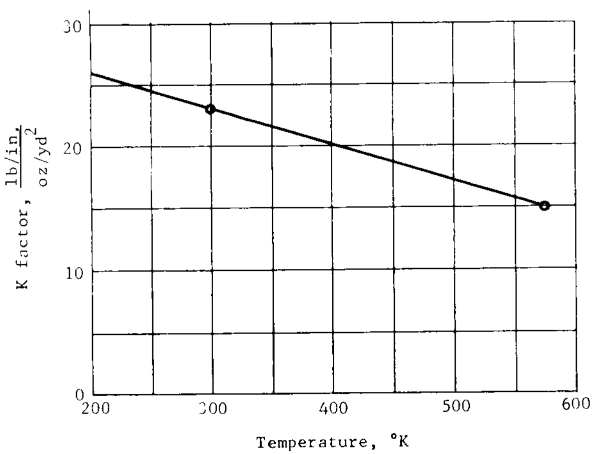


Figure 45. - Strength to Weight Ratio vs Temperature for PBI Film.

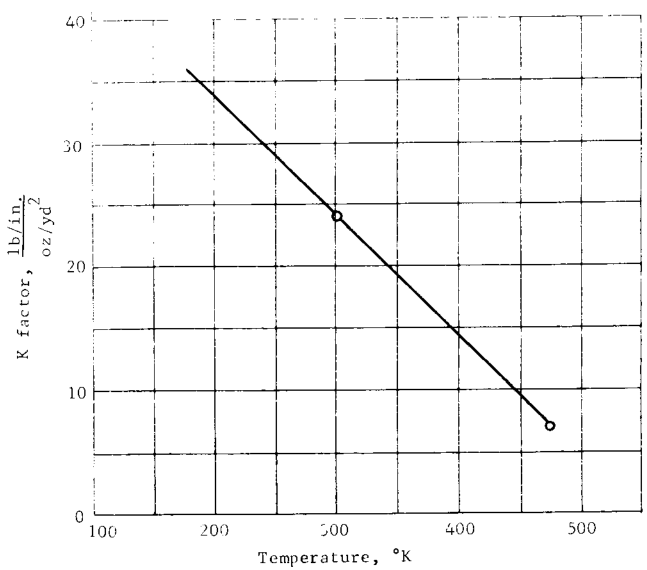


Figure 46. - Strength to Weight Ratio vs Temperature for Mylar

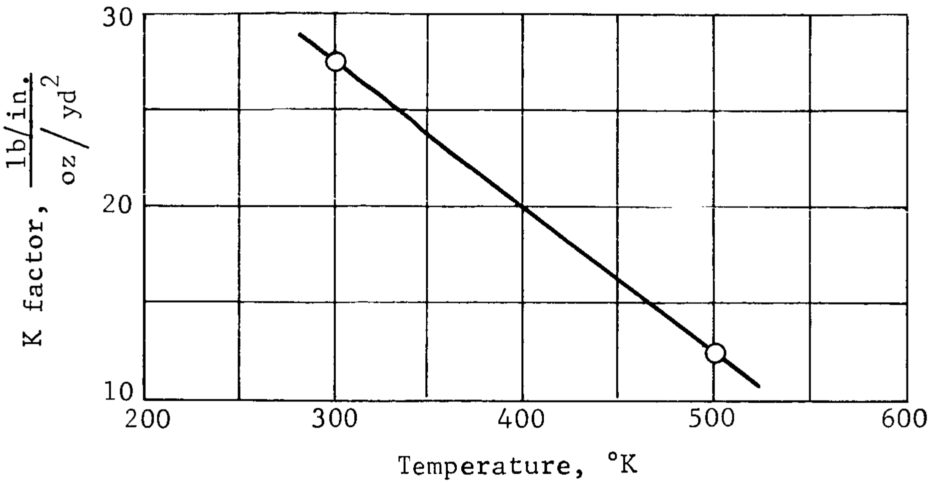


Figure 47. - Strength to Weight Ratio vs Temperature for PBI Fiber

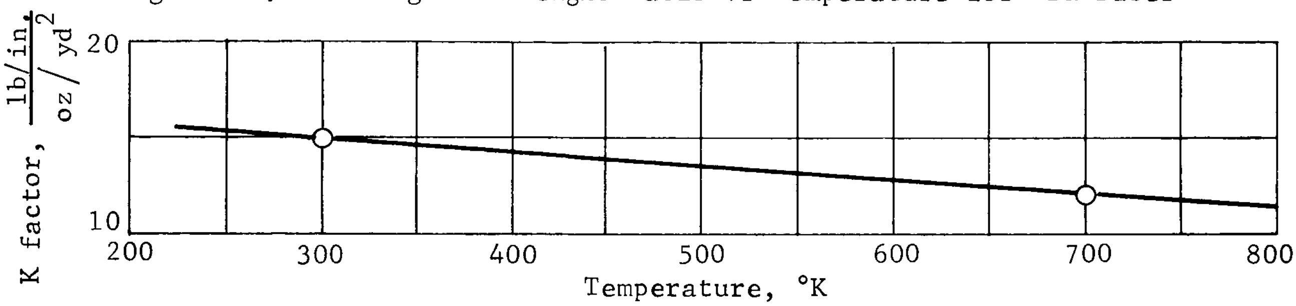


Figure 48. - Strength to Weight Ratio vs Temperature for Titanium Wire

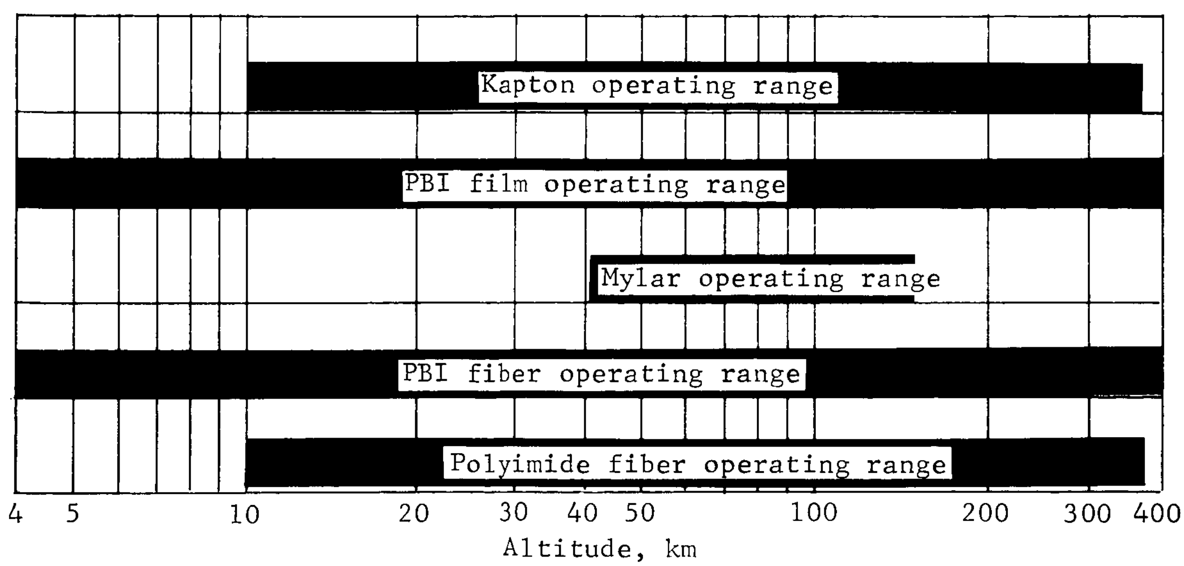


Figure 49. - Mission Limits Imposed by Selected Material Upper Density Model

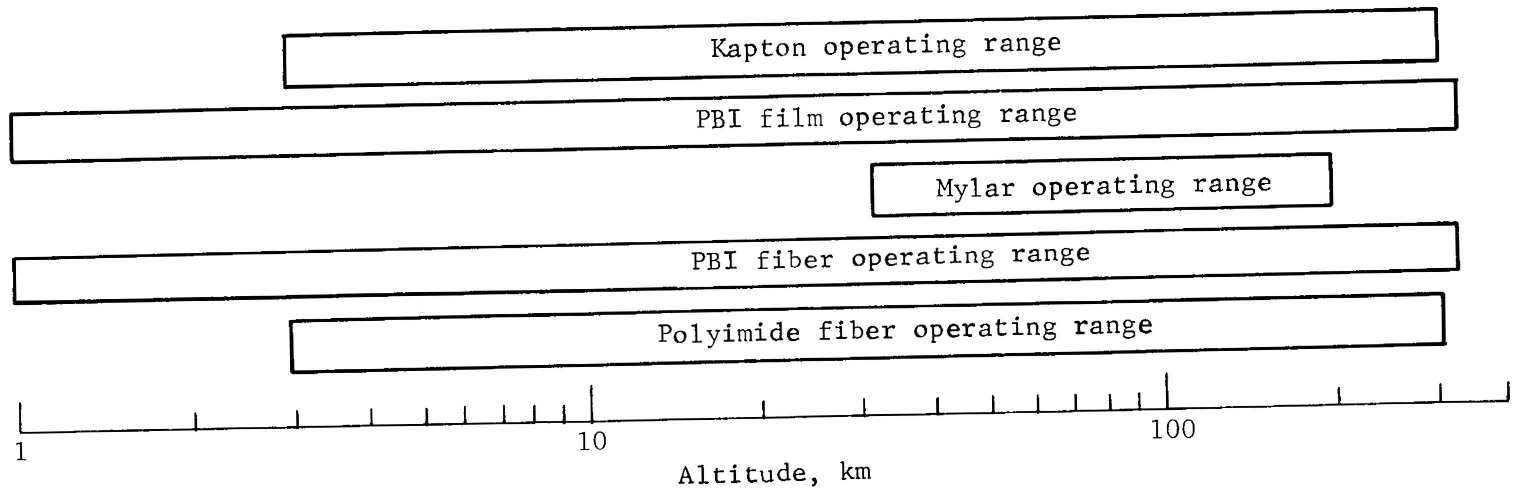


Figure 50. - Mission Limits Imposed by Selected Material Mean Density Model

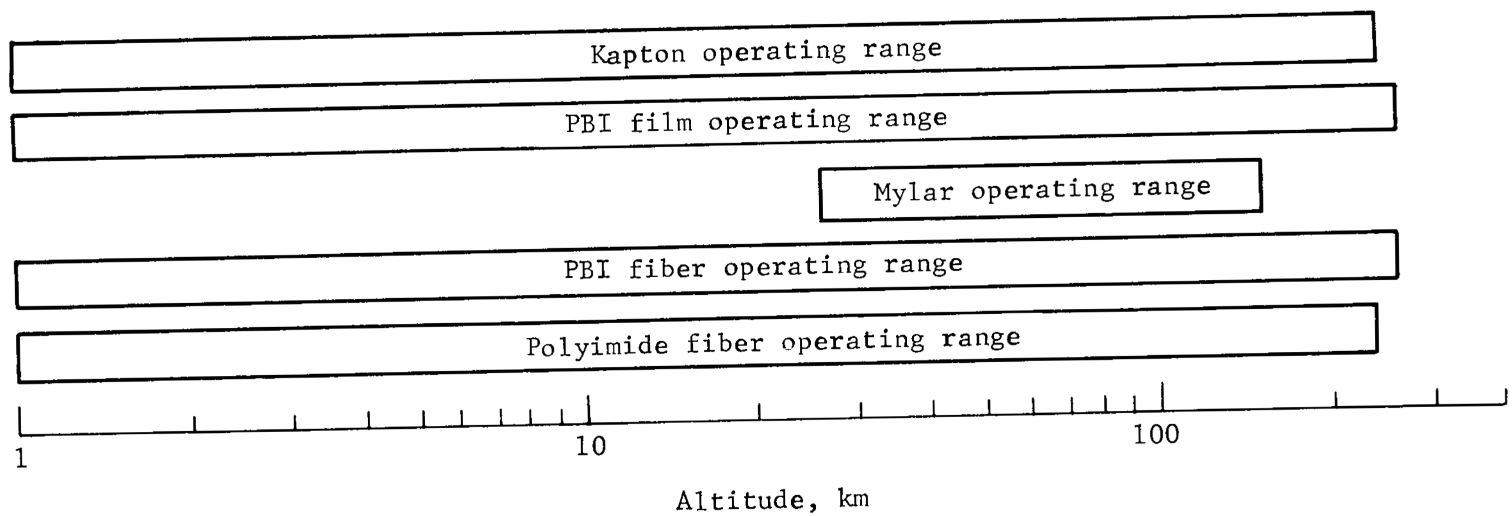


Figure 51. - Mission Limits Imposed by Selected Material Lower Density Model

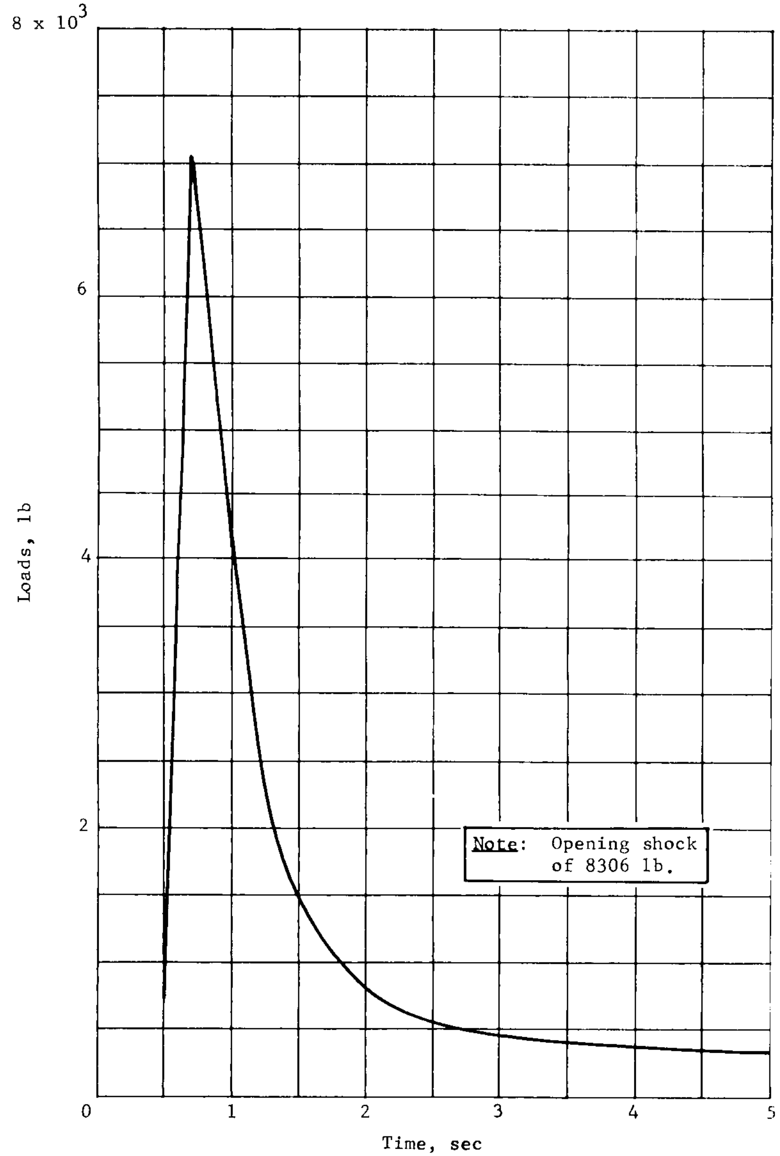


Figure 52. - Parachute Opening Shock and Riser Loads for Mean Atmosphere, 200-lb Station

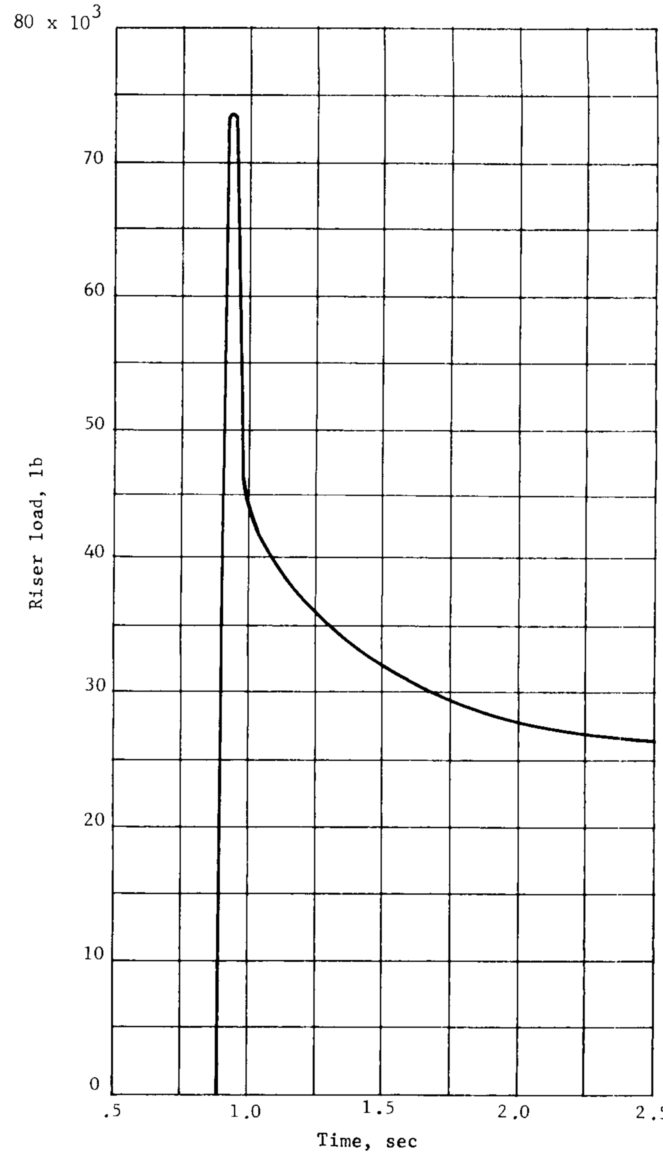


Figure 53. - Riser Loads for 2000-lb Station in Mean Density Atmosphere

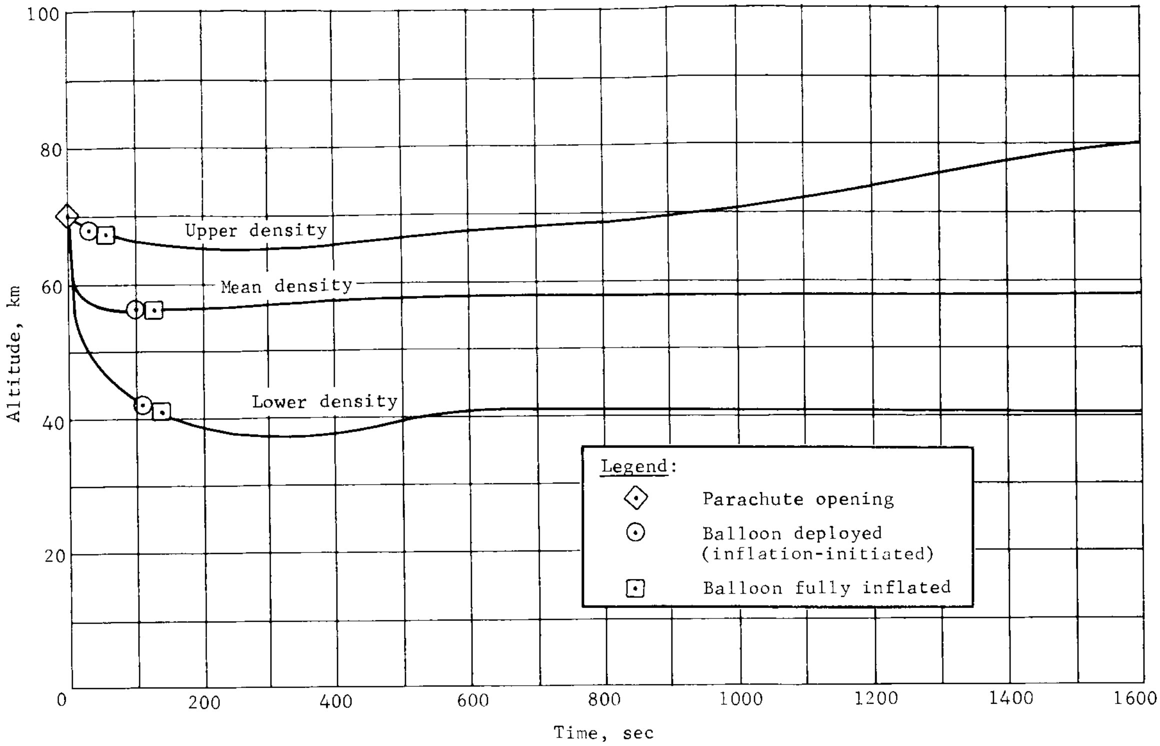


Figure 54. - Deployment Profile of Station into Three Model Atmospheres

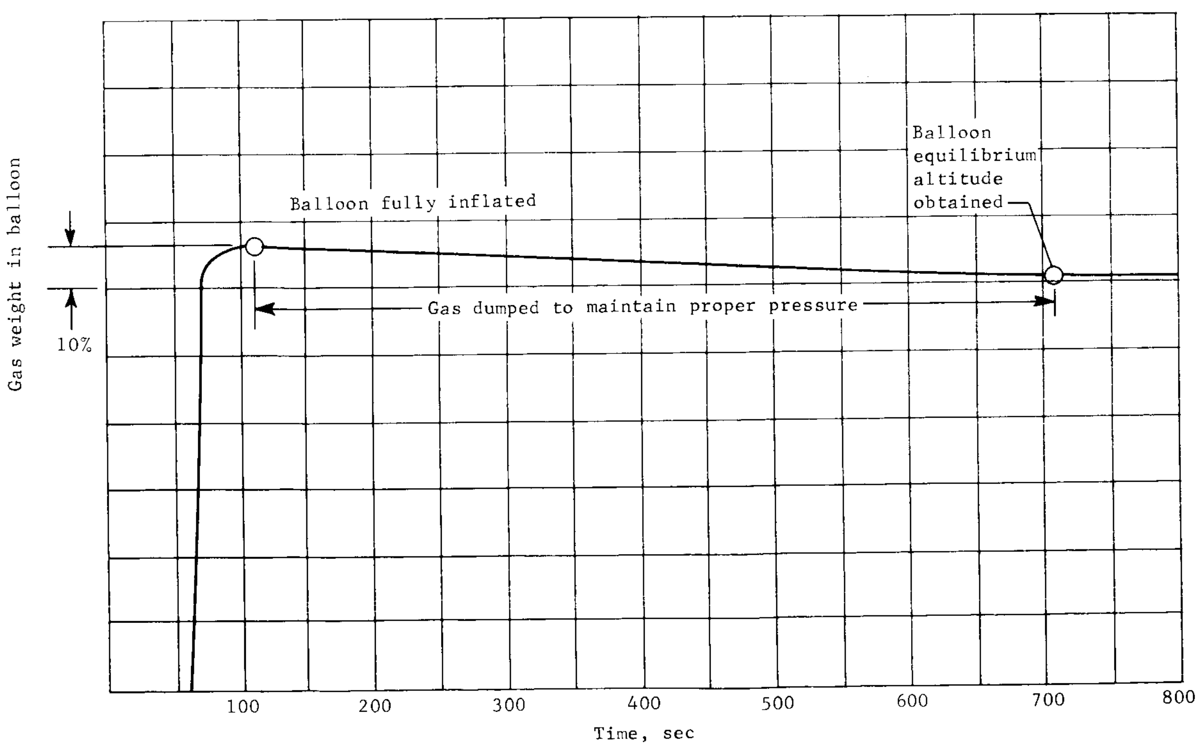


Figure 55. - Typical Gas Weight Profile for Balloon Inflation

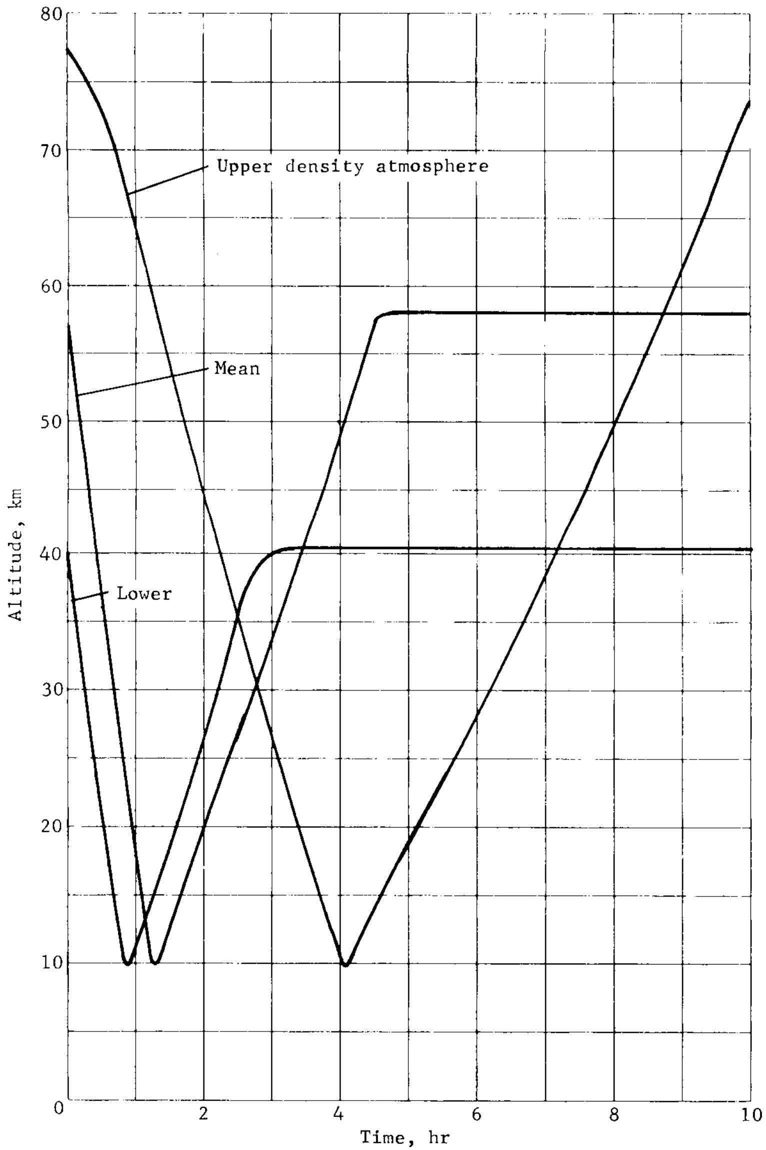


Figure 56. - Cycle Profiles in Three Model Atmospheres with 20% Gas Dump and Makeup, 2000-lb Station

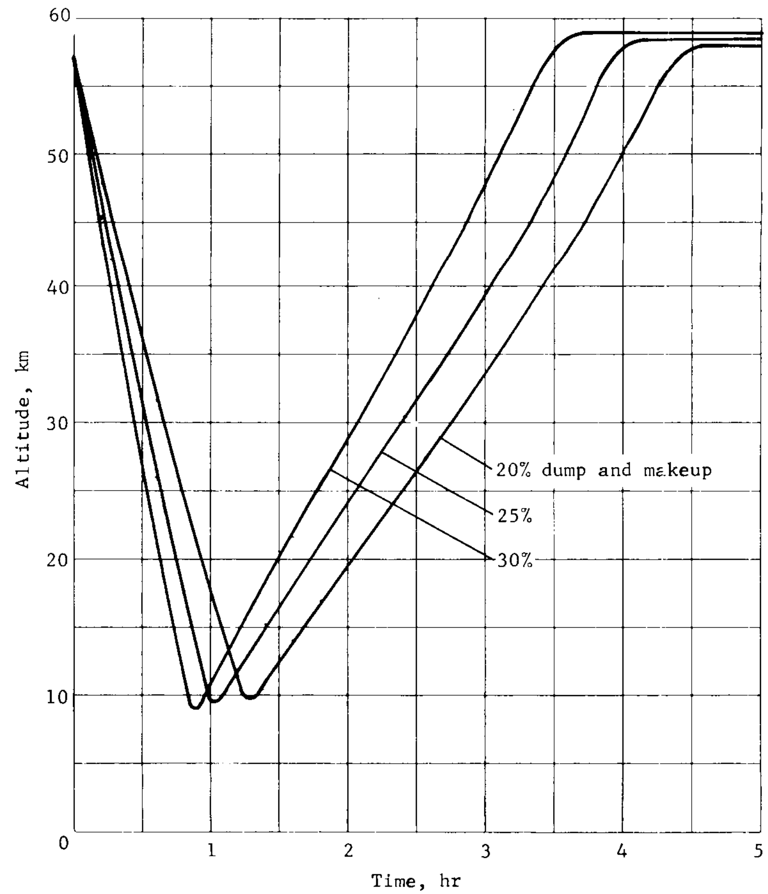


Figure 57. - Cycle Profiles in Mean Atmosphere, 2000-lb Station Gas, Dump and Makeup Mode

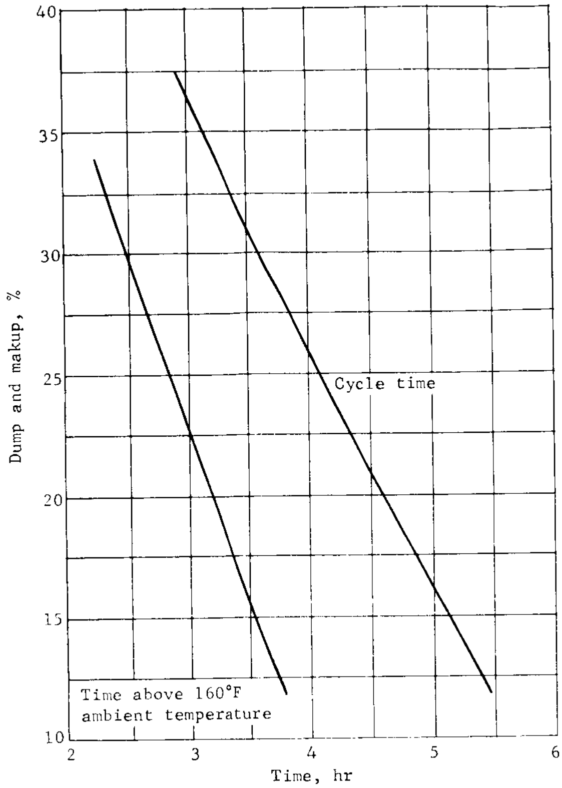


Figure 58. - Cycle Time and Environment for Mean Atmosphere 2000-lb Station Cycle between 57 and 10 km

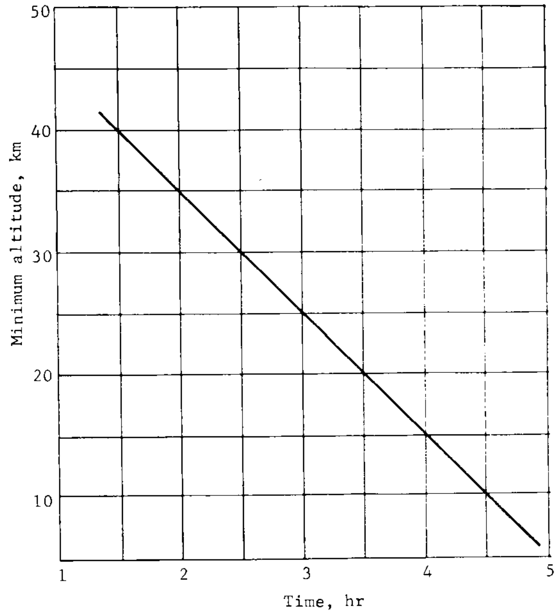


Figure 59. - Cycle Time for 2000-lb Station In Mean Atmosphere at Equilibrium Altitude of 57 km, 20% Gas Dump and Makeup

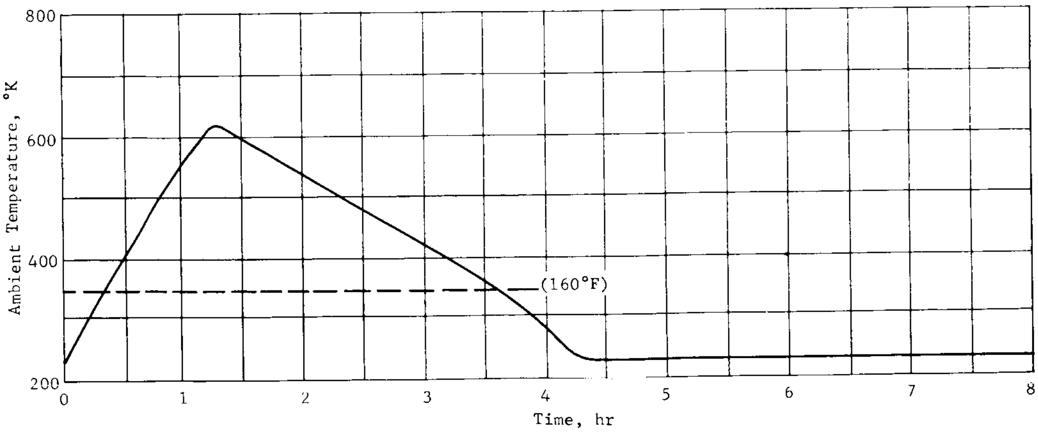


Figure 60. - Payload Ambient Temperature Profile in Mean Atmosphere, 20% Gas Dump and Makeup

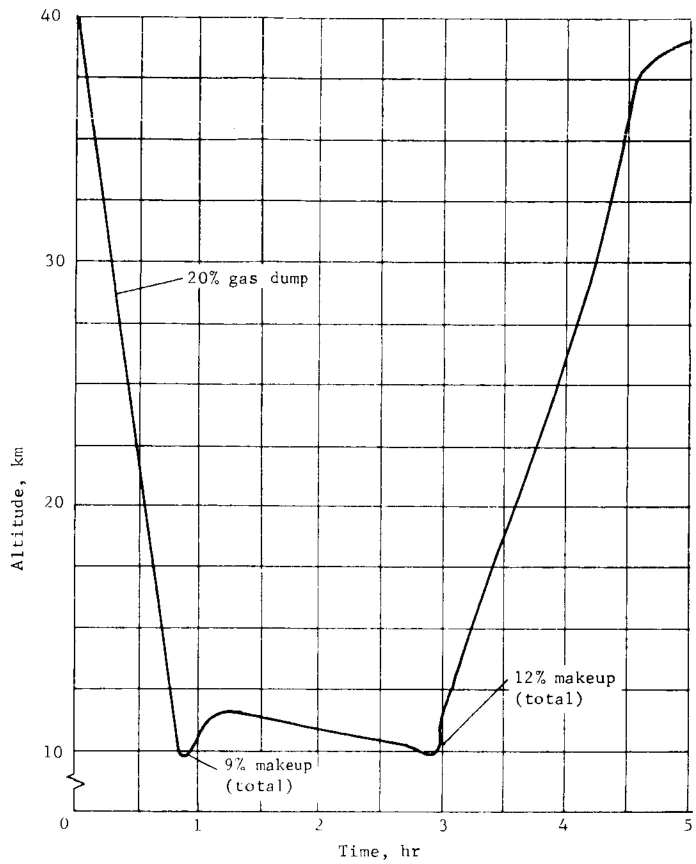


Figure 61. - Lower Density Atmosphere, 2000-lb Station Gas Dump and Makeup, 6 mb Superpressure

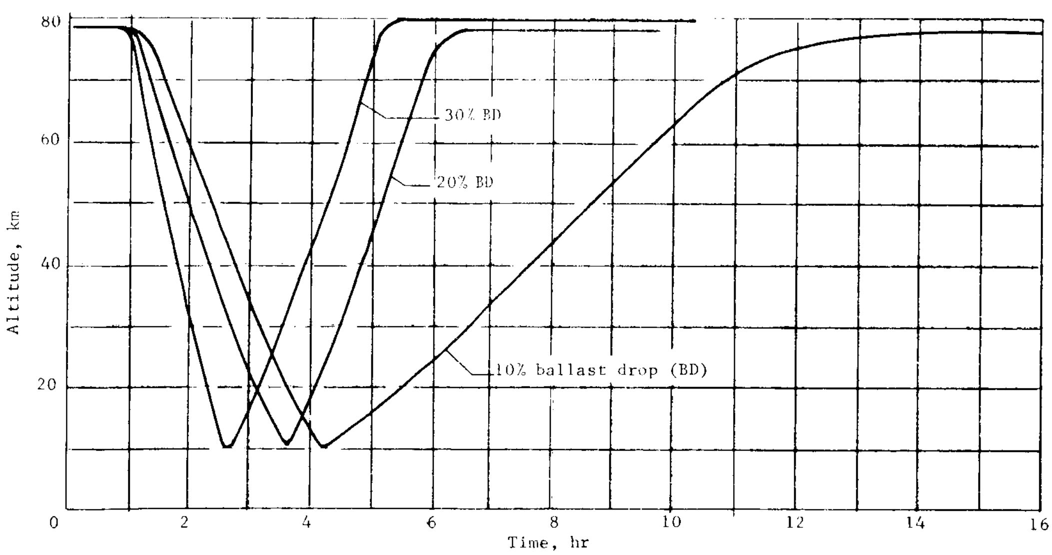


Figure 62. - Cycle Profiles for Upper Density Atmosphere with Gas Dump and Ballast Drop

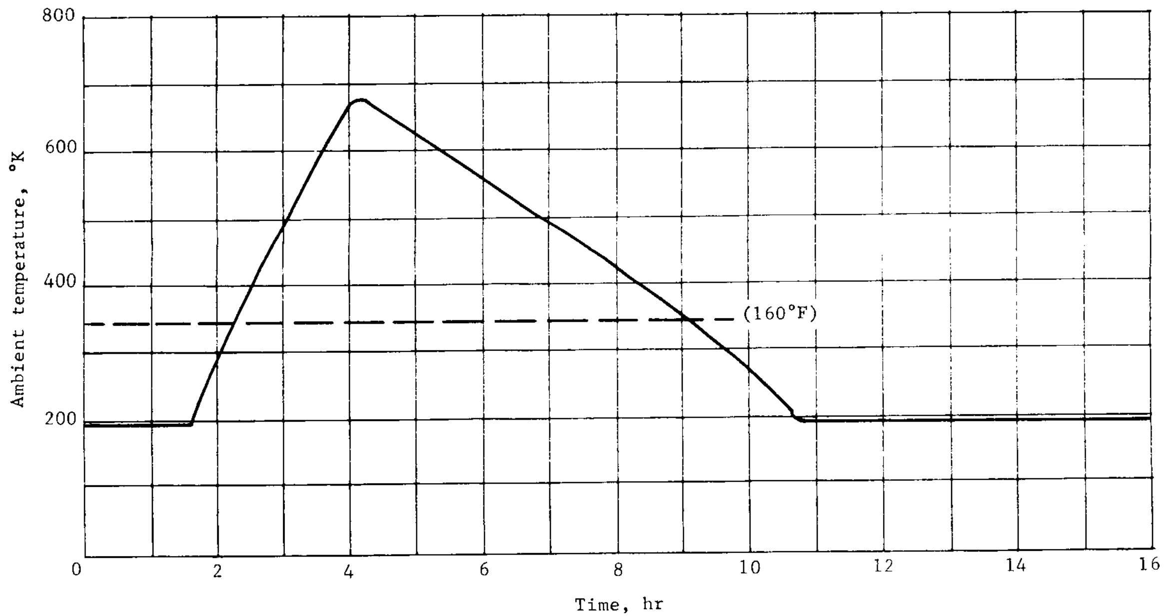


Figure 63. - Upper Density Atmosphere, Ambient Temperature Profile for Cycle between 79 and 10 km, 10% Gas Dump and Ballast Drop

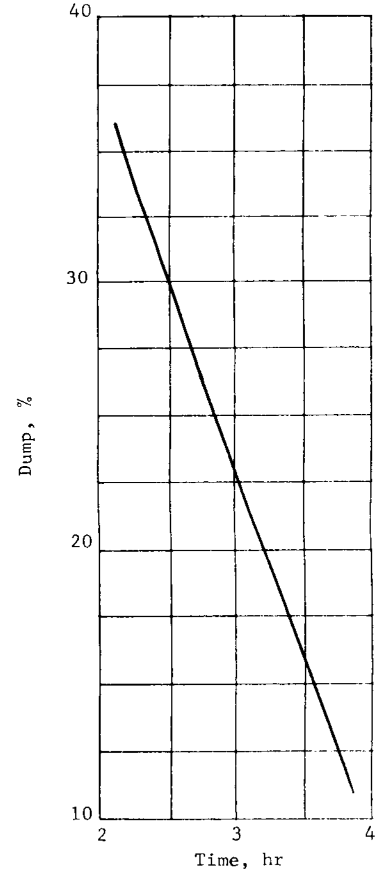


Figure 64. - Time of Payload in Ambient Temperature above 160°F in Mean Density Atmosphere Cycled between 57 and 10 km with Gas Dump and Ballast Drop

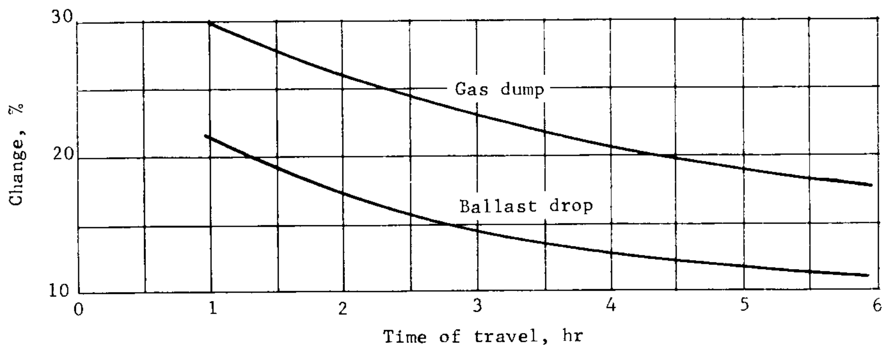


Figure 65. - Effect of Dumping Gas and Dropping Ballast in Mean Atmosphere, Cycle between 57 and 10 km

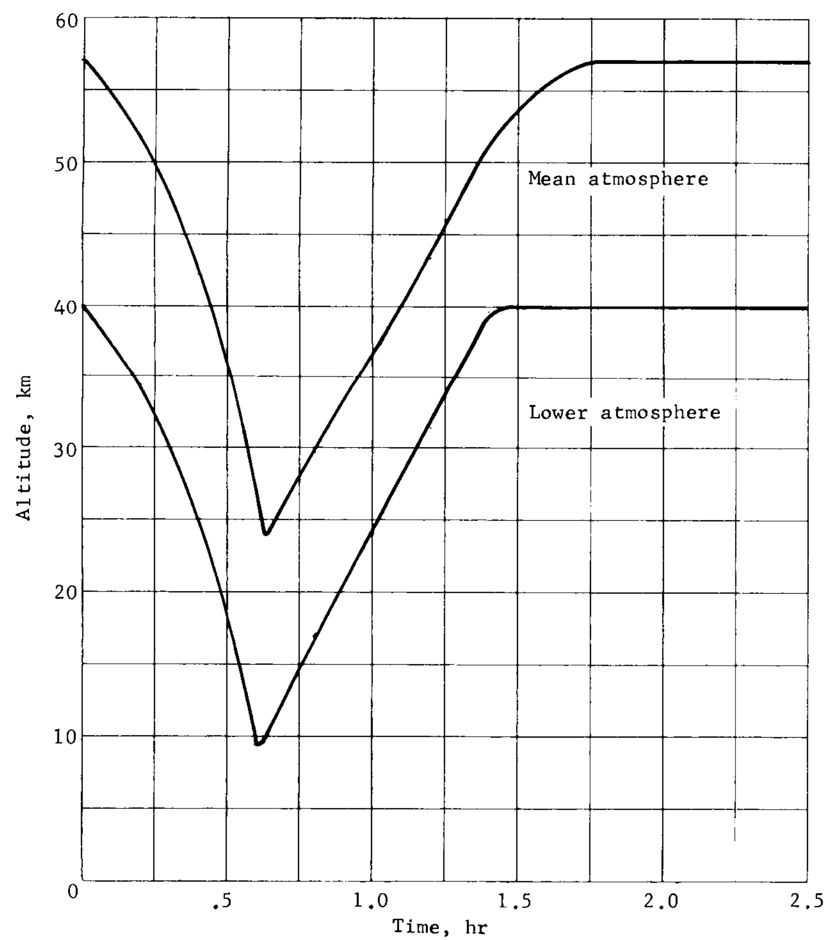


Figure 66. - Cycle Profile for 2000-lb Station Pumping and Dumping Atmospheric Gases, Volume of Receiver 2500 cu ft, Compressor Ratio 4.5

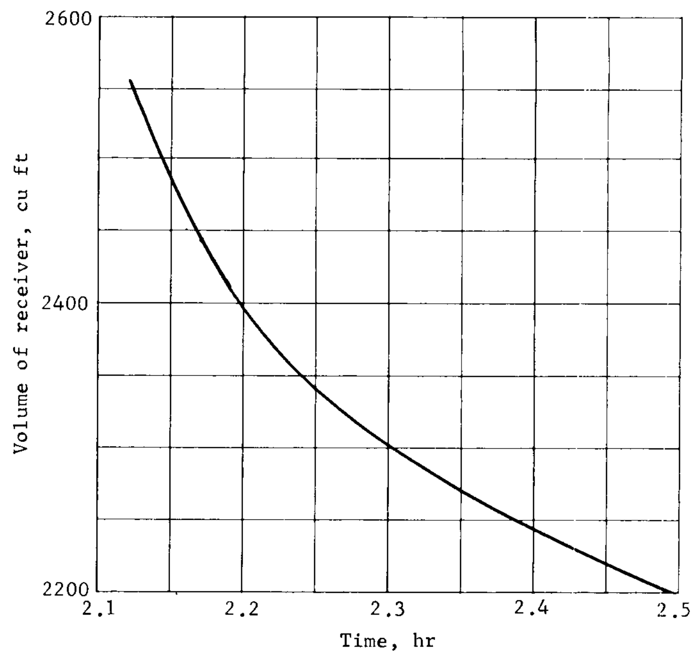


Figure 67. - Mean Atmosphere Cycle Time for 2000-lb Station with 4.5 Compressor Ratio Cycling between 10 and 57 km, Pumping and Dumping Atmosphere

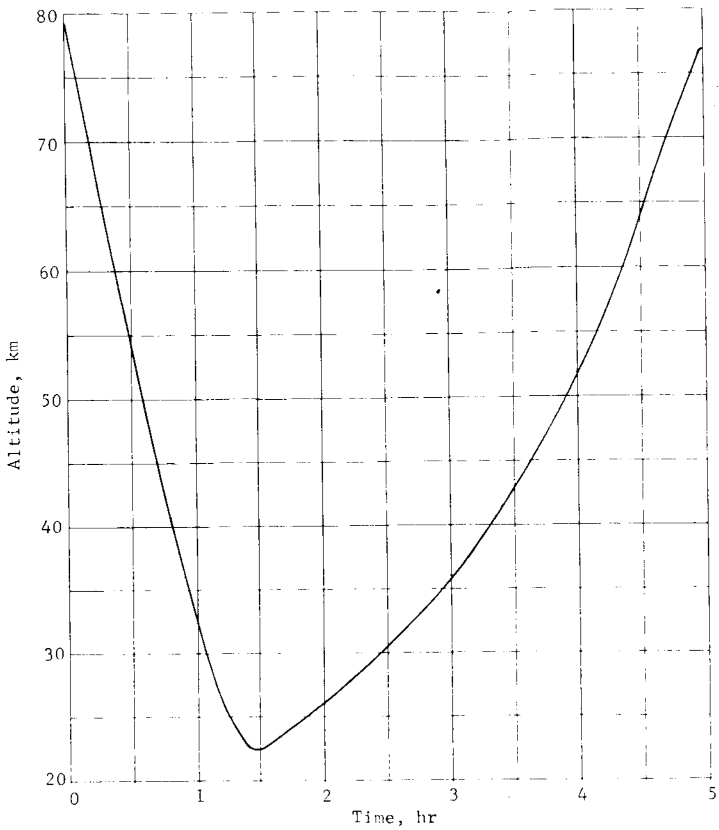


Figure 68. - Heat Cycling, Upper Density Atmosphere, 2000-lb Station, Heat Input of 100 Btu/sec Hydrogen Gas

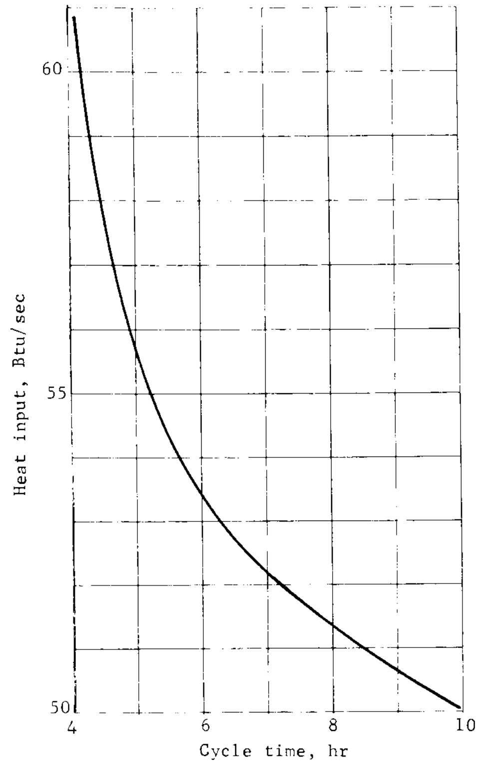


Figure 69. - Altitude Cycling in Mean Atmosphere with Heat Method, 2000-lb Station, Helium Gas (57 to 10 km)

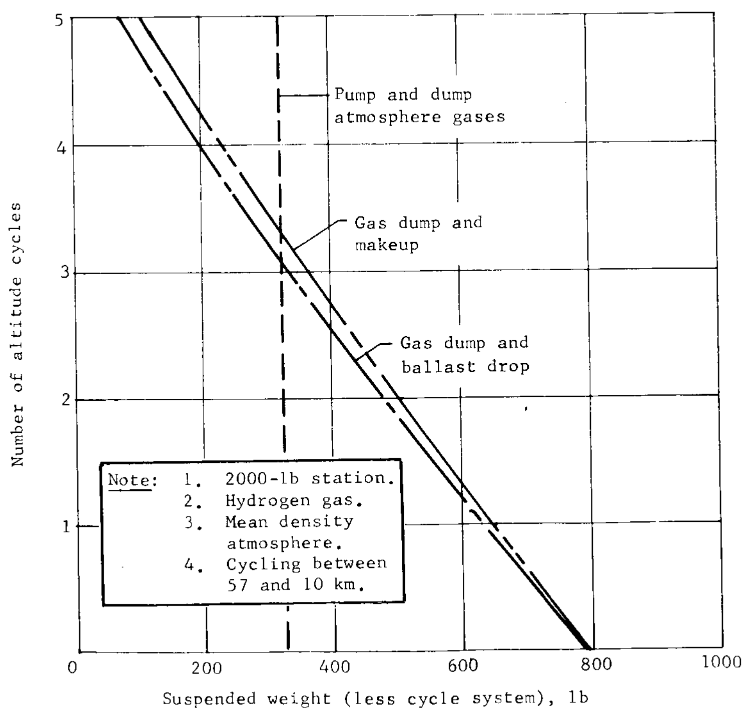


Figure 70. - Cyclic Mode Efficiencies

Undeployed station	
Subsystem	Weight, lb
Parachute	12
Balloon	23
Inflation	95
Payload	70

Note: Deployed weight at equilibrium altitude, 95 lb.

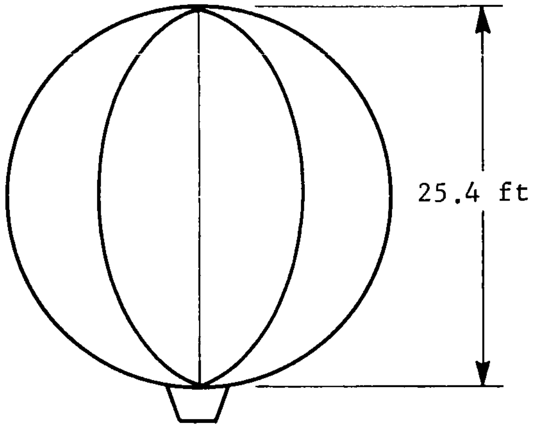


Figure 71. - 200-lb Station (Noncyclic)

Undeployed	
Subsystem	Weight, lb
Parachute	106
Balloon	274
Inflation	850
Payload	770

Note: Deployed weight at equilibrium altitude, 1040 lb.

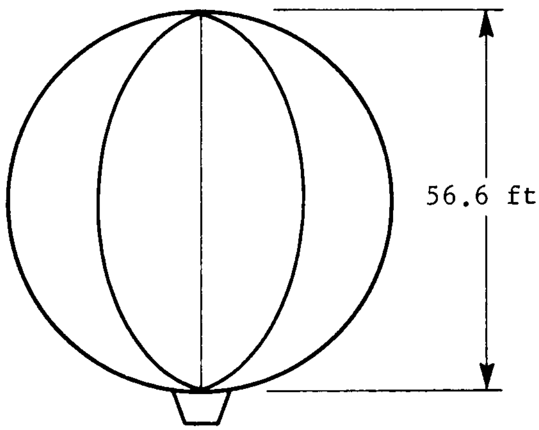


Figure 72. - 2000-lb Station (Noncyclic)

Undeployed	
Subsystem	Weight, lb
Parachute	106
Balloon	261
Inflation	850
Cycle	236
Payload	547

Note: Deployed weight at equilibrium altitude, 1040 lb.

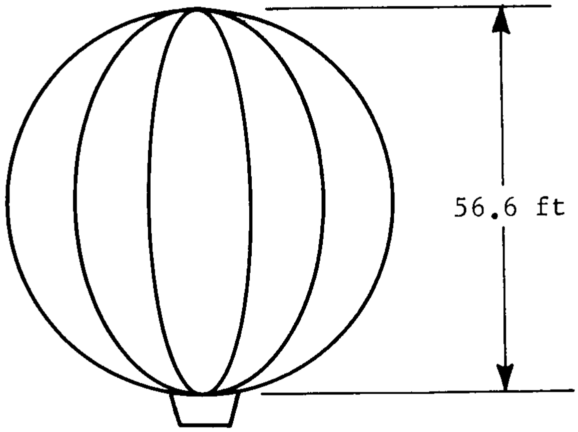


Figure 73. - 2000-lb Station (Cyclic)

Undeployed	
Subsystem	Weight, lb
Parachute	375
Balloon	855
Inflation	940
Cycle	817
Payload	2013

Note: Deployed weight at equilibrium altitude, 3725 lb.

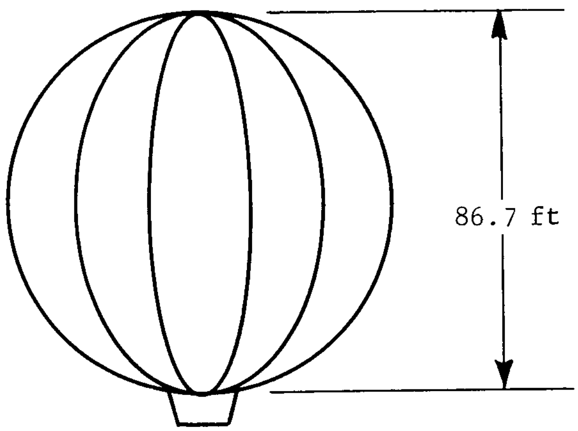


Figure 74. - 5000-lb Station (Cyclic)