NAGW-4

HIGH ALTITUDE

OZONE RESEARCH BALLOON

A design project by students in the Department of Aerospace Engineering at Auburn University under the sponsorship of the NASA/USRA University Advanced Design Program.

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Technical Report for the Design of the High Altitude Ozone Research Balloon

Submitted to: Dr. James O. Nichols

Submitted by: Timothy A. Cauthen
Leslie A. Daniel
Sally C. Herrick
Stacey G. Rock
Michael A. Varias

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ABSTRACT

In order to create a mission model of the high altitude ozone research balloon (HAORB) several options for flight preparation, altitude control, flight termination, and payload recovery were considered. After the optimal launch date and location for two separate HAORB flights were calculated, a method for reducing the heat transfer from solar and infrared radiation was designed and analytically tested. This provided the most important advantage of the HAORB over conventional balloons, i.e., its improved flight duration. Comparisons of different parachute configurations were made, and a design best suited for the HAORB's needs was determined to provide for payload recovery after flight termination. In an effort to avoid possible payload damage, a landing system was also developed.

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INTRODUCTION

The ozone layer shields the Earth's surface from harmful solar radiation that can cause skin cancer, destroy acids in DNA molecules, and have harmful effects on world climate and vegetation. Research has indicated that there is the presence of a seasonal depletion of ozone concentration over Antarctica. Can we conclude that this depletion is a natural occurrence, or are we witnessing a decline in ozone concentration due to chemical processes that will appear later in other regions of the world?

Because 97 percent of the ozone molecules are located in the stratosphere with a maximum concentration at 26,000 meters above sea level, existing analysis methods are extremely expensive, time consuming, and inadequate. Moreover, atmospheric scientists are concerned with the possible further destruction of the ozone concentration due to the chemical contaminates released from presently existing ozone monitoring vehicles. This concern has lead to the development of high altitude research balloons (1).

The presently used high altitude balloons have proven to be cost effective and environmentally safe. However, flight duration time, lateral control, and vertical control have severely limited the widespread acceptance of high altitude research balloons as the primary method for ozone observation and analysis. Lateral control will continue to be a major area of concern; nevertheless, flight duration time and vertical control can be improved.

Currently used high altitude ozone research balloons are very limited in flight duration time. The amount of reserve helium and the amount of ballast that are initially carried on the balloon determine the length of flight time. During the day, the balloon heats up due to solar radiation impinging on the surface of the balloon film. As the temperature of the film increases, the temperature of the helium inside the balloon increases due to natural convection. Since the research balloons are zero pressure balloons, the helium expands and therefore causes the buoyant force on the balloon to increase.

When the balloon ascends above a predetermined altitude, the researchers remotely vent the helium through exhaust vents located at the top of the balloon. As the helium is vented, the volume of balloon decreases and the balloon descends. When the balloon descends below the minimum range of interest, the researchers remotely release ballast in an effort to increase the net upward force on the balloon. Another method used to increase the net upward force on the balloon is the controlled addition of reserve helium. This process of venting, dropping ballast, and adding reserve helium continues throughout the mission. After all the ballast and reserve helium are depleted, the mission is terminated.

In order to retrieve the gondola, a control system activates a terminate package which releases the gondola and its parachute. Since, the parachute is attached to the balloon via a coupling.

Pyrotechnic devices are used to separate the parachute from the balloon. After separation, a rip chord built into the balloon and attached to the parachute rips a hole in the balloon, thereby allowing the torn balloon to fall safely to Earth.

The choice of the parachute is critical for the safe descent and recovery of the payload. The gondola and its sensitive electronic equipment can be damaged if the gondola impacts the surface of the Earth at a high speed. The parachute can limit the downward speed of the gondola, however, an energy absorbing device is necessary to further reduce the shock of impact. The crush pads on the bottom of the gondola structure are used for this purpose.

The initial design of the high altitude ozone research balloon (HAORB) emphasizes continual profile sampling of the ozone layer. The lateral flight path of the HAORB is determined solely by the direction of the prevailing winds present at high altitudes. However, vertical control can be achieved by maintaining a balance between the temperature of the helium within the HAORB and the surrounding atmosphere. This is done by circulating cool atmospheric air over the surface of the balloon film with rotary circulation fans.

The vertical speed of the HAORB is controlled by removing the heat that is transferred to the balloon film from direct and reflected solar radiation, and infrared radiation. By limiting the increase in the balloon film temperature, less heat is transferred to the helium gas. Also, the helium near the surface of the film is cooled by conduction through the cooling duct walls. Therefore, the rate of helium temperature change is reduced and the rate of expansion of the balloon is decreased. Thus, the rate of ascension of the HAORB is lowered.

The navigation system controls the rotary circulation fans which increase the rate of heat transfer from the film and the helium to the atmosphere. By controlling the rate of ascent with the rotary circulation fans, less ballast and reserve helium is required and flight duration time can be substantially lengthened. A longer flight duration translates into reduced consumer expense in both manhours and capital.

SYSTEM ANALYSIS

In order to understand how the atmosphere affects balloon travel, several fundamental equations must be derived and understood. The two basic equations needed for atmospheric analysis are the hydrostatic equation and the equation of state. In order to use these equations effectively, assumptions relating to the specific model need to be defined (1).

Hydrostatic Equation

Although the atmosphere is in constant motion the hydrostatic relationship can be applied with a good degree of accuracy. The hydrostatic equation is as follows:

$$dP = -gpdz \qquad (1)$$

Where P is the atmospheric pressure, g is the acceleration due to gravity, p is the air density, and z is the height.

By assuming that the variation of g through the stratum in which the HAORB is flying is not great the hydrostatic equation can be written as:

$$dP = -go\ pdH \qquad (2)$$

Where go is a constant acceleration of gravity and H is nearly equal to z in altitude.

Equation of state

Assuming that the air is an ideal gas the equation of state can be written as:

$$p = PM/RT \qquad (3)$$

where M is the molecular weight of air, R is the universal gas constant, and T is the absolute temperature of the air. The molecular weight is nearly a constant up to 70 Km and the only correction that may be needed would be for water vapor.

Since the U.S. Standard Atmosphere is being used in this analysis, air is assumed to be a dry gas with no water vapor, so the correction will not be used (7). The temperature (T) is nearly a linear function with altitude through deep layers of the atmosphere and will not change at all in shallow areas. In a layer where temperature varies linearly with height the temperature can be calculated as:

$$T = Tb + L'(H - Hb) \tag{4}$$

Where Tb is the temperature at the base of the stratum whose height is Hb, L' is the vertical gradient of temperature (-lapse rate), and H is the height. The pressure and the density can be calculated from this relation of temperature and altitude (7).

$$P = Pb(1 + L'/Tb(H - Hb))^{(-Mgo/RL')} \tag{5}$$

$$H = Hb + Tb/L'((Pb/P)^{(RL'/Mgo)} - 1)) \tag{6}$$

In a layer where temperature is constant the pressure and altitude can be written as

$$P = Pb \exp(-Mgo/RTb(H-Hb)) \tag{7}$$

$$H = Hb - RTb/Mgo \ln (P/Pb) \tag{8}$$

All of the calculations used to create an atmospheric profile map for the HAORB were derived from the hydrostatic relationship and the equation of state. The above relationships produce the standard atmospheric tables used in the calculations for the HAORB mission (1).

Cooling Ducts

The helium chamber of the HAORB is made of a thin low density polyethylene material. The polyethylene panels are 0.457 mm thick, approximately 90 meters in length, and vary from 1 to 2 meters in width are heat sealed at the seams. The cooling duct is formed by sealing an additional panel on the outside of the chamber. This panel forms a channel that is 7.2 cm deep and 5 m wide. (See Figure 1.)

The cross-sectional area of the channel is approximated by assuming the channel is a rectangle with height of 5.1 cm and width of 5 m. Because the balloon is modeled as a sphere, the effective heat transfer length of the channel is measured from the point where the fan duct connects to the balloon to the point where the duct vents to the atmosphere. This length is determined by calculating the length of the sector of an arc on the sphere that is 160 degrees. The arc angle is set at 160 degrees because the exhaust vent is 10 degrees from the top of the central axis of the balloon and the fan duct is 10 degrees from the bottom of the central axis of the balloon.(See Figure 2a and 2b). The effective heat transfer length changes as the balloon ascends and expands. In order to simplify calculations, the length of the channel is calculated at an altitude of 30 km and the length is assumed constant at 73.7 m (2).

The average convective heat transfer coefficient of the cooling air, ha, is determined by:

$$ha = Nu*kf/Dh \quad (9)$$

where Nu is the Nusselt number, kf is the conduction heat transfer coefficient for the material (.19 for polyethylene), and Dh is the hydraulic diameter which is 4 times the cross-sectional area divided by the perimeter (Dh is 9.36 for the HAORB). The Nusselt number is determined from the ratio of the channel width and the channel height. For the HAORB cooling ducts, this ratio is 98. For a ratio greater than eight, the Nusselt number is constant at 8.23. The average convective heat transfer coefficient of the cooling air calculated for this design is 15.33 W/K m^2.

The rotary circulation fans provide cooling to the film and to the helium. The rate of heat transfer by the rotary circulation fans, q, is calculated by:

$$q = ha*A_s*dT_{LM} \quad (10)$$

where A_s is the heat transfer surface area, and dT_{LM} is the log mean temperature difference. The log mean temperature difference equation is:

$$dT_{LM} = (dT_1 - dT_2)/\ln(dT_2/dT_1) \quad (11)$$

where dT_1 is the difference in the temperature of the incoming air and the surface temperature of the wall, and dT_2 is the difference in the temperature of the exhaust air and the surface temperature of the wall. For the calculations involving heat transfer from the helium, the assumption is made that there is no temperature gradient across the film on the inner side of the air duct and that dT_2 is 0.0001 degrees K.

The temperature of the helium is assumed to be at a uniform average value for all of the heat transfer calculations. The actual temperature distribution in the helium chamber is very difficult to model and empirical data is most commonly used if a uniform helium temperature is not assumed. For this design, the temperature of the film is also assumed to be uniform. This assumption is correct over long periods of time; however, film temperature distribution cannot be easily modeled and empirical data must also be used if the temperature of the film is not assumed to be uniform (3).

Heating of the Helium

The helium is heated by natural convection heat transfer from the balloon film. The convection process inside the balloon is important because it determines the temperature, pressure, and the volume of the helium. Very little research has been done on convection inside a sphere and none has been done on convection inside cavities resembling the shapes of high altitude balloons.

Studies by Hellums and Churchill (3) suggest that there are several types of flow patterns that will exist as the temperature difference between the surface and the helium varies during a 24 hour period. A semi-empirical analysis assuming that natural convection in a sphere resembles that of a flat plate yields results that may be used for a first approximation. However, Clark and Dingwell (3) derived Equation 12 through analysis and empirical methods. The equation is:

$$q_1 = .628*V_g**(2/3)*k_g*(T_f-T_g)*$$
$$(\phi_g^2*g*(T_f-T_g)*Pr_g/(\mu^2*T_g))**(1/3) \qquad (12)$$

where V_g is the volume of the helium, T_f is the temperature of the polyethylene, t_g is the temperature of the helium, g is the acceleration of gravity, Pr_g is the Prandtl number of the helium, and μ is the viscosity of the helium.

Recent experimental data has shown that Equation 12 is not valid for the first 2-3 seconds after a transient occurs. However, no new equations have been determined for these rapid transients.

Radiation Heat Transfer

The radiation heat transfer to and from balloons strongly influences their performance and determines their short term temperature equilibrium. In order to simplify calculations, the Sun and the Earth are considered to be black bodies. The rate of radiation heat transfer is greatly dependant on the properties of the material. Therefore, the choice of balloon material is critical.

Two of the best choices for balloon material are polyethylene and Mylar. Mylar is heavier than polyethylene. However, a Mylar balloon will have a lower skin temperature and will cool quicker in the absence of the sun. Thus the Mylar balloon has less altitude stability. In contrast, the polyethylene will maintain a higher film temperature but will have better altitude stability. The proposed mission of the

HAORB requires high altitude stability, which in turn makes the polyethylene material best suited for the HAORB.

Since the balloon skins are translucent, the transmittance of the material must also be considered. The direction of reflectance has been analyzed in the past and proven to be a small factor when dealing with balloons over one million cubic feet. Consequently, the direction of reflectance is not considered in this report.

The amount of cloud cover can have a significant effect on the temperature of a balloon. Most high altitude balloons are launched in clear weather thus minimizing the effects of clouds. After the balloon ascends past 21,000 meters, the effects of the clouds are reduced. The long term prediction of cloud cover is very difficult and will not be considered in this report.

The effects of radiation heat transfer for the HAORB are considered in three separate catagories: solar radiation, infrared radiation and emitted radiation.

Solar Radiation:

Solar radiation transfers heat to the HAORB in two ways: direct and indirect radiation. Direct solar radiation is radiation from the sun that directly strikes the film. Because, over 99% of the solar energy is contained in a narrow wavelength band, the heat transfer calculations can be performed using a solar constant of 1395 W/m^2. In passing through the atmosphere, the intensity and spectrum of the solar energy are altered by absorption and scattering. Therefore, the radiation on an object is strongly dependant on the path of the lights rays through the atmosphere (optical air mass). Exact calculations of the optical air mass are difficult and can usually be approximated as 1.0. The rate of heat transfer from direct radiation is further simplified by assuming that the balloon is a sphere. The equation for the rate of heat transfer due to direct solar radiation is:

$$q_{2,dir} = 1.21*G(m)*V_g**(2/3)*a*(1+\tau/(1-r)) \qquad (13)$$

where G(m) is the solar energy incident on the balloon surface as a function of optical air mass, a is the absorptivity, τ is the transmittance, and r is the reflectance (3).

Indirect solar radiation is reflected from the surface of the Earth to the balloon film. There have been extensive studies performed on the amount of radiation that is reflected from the Earth, and graphs have been constructed to show the amount of radiation reflected when the skies are overcast, partly cloudy, and clear. The calculations in this report assume clear skies and uniform, diffuse reflection. With these assumptions, the reflected heat transfer rate becomes:

$$q_{2,ref} = 1.21*V_g**(2/3)*a*G_s*2*r*(1-sqrt(z/D_e)) \qquad (14)$$

where G_s is the solar constant, z is the altitude, and D_e is the diameter of the Earth (3).

Infrared Radiation:

The Earth emits infrared radiation to the atmosphere that also affects the heating of the balloon film. The quantitative prediction of this portion of the total heat load is subject to much uncertainty because it depends on several factors that are difficult to specify. Immediately after launch, the balloon receives radiation from the atmosphere over the entire surface, but as it ascends the amount of air above the balloon decreases. Eventually, only the lower portion of the balloon receives infrared radiation from the atmosphere.

The infrared radiation is also highly dependant on cloud cover and cannot be predicted with a high degree of accuracy. The values vary with location above the earth, weather conditions, and the direction of the incoming radiation. However, after the balloon rises above the clouds, the infrared radiation is more easily determined. The calculation for the infrared radiation heat transfer rates are developed from empirical studies performed by Suomi and Kuhn (3).
The following equation for the heat transfer to the balloon film due to infrared radiation is valid only for altitudes above 21 km:

$$q_3 = 4.88*a_{eff}*\sigma*V_g**(2/3)*T_r**4 \qquad (15)$$

where σ is the Stefan-Boltzmann constant and a_{eff} is the effective absorptivity of the surface at high altitudes.

Emitted Radiation:

The balloon fabric transfers heat to the atmosphere by infrared radiation. A typical polyethylene film has an average transmittance of 0.75, an average reflectance of 0.05, and an average absorption of 0.20. To calculate the emitted radiation, it is necessary to know the spectrally averaged hemispherical emittance in the infrared region. The evaluation of an average hemispherical emittance for a given wavelength range or a given temperature is quite simple. However, a surface element of the balloon skin is not only directed into space, but also into the interior where the radiation can pass through the fabric into space. The radiation can be reflected from the interior surface of the balloon fabric or absorbed by the fabric. Therefore, calculation of the "effective emittance" of the balloon fabric requires the knowledge of the bidirectional values of the monochromatic emittance, absorptivity, and reflectivity of the interior surface.

For the balloon design it would actually be much more desirable to measure the actual emittance of a spherical sample of the fabric material filled with helium. However, no such data has yet been taken and calculations are based on a model proposed by Germeles (3). This model assumes that the inner surface of the balloon emits and reflects diffusely. This model also assumes that average values can replace the spectrum of values for the emittance, absorptivity, and reflectivity of the inner surface. The net rate of emission from the entire balloon is then equal to the radiation directly emitted from the outer surface plus the portion emitted by the inner surface which eventually passes through the fabric. These assumptions yield:

$$e_{eff} = e*(1+\tau/(1-r)) \qquad (16)$$

where e is the emissivity for polyethylene.

Use of the effective emissivity gives a simple equation for the rate of heat transfer from the balloon fabric to the atmosphere:

$$q_5 = 4.83*e_{eff}*V_g**(2/3)*\sigma*T_f**4 \qquad (17)$$

Convection Heat Transfer

Another source of heat transfer to the film is the convection heat transfer between the surface of the balloon and the atmosphere. Convective heat transfer between the balloon system and the atmosphere occurs over a wide range of convectional parameters that are used to describe the process.

Although convective heat transfer to and from an object in air has been studied extensively, few investigations extend into the extreme Reynolds numbers encountered by high altitude balloons and none have specifically treated the onion shape of zero pressure balloons. Consequently, approximations and estimations are unavoidable. One assumption made in the formulation of the convection heat transfer equation is that the balloon is a sphere. The point of transition from laminar flow to turbulent flow cannot be exactly determined, thus necessitating the use of an average value of heat transfer coefficient over the entire surface of the balloon. The balloon moves freely with prevailing winds causing the relative velocity of the balloon in the horizontal direction to be small. Therefore, the actual heat transfer is affected by natural convection and can be written as:

$$q_4 = 7.79*V_g**(1/3)*k_a*(T_a-T_f)*$$

$$(1+.322*(\rho_a^2*g*abs(T_a-T_f)*V_g/(Ta*\mu_a^2))**(1/4)) \qquad (18)$$

where k_a is the conduction heat transfer coefficient of air (3).

Cooling System

The cooling system of the HAORB is comprised of four rotary circulation fans mounted on the gondola and four polyethylene cooling ducts attached to the sides of the balloon and extending down to the fans. The cooling ducts cover less than one-fourth of the balloon surface area (See Figure 1.). The size of the cooling ducts may be varied. The configuration in this report is only a first case study of the feasibility of the system. The optimal size and placement of the cooling ducts is a complex function of mission requirements and constraints.

The rotary circulation fans force atmospheric air through the cooling ducts which cools the balloon film and the helium. The cooler helium is less dense and therefore less buoyant. A lower buoyant force reduces the upward velocity of the HAORB. In order to maintain the desired upward velocity set by the researchers, the rotary circulation fans must be cycled in order to control the effect of the changing q_1 and the constant solar heating of the film. The rotary circulation fans are cycled by the velocity control system and maintain the desired upward velocity of the HAORB within a set tolerance. The tolerance is designed to reduce the amount of cycling by the rotary circulation fans in an effort to conserve energy. The response of the helium temperature to the cycling of the rotary circulation fans is evident in Figure 3.

The total rate of heat transfer to the balloon film can now be written as:

$$q_T = q_2 + q_3 - q_1 - q_4 - q_5 \tag{19}$$

The values for each of the heat transfer rates change as the corresponding temperatures and helium volume change. Due to the vast changes in these parameters, a FORTRAN program (Appendix A) was written to calculate the temperatures, heat transfer rates, altitude, and velocity of the HAORB and a conventional high altitude balloon (i.e. no rotary circulation fans) every second. The output of the program is used to compare the two balloons. The graphical representation of the film temperatures are shown in Figure 4. The film temperature of the HAORB is shown to be kept within the required tolerance limit. This fluctuation of the film temperature is directly responsible for the helium temperatures shown in Figure 3. The helium temperatures in turn control the volume of the balloon.

A graph of balloon volume versus altitude is displayed in Figure 5. The buoyant force on a balloon is a function of volume, helium density, and air density. In turn the acceleration and velocity of the balloon are a function of the buoyant force. Therefore, by controlling the temperature of the HAORB film, the velocity and consequently the altitude of the HAORB are controlled.

The velocity of the HAORB is shown to remain relatively constant throughout the entire altitude range. The velocity of a conventional balloon increases rapidly and levels off as float altitude is reached (See Figure 6). The altitude of the HAORB and a conventional balloon are represented in Figure 7. This graph shows that the ascension time of the HAORB can be extended to at least twelve times that of a conventional balloon. Thus, decreasing the number of ballast changes required and increasing total mission time.

The first part of the program sets all of the constants for the calculations. These constants include the conduction heat transfer coefficients for the polyethylene and the helium, the initial charge of helium, the thickness of the polyethylene and the weights of the HAORB and the conventional balloon. The effective heat transfer area for the rotary circulation fans is also set at this point.

The next part of the program sets the initial conditions for the beginning of the step-wise integration. The initial conditions assume that the initial velocity and acceleration of the HAORB and the balloon are zero. The initial temperature difference is set at this point and considered to be instantaneous. Initially, the temperature of the film is set to 5 degrees above atmospheric, and helium temperature is set to 2.5 degrees above atmospheric. This temperature difference is unstable for the given initial conditions. This instability is evident in the initial cooling of the helium in the conventional balloon model (See Figure 8.). The large values for temperature difference were assumed to ensure that the actual temperature difference that does occur would be within the cooling capability of the rotary circulation fans on the HAORB.

The input to the program is a table of standard atmospheric pressures and temperatures with their corresponding altitudes. The program starts at 26,000 meters and first tries to find the altitude in the input tables. If this value of altitude is not found, the program interpolates between the altitude above it and below it to determine the pressure and temperature at the actual altitude. The pressure and temperature are used in the equation of state to determine the density of the air. The temperature of the helium and the atmospheric pressure are also used in the equation of state to determine the density of the helium.

The density, temperature, and pressure of the helium are then used to determine the volume of helium. This volume is also assumed to be the displaced volume of air. From the displaced volume of air, the buoyant force on the HAORB can be determined by:

$$B = \rho_a * V_g * g * (1 - \rho_g / \rho_a) \qquad (20)$$

The acceleration is calculated from Newton's second law:

$$accel = (B - W - D)/m \qquad (21)$$

where W is the weight and m is the mass of the HAORB. The drag is represented by D and calculated by:

$$D = \tfrac{1}{2}\ \rho\ V^2\ C_d\ Ad \qquad (22)$$

where V is the velocity of the HAORB, C_d is the coefficient of drag for a balloon, and Ad is the area of the balloon's cross section. The densities, temperature differences, constants and helium volume are input into the heat transfer equations to determine the total rate of heat transfer to the film and the helium.

The rate of heat transfer to the film and to the helium is integrated over one second and a temperature change for the helium and the film is calculated. The equations for the temperature changes are

$$T_f = q_T * \mathrm{thick} / (A_s * kf) \tag{23}$$

$$T_g = q_1 / (Hg * A_s) \tag{24}$$

where thick is the thickness of the polyethylene and hg is the average natural convection heat transfer coefficient of the helium. This temperature change is added to the previous temperature there by providing an updated temperature for the calculations at the next altitude / second.

The rotary circulation fans are only energized when the fans will remove heat from both the film and the helium. The question of whether the fans should be on or not is answered by comparing the atmospheric temperature, the film temperature, and the helium temperature. A temperature monitoring system is utilized to check if the atmospheric temperature is greater than either the film or helium temperature. If so, the fans will not run. Currently, the fans are set to cause the HAORB to ascend from 26,000 meters to 34,600 meters in a 12 hour period. Hence, the HAORB will need to travel at a velocity of 0.27 m/s.

In order to minimize the cycling of the rotary circulation fans, a velocity range is set with the average velocity being 0.27 m/s. A fan control system is employed to evaluate the temperature and acceleration data in order to maintain the velocity range. If the velocity of the HAORB is greater than 0.27 m/s then the fans will be energized. If the velocity is between 0.27 m/s and 0.2 m/s, then the fans will run only if the acceleration is negative. If the velocity of the HAORB is less than 0.2 m/s then the fans will be off.

The rotary circulation fans are squirrel cage fans that produce .5097 m^3/sec of air flow each. This volumetric flow rate requires 720 watts of power per fan.

The program stops when the HAORB expands to 467,228 m^3 (16.5 million ft^3). This volume corresponds to the altitude at which the HAORB will remain until helium is vented. For the case when maximum volume is reached, the program sets all velocities and accelerations equal to zero, because the program does not account for venting of helium.

This program makes subtle assumptions that may not be obvious, such as the cooling air is not heated by the fans, the work done in expanding the HAORB is negligible, and the thermal and velocity boundary layers are fully developed within the channel.

Power Requirements

For the profile from 26 to 34.6 km, the fans have a total run time of 6.47 hours per 12 hours of sunlight (See Figure 9a and 9b). An estimation of extra power required to start the fans brings this total to an equivalent of 8 hours of fan run time per 12 hours of sunlight. A solar panel will deliver approximately 140 W/m^2 under direct sunlight. In order to completely power the four rotary circulation fans, the solar panels need to have an exposed surface area of 20.57 m^2. By placing the solar panels on the outer surface of the gondola, (Figure 10) the solar panels have an exposed surface area of 23.17 m^2. The extra power generated is used to recharge the battery bank. The batteries can be utilized during the night time hours if needed. As long as there is sunlight on the HAORB, the fans will have enough power to run indefinitely. If there is no sunlight present, then the need for cooling of the HAORB will be reduced because of the natural convection of the atmosphere surrounding the balloon. Nevertheless, if cooling is necessary, the battery bank can provide 8 hours of continuous fan operation.

Other power requirements include the electronics and the control systems for releasing ballast and venting helium. The electronic equipment required for the mission requires a negligible amount of power when compared to the fans. The control system that releases ballast and adds helium requires a more substantial amount of power; however, this system only operates for short periods of time.

Advantages of the HAORB

The conventional balloon with no fans will reach a maximum velocity of 8.5 m/s during ascent and will travel the range of 8,600 meters in about 58 minutes. The HAORB is maintained within a range of velocities of 0.15 to 0.32 m/s. The lower velocity of the HAORB provides a more stable platform for sampling and will travel the same range of 8,600 meters in 11.7 hours (Figure 7).

The conventional balloon must vent helium in order to prevent leaving the desired sampling range. The HAORB, however, will maintain the maximum altitude indefinitely under sunlight conditions. In order to lower the altitude of the HAORB while in sunlight, helium must be vented. It is obvious that this venting will only be required every 12 hours as compared to the conventional balloon which requires venting every hour. This primary advantage of the HAORB translates into increasing the mission time by a factor of 12 assuming all other variables remain constant.

The mission length of the balloon with no fans is greatly restricted by the initial amount of ballast and reserve helium supplied at launch. The usual mission time of a conventional balloon is 3 to 7 days. With the lengthened mission time of the HAORB (36 to 84 days), there is less capital required for refurbishment and subsequent flights.

Disadvantages of the HAORB

The HAORB requires a large number of solar cells and batteries. The batteries are very heavy and reduce the amount of payload available. However, the payload for an ozone monitoring mission is less than 900 kg and is not very significant when determining the size of the helium chamber required for the mission.

The polyethylene for the HAORB has a weight of 1.25 times the weight of a conventional balloon of the same volume. This extra weight is a result of extra material needed for the cooling ducts which cover 1/4 of the surface area of the balloon. The extra weight also means extra capital required for the initial flight of the HAORB. The extra weight required for the operation of the HAORB also requires a larger parachute system.

Overall, the HAORB weighs more and has a higher initial cost, but lower subsequent costs. The HAORB has virtually an unlimited flight time when compared to conventional balloons and a far greater range of altitudes and mission capabilities.

Mission Scenario

Preplanning:

Stratospheric easterlies in the summer are of primary importance to balloon researchers. They are the steadiest winds known, and during the season in which they blow, one can launch a balloon a considerable distance upwind from a target area with reasonable confidence that it will cross the pre-specified target in the pre-calculated time. The optimum times for flights of this nature are July and August at latitudes 35 N at any altitude above 25 Km.

In the stratospheric winter, transcontinental flights of up to three days duration can be achieved. However, winter ballooning in temperate latitudes is severely limited by unfavorable surface weather.

West coast sites are also inoperative for several weeks during periods of circulation reversal. These winds, unlike the easterlies, are often characterized by waves of great amplitude.

So tracking and recovery of the balloon is very difficult.

The stratum of minimum winds found at approximately 20 Km may be used in spring and fall for long duration flights of limited horizontal displacement. Vector mean winds may be zero, but the scaler winds are never really equal to zero.

Hovering flights are also feasible in the early summer. In these flights, the balloon rises during the daytime to the edge of the easterlies and descends at night into the light westerlies below. Careful planning and coordination are required for this type of flight (6).

After analyzing the wind patterns for different seasons and different latitudes the optimum conditions for the HAORB launch have been chosen. The first flight will be performed during spring on the approximate launch date of May 10. The HAORB will be launched from a site approximately 45 degrees North of the Equator. For the second launch, the date approximate date will be September 18. The site will be set at approximately 30 degrees North of the Equator. Both of these flights are scheduled to last roughly between one and two months duration.

The sunlight hours for these launch dates and several other dates have been computed using a Fortran program that is contained in Appendix A. The sunlight hours present for the launch of the HAORB are contained in Figures 11 and 12 (1).

Inflation

The danger of balloon destruction during the early stages of inflation is a function of wind speed and balloon fabric toughness. Steady winds of less than 8 km/hr are acceptable for inflation of a balloon made of thin polyethylene material. These light winds are rarely steady and a strong gust of wind only a few seconds in duration can destroy a balloon. Therefore, extensive meteorological studies of the launch site must be conducted before launching the HAORB. Humidity can cause various problems during balloon inflation by increasing the static conductivity if the inflation gas is flammable. This is one of the many reasons the HAORB is designed to use helium rather than hydrogen as the lift gas (2).

Launch

There are many different means of launching a balloon. The two means that seemed the most suited for the launching of the HAORB are the static and the dynamic type launch.

In a static launch a large balloon standing erect can form huge spinner-like sails. When this happens the balloon is most likely to be destroyed and the forces that are created are powerful enough to drag and tear payloads apart. In order to avoid this situation, the winds in the stratum must be less than eight meters per second. It is also standard procedure to launch balloons during the time when the diurnal winds are at a minimum. In order to avoid a damaging low-level jet (nocturnal condition, appearing around midnight and disappearing around dawn, which makes launching a balloon of the HAORB's size nearly impossible), inflation must start early enough for launch to be completed before late evening.

In a dynamic launch the winds must also be less than eight meters per second. Besides wind, another critical factor is the maneuverability of the launching vehicle. After the balloon has been lifted off the ground, the vehicle must move faster than the wind at that level of the balloon and overtake it. This requires a large surface area of maneuverability for launch (6).

The HAORB will be launched using a static type launch because there are many problems associated with dynamic launches that have not been detailed here. A static launch will be more economical and safer for the balloon, the payload, and personnel (1).

Ascent

During ascent the horizontal speed of the balloon is equal to the speed of the ambient air. An atmospheric study of the launch site winds will be done and a profile of the balloon's estimated horizontal movement with altitude will be formulated. The rate of ascent of the balloon is a function of the lapse rate of temperature (-dT/dH) and the thermal environment of the balloon. As the balloon ascends through the tropopause it encounters extreme cold. The polyethylene material of the HAORB can withstand very low temperatures down to the minimum temperature -80 C. A flight during the spring or fall should not be faced with such extreme temperatures, so minimum temperature will not be a critical factor in the HAORB atmospheric analysis (1).

Inflight

The HAORB will begin sampling of the ozone at an altitude of 24,000 meters. The cooling ducts for the fans will be partially extended and will allow without high head loss in the duct at 26,000 meters. As the HAORB initially heats up due to radiation, the helium becomes less dense and starts to ascend. The navigation system measures the velocity and acceleration and sends a signal to the fan control system calling for fan operation when the velocity reaches 0.27 m/s. The temperature monitoring system which consists of thermocouples on the balloon and in the helium chamber as well as on the gondola, checks the temperatures of the film, the helium, and the atmosphere. The temperature differences between the film and the air, and between the helium and the air must be greater than 0.1 degrees K before the fans will be energized. In order to ensure that the rapid heating of the film and helium does not occur, the fans remain secured with a small temperature difference.

When the rotary circulation fans are running, heat is being removed from the film as well as the helium. The navigation system continually updates the velocity, and the temperature monitoring system continually update the temperature differences. When the velocity of the HAORB reduces to 0.27 m/s, the navigation system checks the acceleration of the HAORB. If the HAORB has a negative acceleration, the fans remain on until the velocity reduces to 0.2 m/s. The overlap in velocities for the fan set points is necessary in order to reduce the frequency of the fan cycling. When the velocity of the HAORB reduces to 0.2 m/s, the fans are secured and the HAORB begins to heat up again. When the HAORB reaches the maximum altitude, which is determined by the initial helium charge, the fans will cycle and keep the HAORB from discharging helium out of the open bottom of the balloon. When the HAORB needs to descend, the vent in the top of the HAORB can be opened to vent helium thus causing the HAORB to fall. In the event that the HAORB falls below the intended range, ballast will be remotely dropped in order to reestablish the equilibrium altitude.

Tracking and Float

During ascent, tracking will be done visually and electronically via the data link system located at the launch site. If tracking becomes difficult because of the differing reflective-index gradients near the radio horizon, tracking will be done by airplane.

Termination

The process of venting and dropping ballast will continue approximately every 12 hours until mission is terminated. Upon mission completion, the safety of the electronics, batteries, fans, and monitoring equipment rests with the parachute system and the crush pads.

PARACHUTES

Parachutes are utilized on most scientific balloon flights to recover the scientific payload after the ballooning phase of the flight is terminated. This section describes a typical parachute system, a method for selecting the parachute, and a procedure for determining the size of a parachute necessary for mission completion.

Describing a Parachute System

A descending parachute with an attached payload is schematically illustrated in Figure 13. The parachute with its payload and auxiliary equipment will be termed a parachute system. Although variations among existing parachute systems may be found, most of the features used in scientific ballooning are shown in Figure 13.

A parachute is made of a woven textile or plastic canopy that is attached to the payload by means of suspension lines. The canopy, with or without vents, is usually axially symmetric to the vertical axis. Suspension lines, commonly known as shroud lines, are joined at the canopy's skirt. These suspension lines are normally fastened to the skirt at the seams between gores, and may or may not continue upward towards the vent on top of the canopy. Gores are panel sections that make up the canopy. Not all parachutes have vents, but an axially symmetric canopy can benefit from a parachute vent.

The payload can be attached directly to the lower ends of the risers. Risers are stronger lines that gather groups of suspension lines together. If there is any reason for suspending the payload at a further distance from the canopy, extension lines may be utilized. Extension lines will allow for the parachute to fall away from the payload upon impact of the ground. A swivel is placed anywhere below the risers in the suspension system to permit the payload to turn freely and separate from the parachute.

Parachutes are described by their nominal diameter. The nominal diameter is defined as the circle whose area is equal to the drag producing surface area of the canopy. In other words, the nominal diameter of a flat circular canopy is the diameter of the canopy in its flat form. The projected or effective diameter is the diameter of the inflated parachute as illustrated in Figure 13. The latter diameter is a function of the parachute's design and the load it is carrying.

Packed parachutes are occasionally used in scientific ballooning. In most cases, the parachute is fully deployed, and its inflation begins immediately upon separation from the balloon. There is a termination device affixed at the top of the parachute that accomplishes this separation. The parachute serves as a link between the balloon and the payload (4).

Selecting a Parachute

Parachutes used in scientific ballooning should be very reliable and should prevent downward accelerations from exceeding a maximum predetermined point. Some of the equipment carried are sensitive to extreme accelerations. Selecting one particular type of parachute over another is often a matter of personal preference because of conflicting demands and incomplete knowledge of parachute behavior at high altitudes. However, the most important factor in the selection of a parachute is safety.

The parachute must open reliably, withstand opening shocks, and slow the payload to an acceptable vertical velocity at landing. It is essential for the parachute to perform these functions in any given situation, in order for the payload to land safely without damage to equipment or, most importantly, injury to human life. Other features may be desirable, such as the prevention of spin or swing during descent, but these added features must not replace features that are essential to safety.

There are two types of parachutes currently in use that have proven to be effective for scientific ballooning. One parachute has a flat circular canopy with a vent in the center, while the other, has a canopy in form of a cross with no vent. The flat circular canopy has demonstrated both reliably and quickness at high altitudes associated with scientific ballooning. This canopy is commercially available in manufacturing sizes up to 30 meters in diameter. Canopy sizes an excess of 30 meters in diameter are undesirable because it adds more weight to the total mass and raises the cost for manufacturing. Two or more canopies can be used together, and when proper load limits are employed, the terminal velocity can be predicted with a high degree of accuracy. A main drawback of the flat circular canopy is its undesirable tendency to oscillate during descent.

In comparison with the flat circular canopy, the cross-shaped canopy is exclusively serviced only by the Naval Research Laboratories which manufactures them. A representative of the Naval Research Laboratories reports that the canopy performs well in all aspects and oscillates less than the flat circular canopy during the time of descent. One major area of concern of the cross-shaped canopy is the fact that no tests have been preformed with a load more massive than 365 kg (800 lbs). Also, no flights have been made with two or more cross-shaped canopies operating together.

Currently, the desired parachute for heavy loads greater than 365 kg is the flat canopy parachute. The flat canopy parachute has a history of satisfactory descents, therefore, the best parachute suited for the HAORB is the flat canopy parachute. Since the maximum payload of the HAORB is approximately 550 kg (1212 lbs), the flat canopy parachute is capable of safely and efficiently descending this maximum payload down to the desired landing area. Furthermore, the flat canopy parachute is known to operate reliably, decrease terminal velocity efficiently, and open quickly at high altitudes. Each of these features are all necessities for the HAORB (4).

Determining the Size of the Parachute

To determine the parachute size required for a particular mission in scientific ballooning, the payload mass and the permissible vertical velocity at impact must be known. The mass of the payload, m_p, can be found simply by weighing the payload, but the permissible vertical velocity at impact is based on a value judgement. An acceptable value for a vertical landing speed, or terminal velocity, v_T, at the altitude where the landing is anticipated is approximately 7-8 m/sec (25 ft/sec). This vertical speed established by early scientific ballooning experiments has given results which are acceptable for most heavy payloads.

In most circumstances, the mass of the parachute is unknown. Thus, an adequate approximation of the total parachute system mass, m_s, must be determined. This approximation is performed by multiplying the mass of the payload by 1.05. With the value of v_T known, v_{To}, the vertical speed the system would have at sea level, can be calculated. It may be approximated by the equation

$$v_{To} = v_T/(1 + 5 \times 10^{-5} H) \qquad (25)$$

where H is the height of the landing site above sea level in meters.

Since the values for the parachute system mass and the sea level terminal velocity are known, Figure 14 can be utilized to determine a value of C_DA, the product of parachute area and drag coefficient. If the value of C_D, drag coefficient for an inflated circular parachute, and C_DA are known, Figure 11 can be used to obtain the value of the parachute's nominal diameter, D. Figure 11 is a graphical representation of the equation

$$C_DA = C_D\pi(D/2)^2 \ . \tag{26}$$

A drag coefficient that is often quoted for a flat, circular canopy is 0.75. With the value of the nominal diameter known, a manufacturer is capable of sizing the required parachute to meet the buyer's specifications.

Large parachute can be utilized if a payload is particularly sensitive to shock. However, an oversized parachute is unlikely to give more protection than a smaller one unless there are low surface winds. In other words, using a large parachute will increase the time one must wait for satisfactory weather conditions at the landing site. Although large parachutes increase the time on station, they are still considered optimum for general safety.

Parachutes can be manufactured in any size, nonetheless, it is more practical to manufacture them in certain discrete sizes. Normally, the determined parachute size necessary for a particular mission will usually agree with one of the sizes commonly made by parachute manufacturers.

It is sometimes convenient or necessary to use multiple parachutes to lower a load. Many low level, multiple parachute drops have been made; a few have been made successfully from float altitudes. Thus it is known that drops using a cluster parachutes are feasible, but the number of multiple parachutes flights on balloons to date has been too limited to warrant the degree of confidence that has been established for parachutes used singularly.

The size of the HAORB's parachute is determined by the method previously mentioned. The steps and respective parachute values for the HAORB are as follows:

1) Determine m_p (Maximum).

$$m_p = 550 \text{ kg } (1212 \text{ lbs}).$$

2) Determine approximation of m_s.

$$m_s = (1.05)(550 \text{ kg}) = 577.5 \text{ kg}.$$

3) Determine v_T (Acceptable value).

$$v_T = 7.5 \text{ m/sec} .$$

4) Determine v_{T_0} (Landing site at sea level, H=0).

Using Eq. (1), $v_{T_0} = v_T = 7.5$ m/sec .

5) Determine C_DA by using Figure 14.

$$C_DA = 180 \text{ m}^2 .$$

6) Determine D by using Figure 15 (Design value $C_D = 0.75$).

$$D = 15.5 \text{ m (approx. 51 ft.)} .$$

In summary, the parachute adequately designed for the HAORB is a flat circular canopy parachute that can support a maximum load of 550 kg, and is measured at 15.5 m in diameter (4).

LANDING ENERGY ABSORBER

Due to the sensitive nature of most scientific payloads, the acceleration upon impact must be limited to a safe value. The acceleration is a function of the kinetic energy of the system on landing. The role of landing energy absorbers is to increase the time in which the kinetic energy is absorbed, thus decreasing the average acceleration. The HAORB will utilize paper honeycomb crush pads to limit the acceleration on landing.

Kinetic Energy and Acceleration

The kinetic energy that an energy absorption system must dissipate is only a function of mass and velocity upon impact. The mass of the system at impact is set by the final weight of the payload plus the parachute, and the velocity of the system at impact is set by the terminal velocity of the parachute system. The energy dissipated in bringing the system to rest is

$$KE = \tfrac{1}{2} mv^2 , \qquad (27)$$

where KE is the kinetic energy, m is the mass of the payload and v is the terminal velocity. The velocity has components in the vertical and horizontal directions, but for preliminary calculations the velocity in the horizontal direction is assumed to be negligible.

If energy absorption devices were not used, then all of the kinetic energy could be transferred into the gondola and the scientific equipment. The scientific equipment would certainly be damaged and would possibly be damaged beyond the point of repair. The amount of kinetic energy cannot be changed, but the average acceleration of the payload during dissipation of this kinetic energy can be limited to an acceptable value. A relationship between vertical velocity, distance, acceleration, and time may be stated as

$$d^2 z/dt^2 = dv/dt = a \ , \qquad (28)$$

where z is the vertical component of distance, v is the terminal velocity, a is the acceleration, and t is time. Integrating this yields

$$vi = \int_{ti}^{tr} a \, dt = - \bar{a} \, tr \ , \qquad (29)$$

where vi is the velocity at the time of impact, ti, and vr is the velocity at the time the payload comes to rest, tr. The average acceleration for the time tr - ti is $\bar{a}$. By integrating Eq. 28 twice the following equation is obtained

$$(zi - zr) = \tfrac{1}{2} \, \bar{a} \, tr^2 \ , \qquad (30)$$

where (zi - zr) is the distance the payload travels from impact until it comes to rest. Eliminating time between Eqs. 29 and 30 and multiplying by mass yields

$$m\bar{a}(zi - zr) = \tfrac{1}{2} \, mvi^2 \ . \qquad (31)$$

Therefore, an energy absorption system that can deliver a force $m\bar{a}$ through a distance (zi - zr) can completely absorb the required kinetic energy (5).

Crush Pad Design

The general equations that govern the construction of the crush pads are derived above; however, these equations must be modified to account for material properties and behavior. The most widely used crush pad material is paper honeycomb. Paper honeycomb is inexpensive and more importantly light weight. A honeycomb structure typically yields in a direction parallel to its tubes. Also, the compressive load required to yield the material is greater than the compressive load required to continue crushing the material. However, the continuing strength remains constant after yield has started and before the cellular structure is so destroyed that the paper itself starts being compressed.

If a sheet of paper honeycomb is precrushed just enough to start yield, its subsequent yield can be made nearly equal to its continuing strength. It will then have a nearly constant crush strength through about two-thirds of its thickness. The continuing crush pressure (strength) is denoted by Pc. This value is dependent upon honeycomb cell size and cell wall thickness. Various strengths of honeycomb are available from manufacturers. Selected data from one manufacturer are provided on the following page (5).

TABLE 1. Paper Honeycomb Strength Data

Verticel * Designation		Shear Strength	Compression Strength
		N/m^2 x 10^{-4}	
½"	40-50-15%	22.7	21.6
½"	60-80-20%	42.5	42.6
3/8"	40-50-15%	31.4	27.1
3/8"	60-80-20%	69.0	52.1
¼"	40-50-15%	78.0	71.0
¼"	60-60-20%	102.	96.0
½"	30-30- 0%	---	4.8
½"	60-80- 0%	---	14.8
¼"	60-60- 0%	---	44.5

If the maximum acceleration the payload can withstand on landing is ng, where g is the acceleration due to gravity, then the force that will produce the acceleration of the mass is mng. The area, A, of the honeycomb required to support this force is

$$PcA = mng. \qquad (32)$$

Given a maximum number of g's the payload can withstand, the area of honeycomb can be calculated using Eq. 32. By substituting ng for acceleration into Eq. 31, the height, H, or thickness of the honeycomb required may be calculated, $H=(zi - zr)$. Because the crush pad is not effective for $H/H < 2/3$, the total thickness of the honeycomb needed is 1.5 H . Therefore, Eq. 31 in terms of H becomes

$$H = 0.75\ vi^2/ng\ . \qquad (33)$$

Eq. 6 can be rewritten as $A = mng/Pc$. Consequently, the product of A and H gives the volume of the energy absorber needed to bring a mass with a terminal velocity of vi to rest with an average acceleration of ng.

$$Vol = HA = 1.5/Pc \left(\tfrac{1}{2} m v_i^2\right) \qquad (34)$$

The volume of the crush pad needed is only a function of kinetic energy and not the required acceleration. For this reason, it is apparent that the dimension of the crush pads may be changed without changing the overall energy absorption capacity. If the area of the base is reduced and the height is increased the acceleration on impact can be reduced. Accordingly, a crush pad with a small horizontal area and a large vertical depth is more efficient at reducing acceleration. However, this configuration is not practical. The base area required is a function of stability requirements on impact. The base area must be large enough to insure that the payload will not overturn on impact.

The value of Pc may also be varied if the dimensions of the payload are such as to restrict the size of the crush pads. Occasionally, the area required to control the acceleration on impact may be less than the area required for stability reasons. If this is the case, the crush pad can be constructed in layers of varying strength with the weaker sections at the bottom and the strongest sections mounted against the gondola structure.

To calculate the size of crush pads for the HAORB, the mass of the payload must first be determined. Because mass varies with mission requirements, (number of batteries, scientific payload, etc.), calculations were first performed with mass a variable. The terminal velocity of our payload set by the parachute design is approximately 7.5 m/s. A typical value for crush strength of $P_c=48{,}000\ N/m^2$ was chosen. A graph of crush pad area versus mass for a 10g acceleration is shown in Figure 16. For a payload of 500 kg to 1500 kg, the total crush pad area should be between 1.0 m^2 and 3.0 m^2. Figure 17. is a graph of crush pad height versus required acceleration for a terminal velocity of 7.5 m/s. This parameter is not dependent on mass. Typical values of crush pad height vary between 0.25 m and 0.50 m for accelerations from seventeen to eight times that of gravity. The crush pad volume versus mass is shown in Figure 18. Typical crush pad volumes vary from 0.4 m^3 to 1.2 m^3 for masses between 500 kg and 1500 kg respectively.

The final mass of the termination payload was set at 550 kg with a terminal velocity of 7.5 m/s and an acceptable average acceleration of 10g. Using a $P_c = 48{,}000\ N/m^2$, the volume of crush pads required is

$$\text{Volume} = 0.4834\ m^3 .$$

The height required to obtain the average acceleration of 10g is

$$H = 0.4300\ m .$$

If the volume is divided into four pads of height H that are to be distributed about the center of mass, then the dimensions of each of the four crush pads is given by

$$h = 0.4300\ m$$
$$\text{base} = 0.53\ m^2 .$$

The crush pads are roughly shortened cubes (See Figure 19). For small horizontal speeds, less than 1.0 m/s, the crush pads should not affect the stability of the HAORB (5).

SUMMARY AND CONCLUSIONS

Because the maximum ozone concentrations exist 26,000 meters above sea level, methods for analyzing ozone are expensive, time consuming, and inadequate. Although, the existing high altitude balloons used for this research are cost effective and environmentally safe, problems with flight duration time, lateral control, and vertical control have severely limited their acceptance. Lateral control will continue to be a major area of concern; however, vertical control can be attained by the HAORB.

Existing research balloons maintain their float altitude by venting helium and dropping ballast. When the balloon ascends to an altitude above the desired sampling range, the balloon is remotely vented and helium is released. As the mass of helium is reduced, the volume of air displaced by the balloon decreases. Therefore, the buoyant force on the balloon decreases and the balloon descends.

When the balloon descends to an altitude below the sampling range, a portion of the ballast carried on the gondola is released. Once all the reserve helium and ballast have been released, the mission will be terminated. Currently, average flight times for conventional balloons of this type are three to seven days.

Because helium is transparent to radiation, convection from the balloon film is the only heat transfer mechanism into the interior of the balloon. Therefore, the vertical speed of the HAORB is controlled by removing the heat that is transferred to the balloon film from radiation. By limiting the increase in balloon film temperature, less heat is transferred to the helium gas by convection. The HAORB uses forced convection heat transfer over 1/4 of the balloon's surface area. Using an iterative process and the FORTRAN code, a heat transfer area of less than 1/4 of the surface area of the balloon was determined to provide inadequate heat removal and poor vertical control. A heat transfer area greater than 1/4 of the surface area of the balloon provided excellent vertical control; however, fully developed flow cannot be guaranteed within the cooling ducts. Also the increase in weight of balloon material is unnecessary and expensive.

Vertical control of the HAORB can be achieved by maintaining a balance between the temperature of the helium within the HAORB and the surrounding atmosphere. This balance is attained by use of rotary circulating fans and their associated cooling ducts. The rotary circulation fans force air through the cooling ducts and remove heat from both the balloon film and the helium by means of convection. Therefore, the rate of temperature increase of the helium will be reduced. Consequently, the change in the volume of the balloon and the change in the buoyant force on the HAORB will be reduced. As a result, the HAORB will ascend at a slower rate than a conventional balloon.

For the 467,228 cubic meter (16.5 million cubic feet) HAORB, the operation of the cooling system has a lower altitude limit which is set by the length of the cooling tubes extending from the fans to the balloon. At altitudes below 26,000 meters, the cooling tubes are only partially extended. Therefore, both the head loss and the differential pressure required to force the air through the cooling ducts is substantially increased. However, for a smaller balloon operating at a lower altitude the cooling tubes would be fully extended and efficient operation of the cooling system would be possible.

For the test profile conducted from 26.0 kilometers to 36.4 kilometers, the HAORB reached its maximum volume in approximately 12 hours. In contrast, the conventional balloon reached its maximum volume in approximately 58 minutes. Thus the mission time of the HAORB was increased by a factor of 12 over that of the conventional balloon. Because the rotary circulation fans increase the mission time by a factor of 12 as compared to conventional balloons, the tradeoff between adding more ballast and reserve helium as compared to having rotary circulation fans is not considered. Furthermore, in order to achieve a comparable mission time for a conventional balloon the amount of ballast and reserve helium would be excessive and expensive.

The fans had a estimated run time of 6.7 hours for the 12 hour ascension to 35 km. Because the HAORB operates at such a high altitude, the best method for powering the gondola support equipment is solar energy. The pyramidal design of the gondola provides both structural integrity and a low center of mass necessary for landing stability. The solar panels are placed on the gondola support structure in order to take advantage of the angle of the incident radiation. Also, because the solar cells enclose the electronic equipment, a more stable temperature environment within the gondola is maintained. Therefore, the support equipment is subjected to fewer thermal stresses. Based on the theoretical analysis performed, the size of the of solar array required to power the rotary circulation fans and support equipment is 20.5 square meters. The actual solar array size was increased to 23 square meters to allow for intermittent cycling of the rotary circulation fans.

A typical mission of the HAORB would include a cycle from the minimum sampling altitude to the maximum sampling altitude and then back to the minimum altitude. This cycle would ideally be carried out over a 12 hour day and 12 hour night, respectively. The purpose of constantly varying the altitude of the HAORB is to obtain as broad an ozone sampling range as possible. The balloons position is constantly monitored by radio telemetry from ground bases and support aircraft. Upon completion of the mission, the ozone data and a plot of the position of the HAORB can be employed to develop a detailed map of ozone concentrations.

When the HAORB has reached the conclusion of its mission, a pyrotechnic charge separates the parachute and payload from the balloon. The balloon is not reusable and it is discarded. The flat circular canopy parachute opens seconds after release and the payload slows to its terminal velocity as determined by the parachute design. Upon impact, the kinetic energy of the payload must be dissipated in order to limit the decceleration experienced by the scientific equipment. To prevent payload damage, the HAORB utilizes paper honeycomb crush pads because of their low cost and high strength to weight ratio.

After the payload is recovered, it is refurbished and prepared for another mission. The reconditioned payload must be integrated with a new balloon. The value of the HAORB becomes quite clear when the turn around costs are considered. When considering the cost of readying a balloon for a flight may be in the millions of dollars, the cost savings alone incurred by the HAORB are enough to precipitate its production. However, the scientific advantages gained from a long duration high altitude platform are more immediate.

Although the HAORB is designed as an ozone testing platform, it can be employed for a wide range of high altitude experiments. One example where the HAORB platform would be of great benefit is in the deployment of imaging devices to study solar radiation, where the platform is required to stay aloft for as long as possible during periods of maximum solar activity. The rising cost of alternative methods is also pointing toward the further development of scientific ballooning systems. For these reasons, the HAORB is urgently needed to fill the gap in existing high altitude research platforms.

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FIGURES

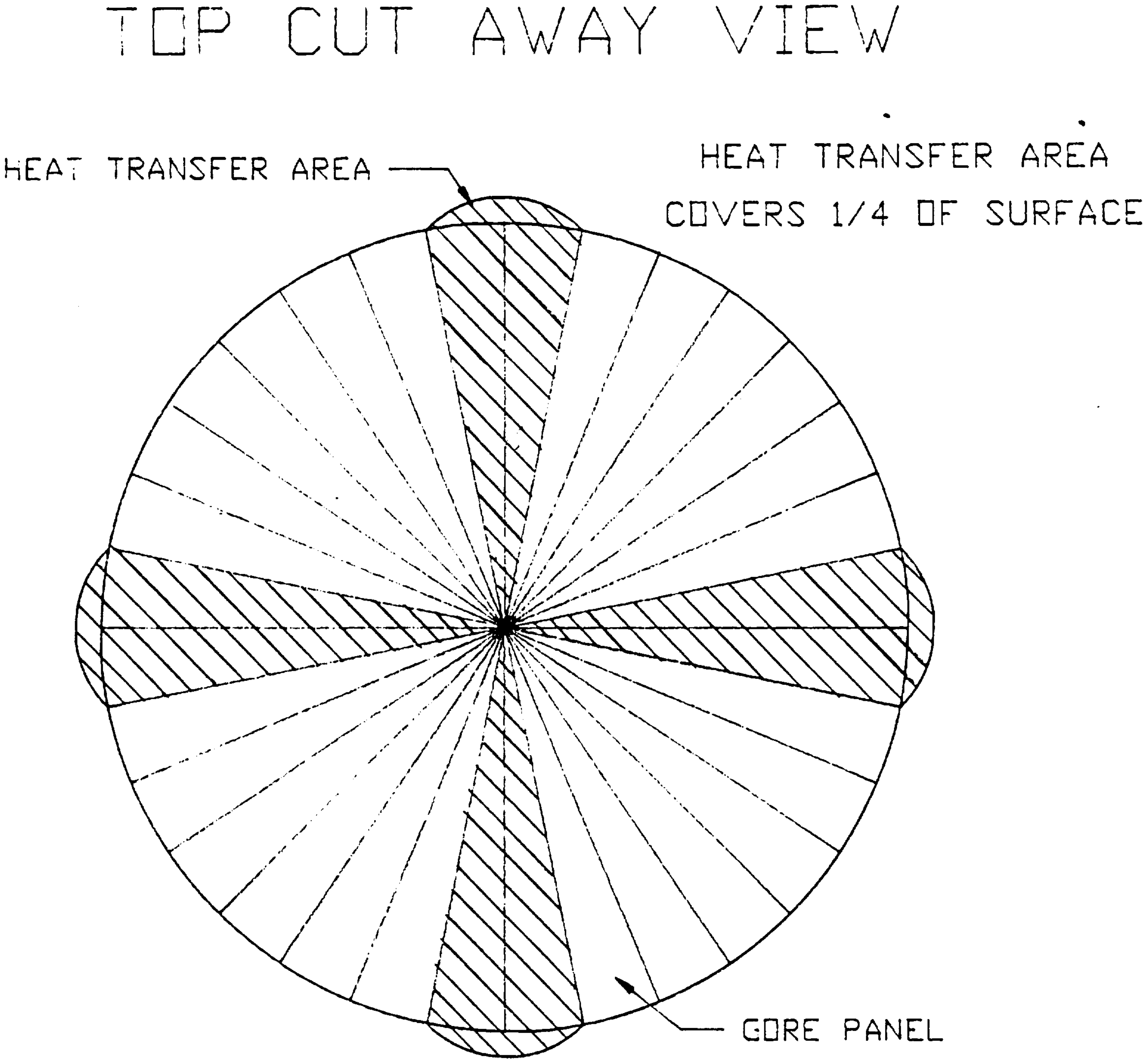

Figure 1. Top Cut Away View of the HAORB

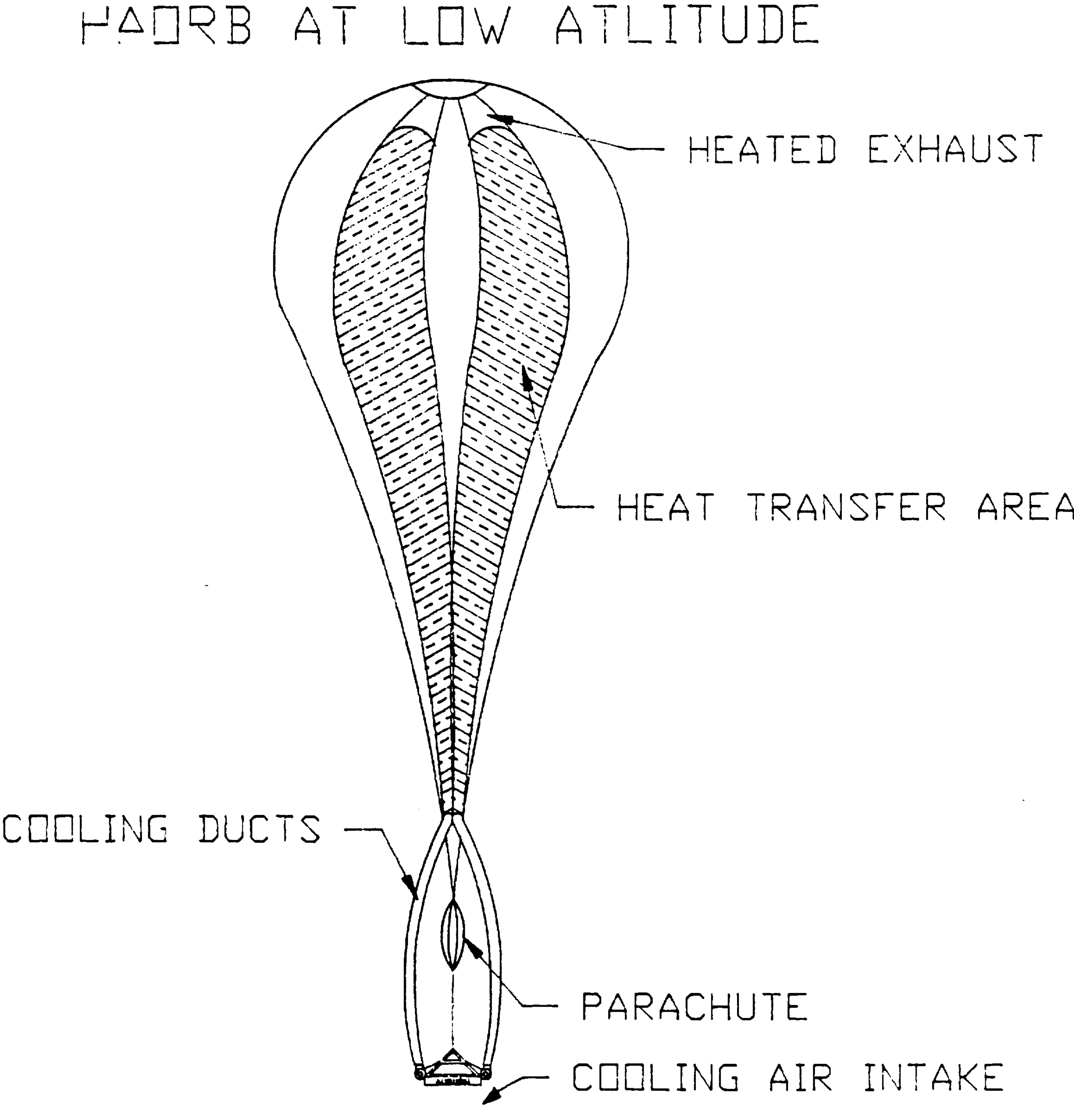

Figure 2a. Configuration of the HAORB at Low Altitudes

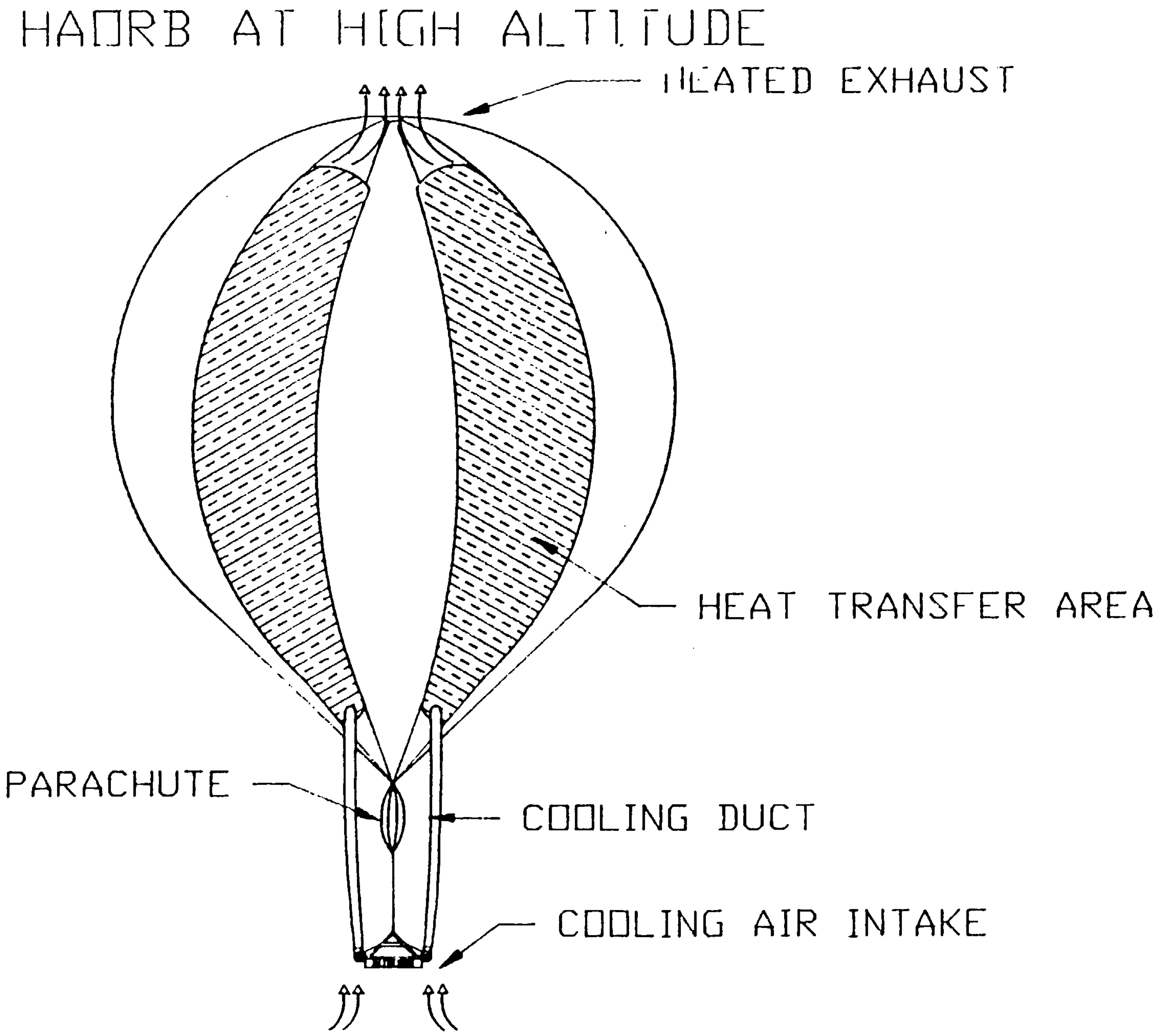

Figure 2b. Configuration of the HAORB at High Altitudes

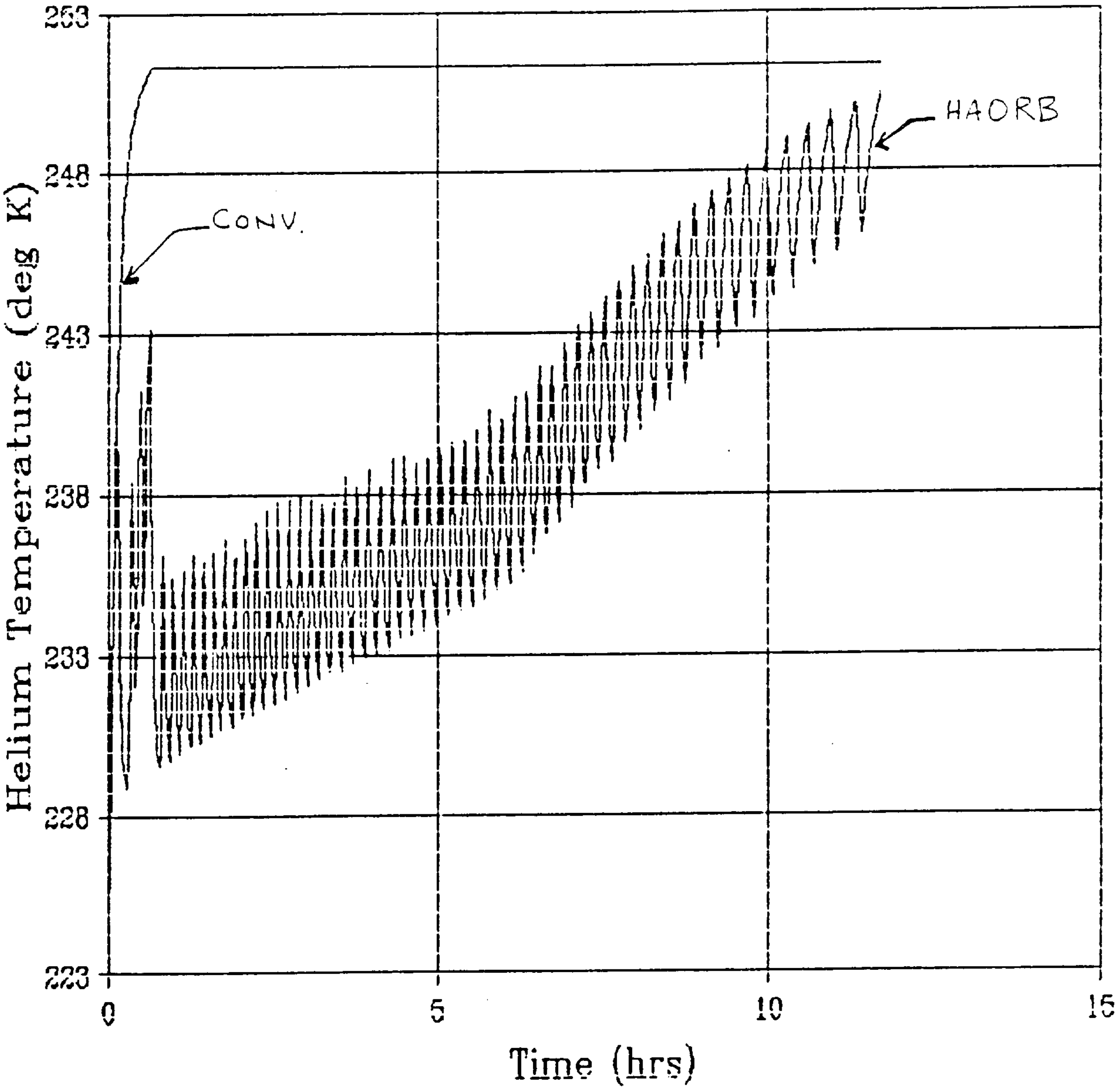

Figure 3. Helium Temperatures of the HAORB and the Conventional Balloon versus Time

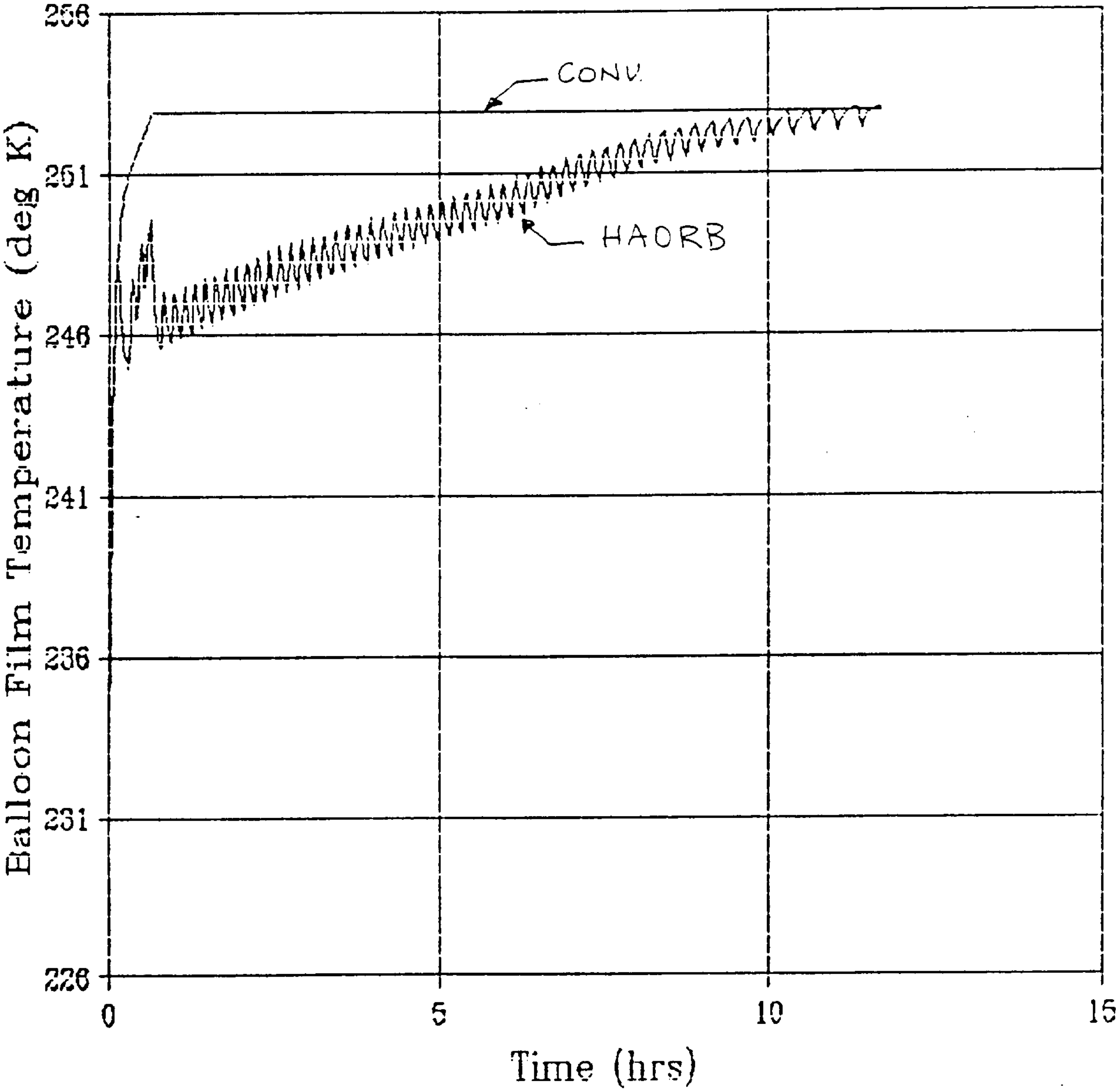

Figure 4. Balloon Film Temperature of the HAORB and the Conventional Balloon versus Time

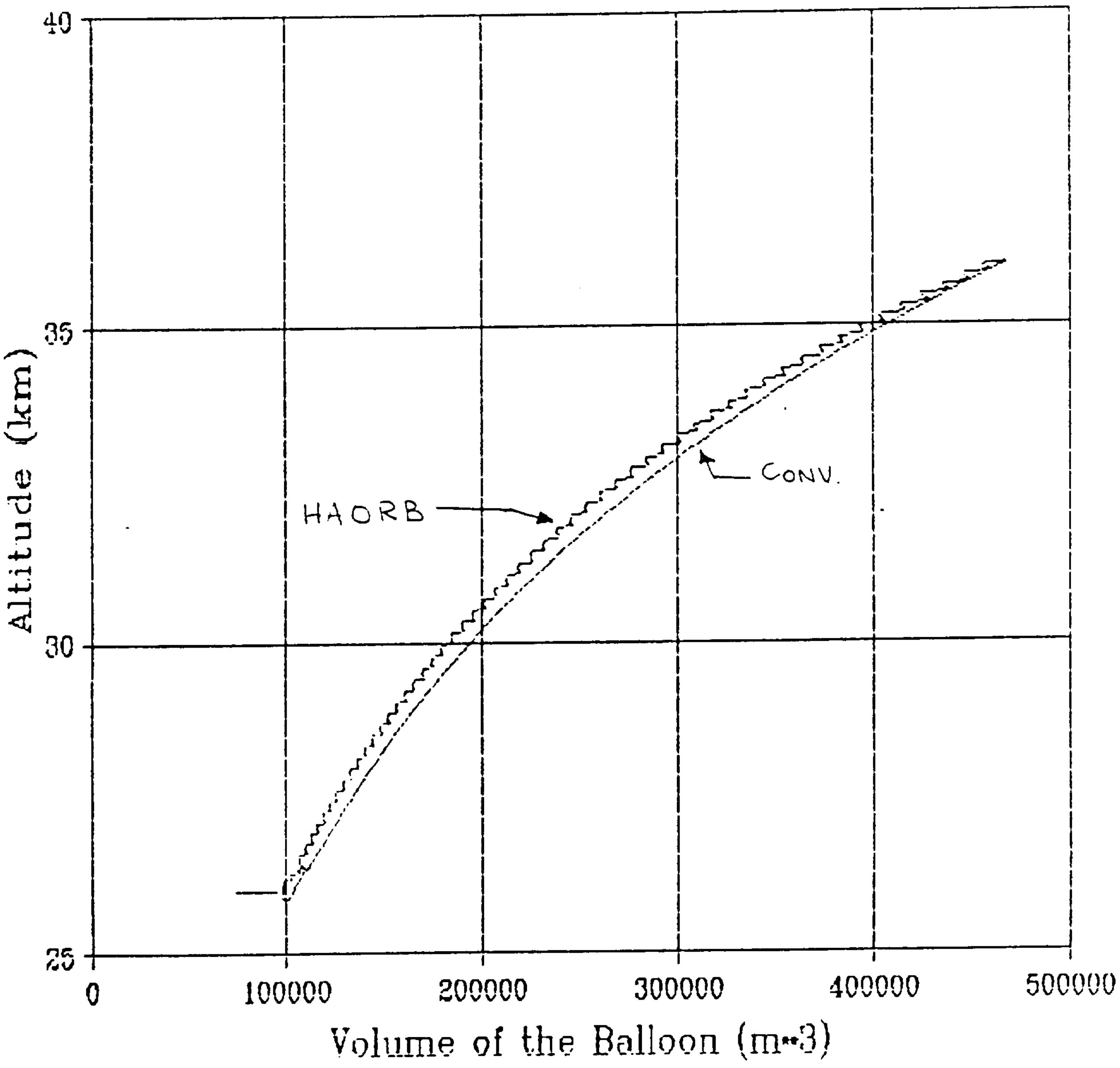

Figure 5. Altitude versus Volume of the HAORB and Volume of the Conventional Balloon

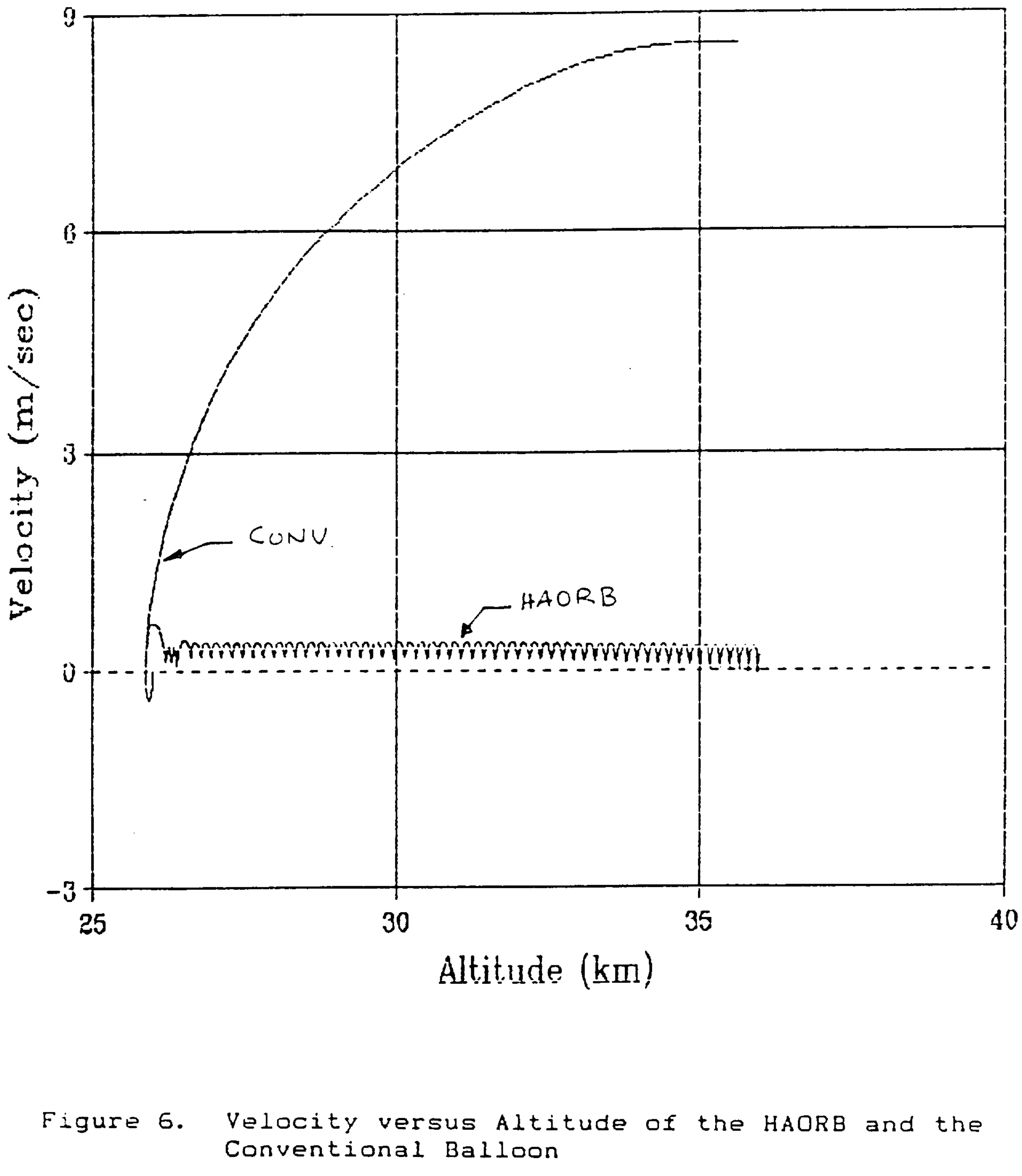

Figure 6. Velocity versus Altitude of the HAORB and the Conventional Balloon

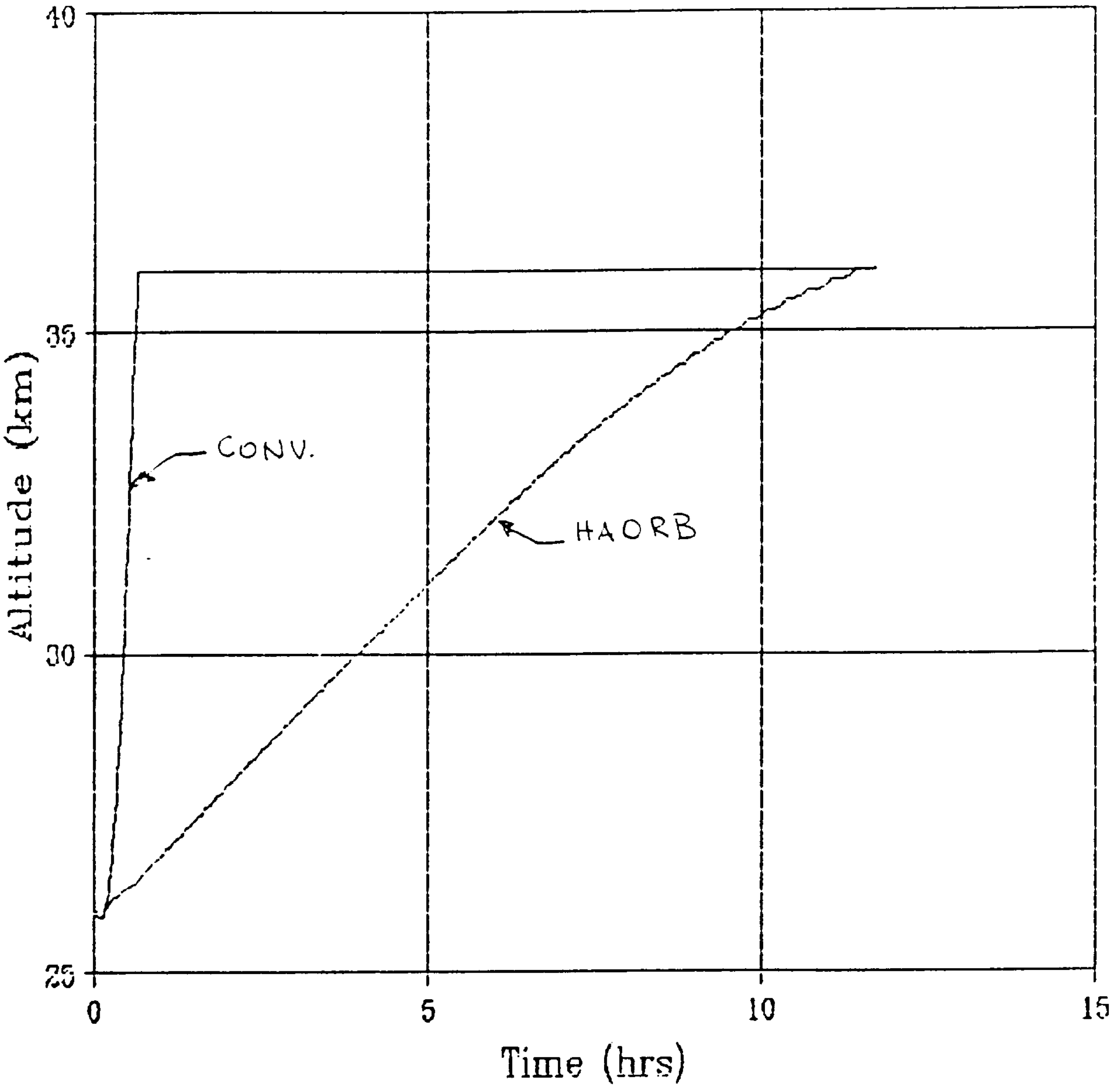

Figure 7. Altitude versus Time of the HAORB and the Conventional Balloon

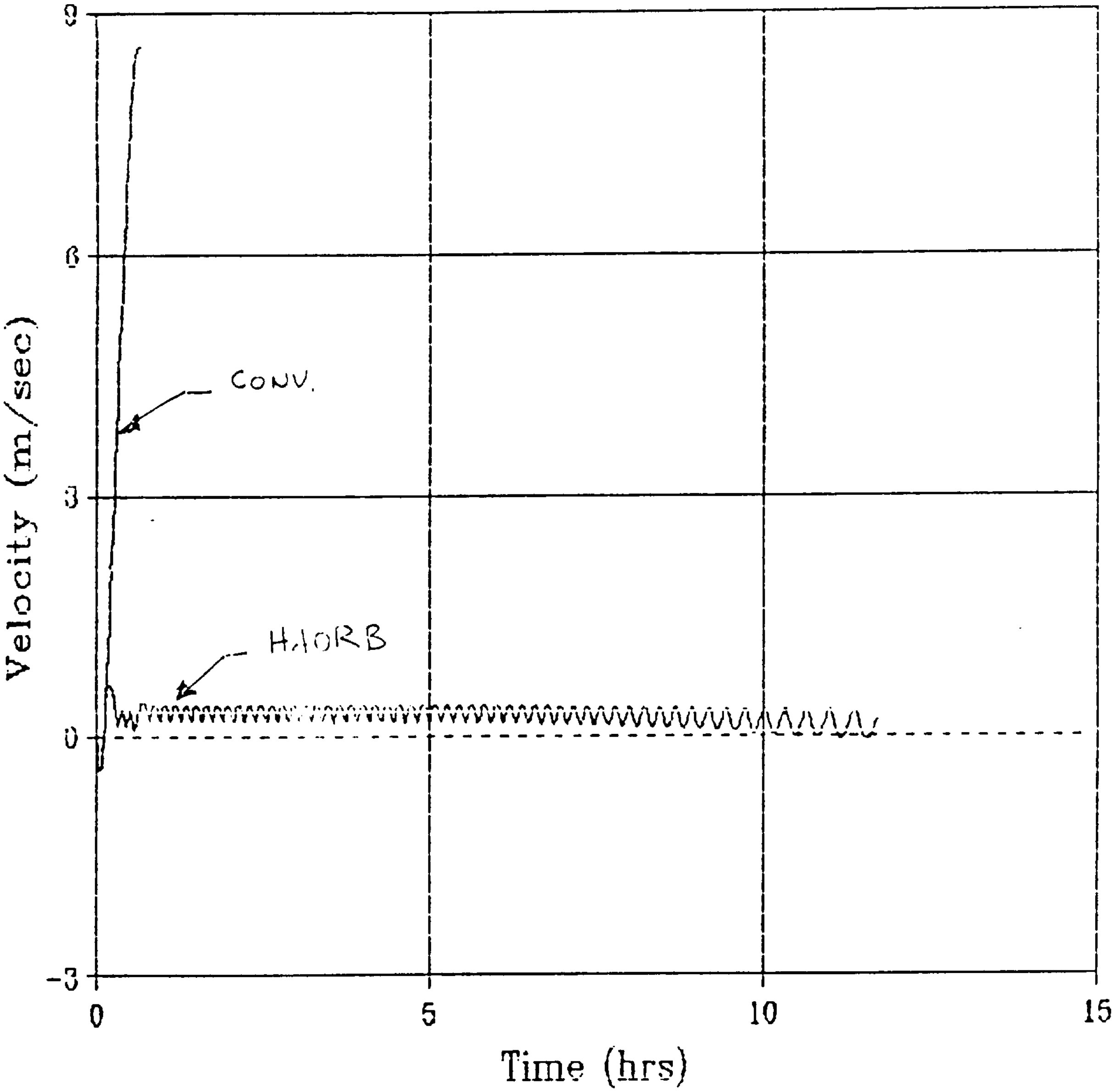

Figure 8. Velocity of the HAORB and the Conventional Balloon versus Time

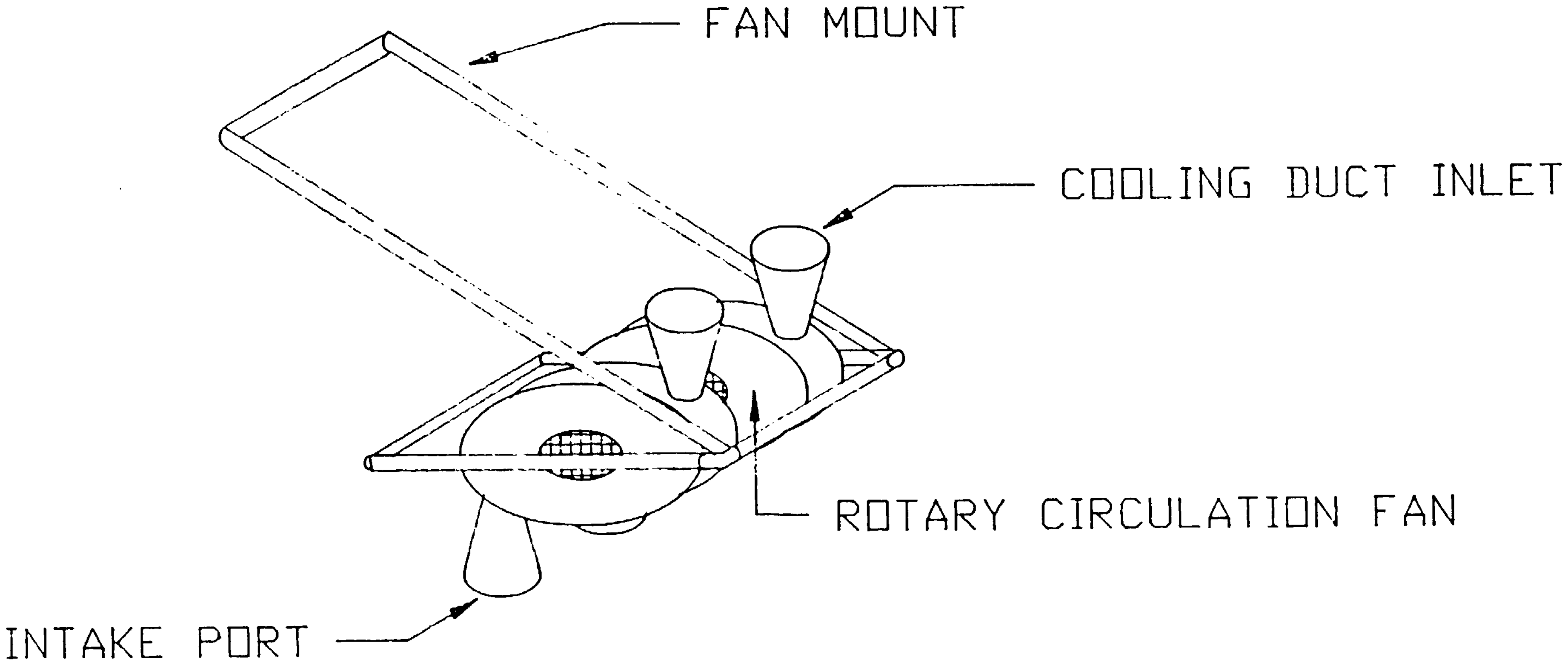

Figure 9a. Configuration of the Fan System

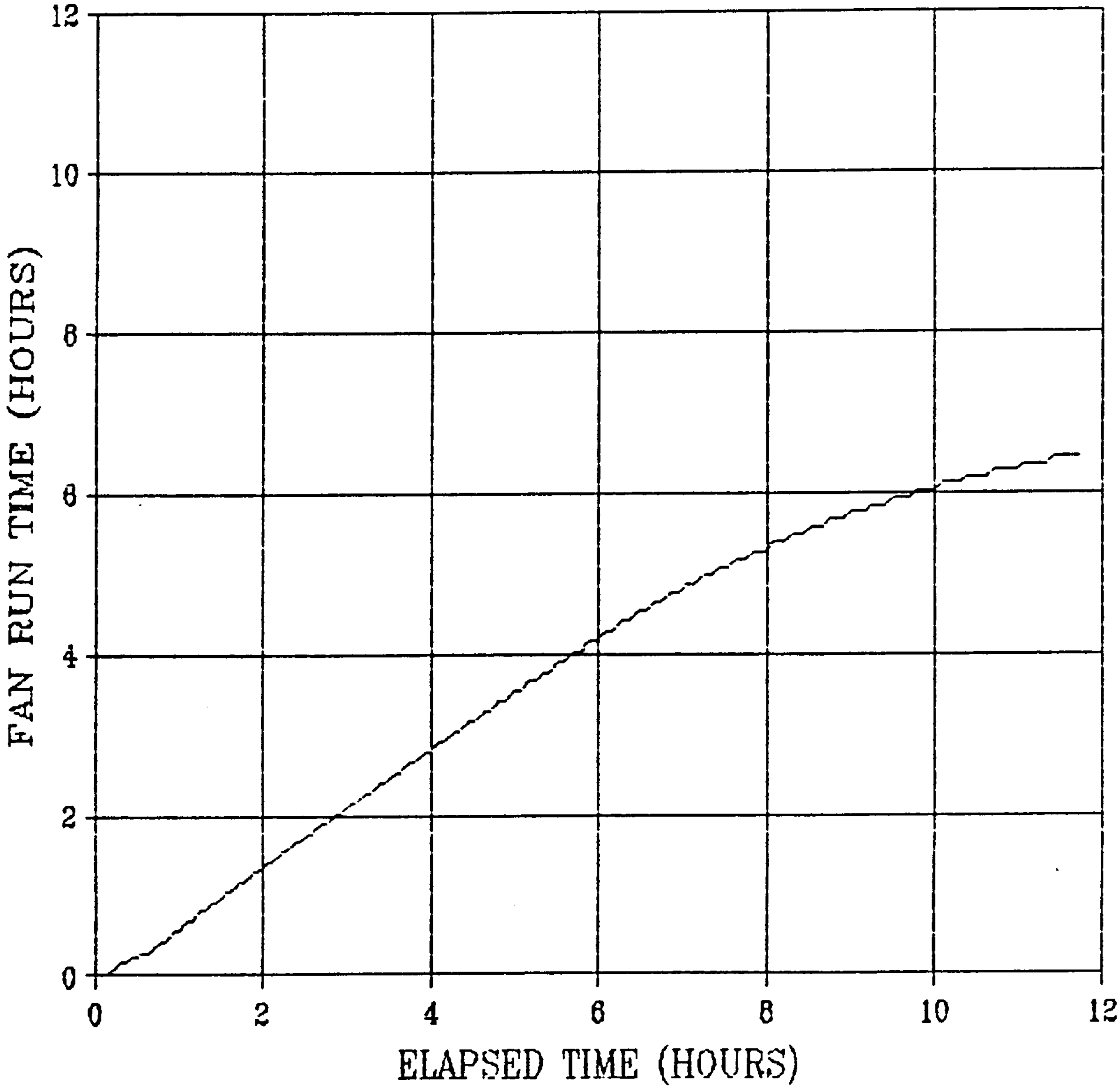

Figure 9b. Fan Run Time versus Elapsed Time

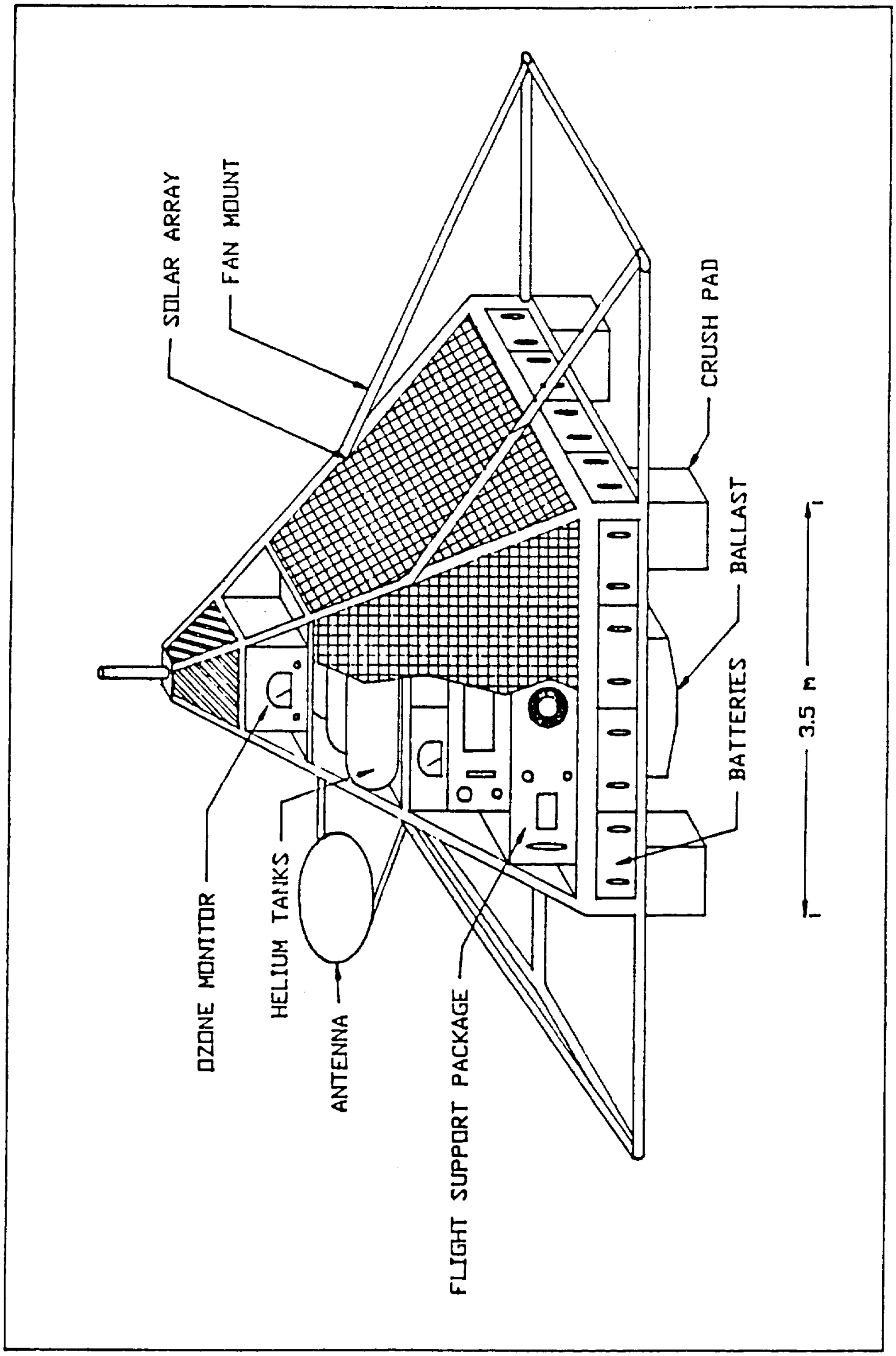

Figure 10. Configuration of the Gondola Structure

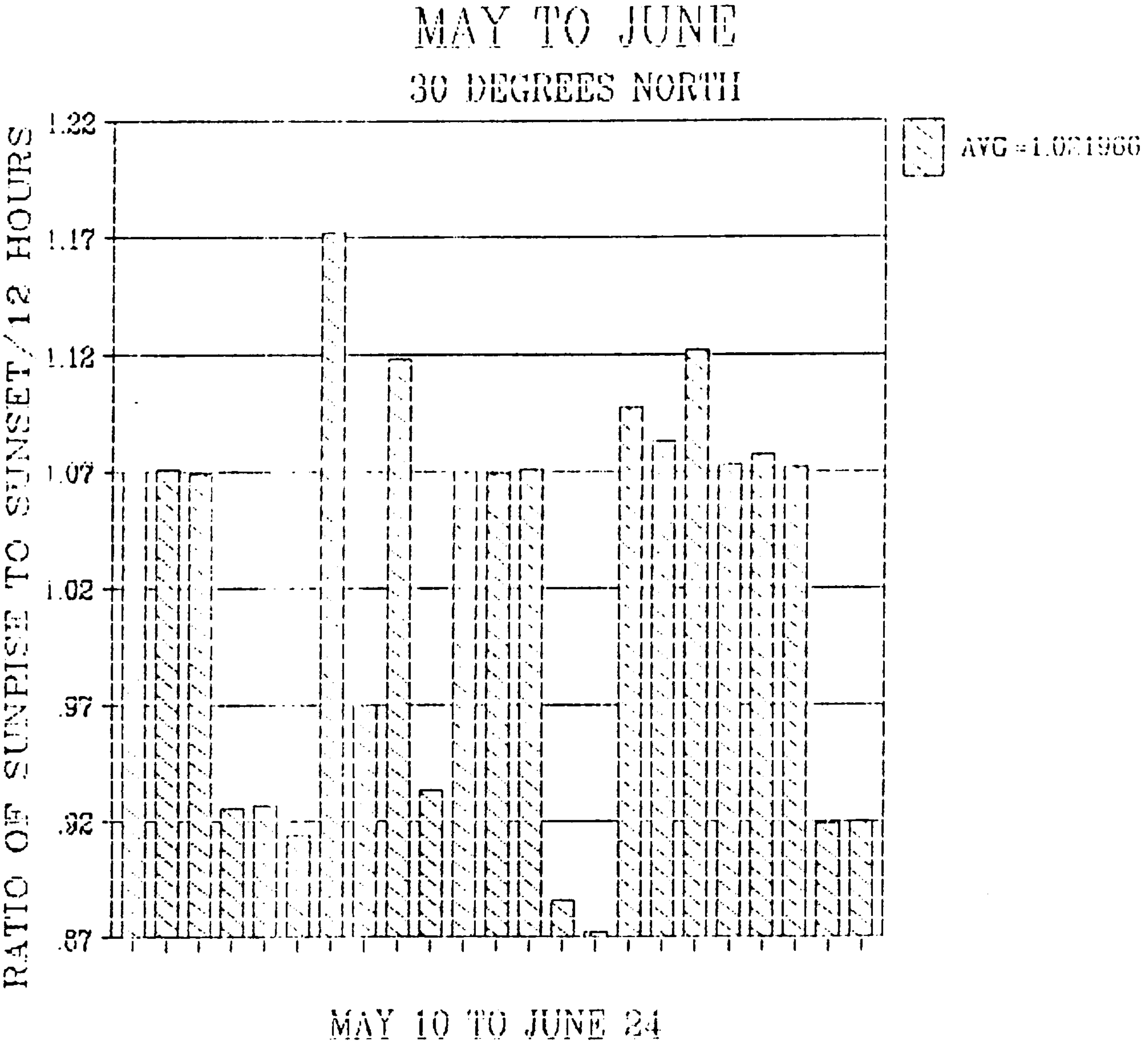

Figure 11. Ratio of Sunrise to Sunset/12 hours for Spring Launch Dates

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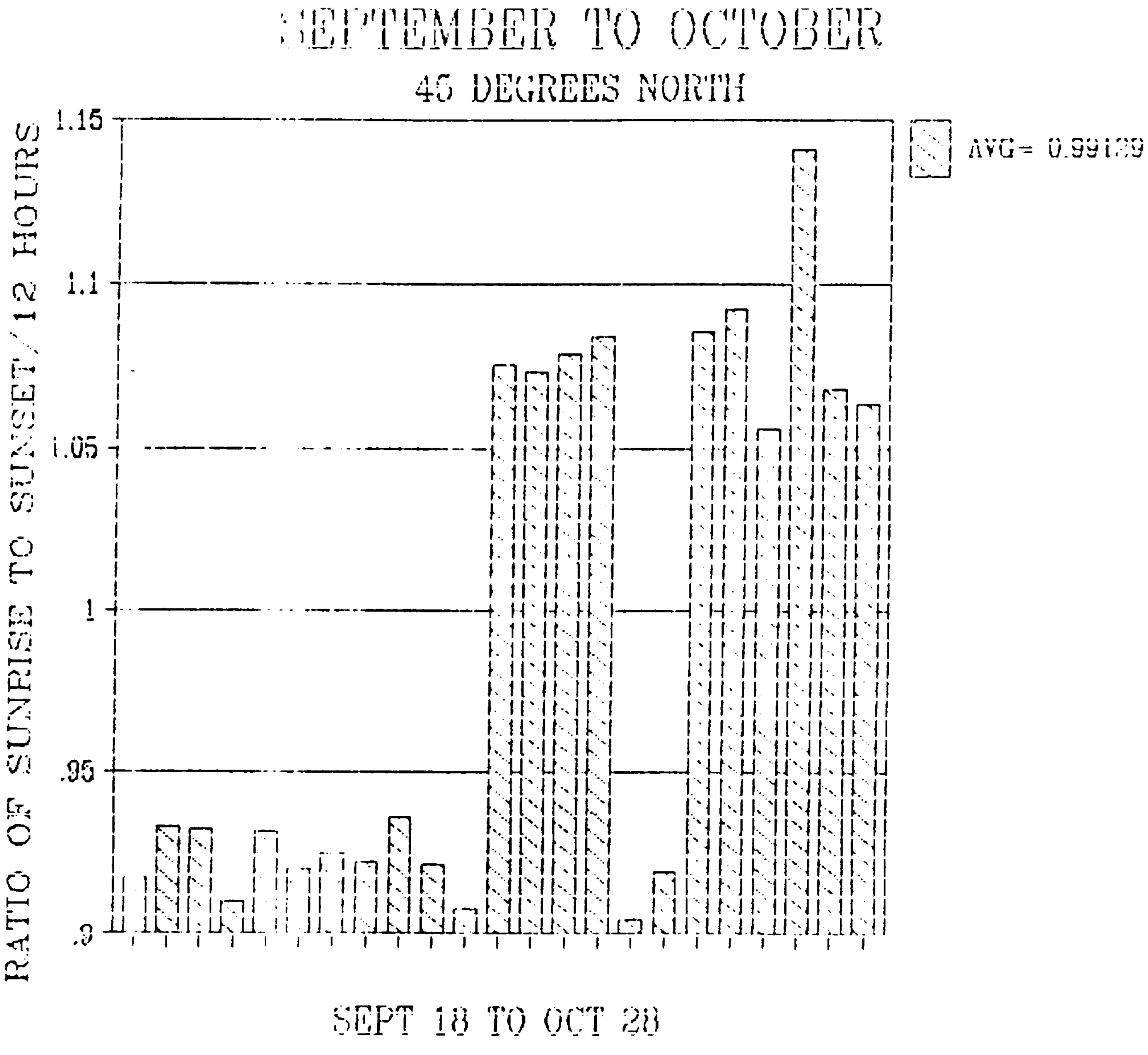

Figure 12. Ratio of Sunrise to Sunset/12 hours for Fall Launch Dates

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OF POOR QUALITY

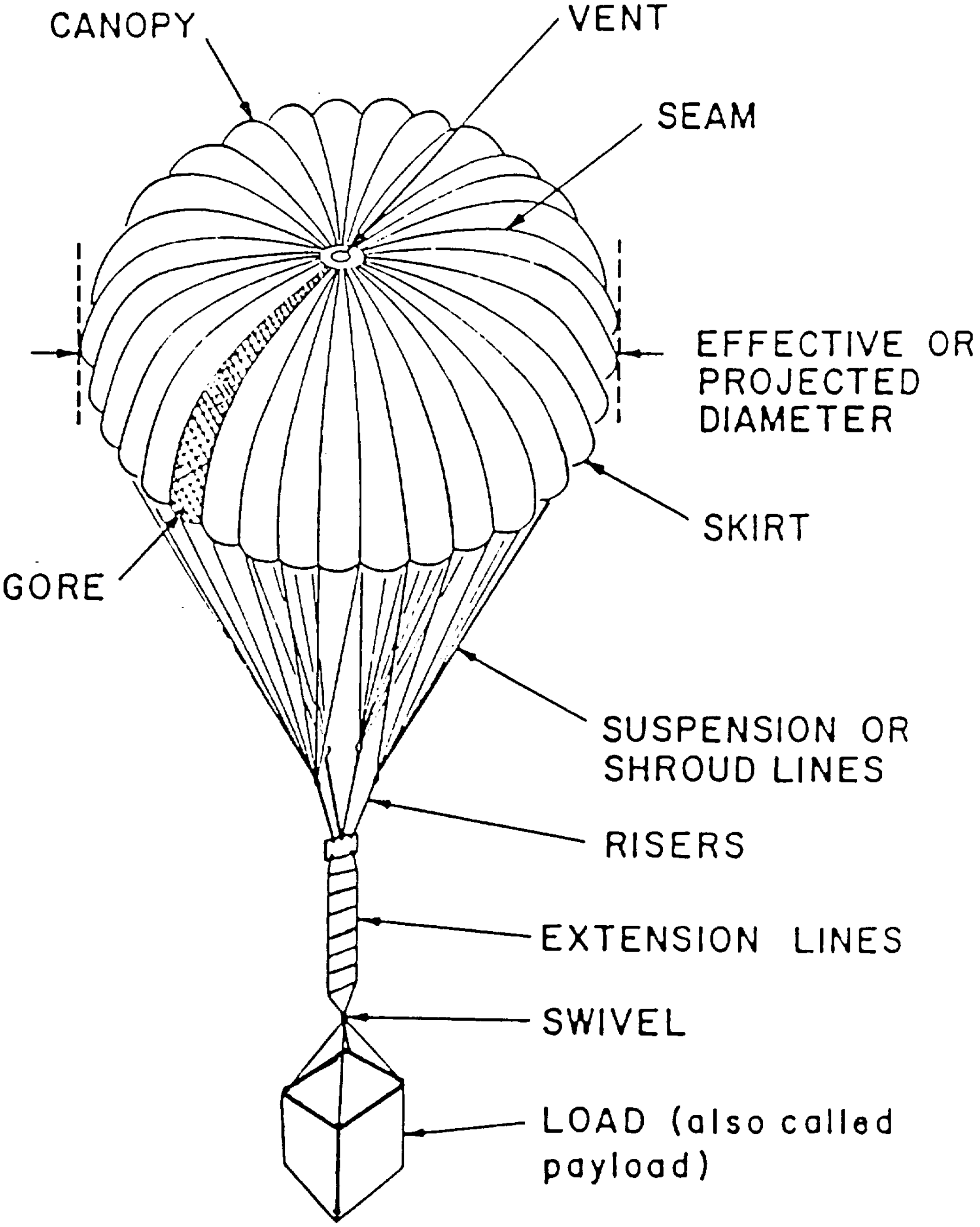

Figure 13. Parachute Nomenclature (2)

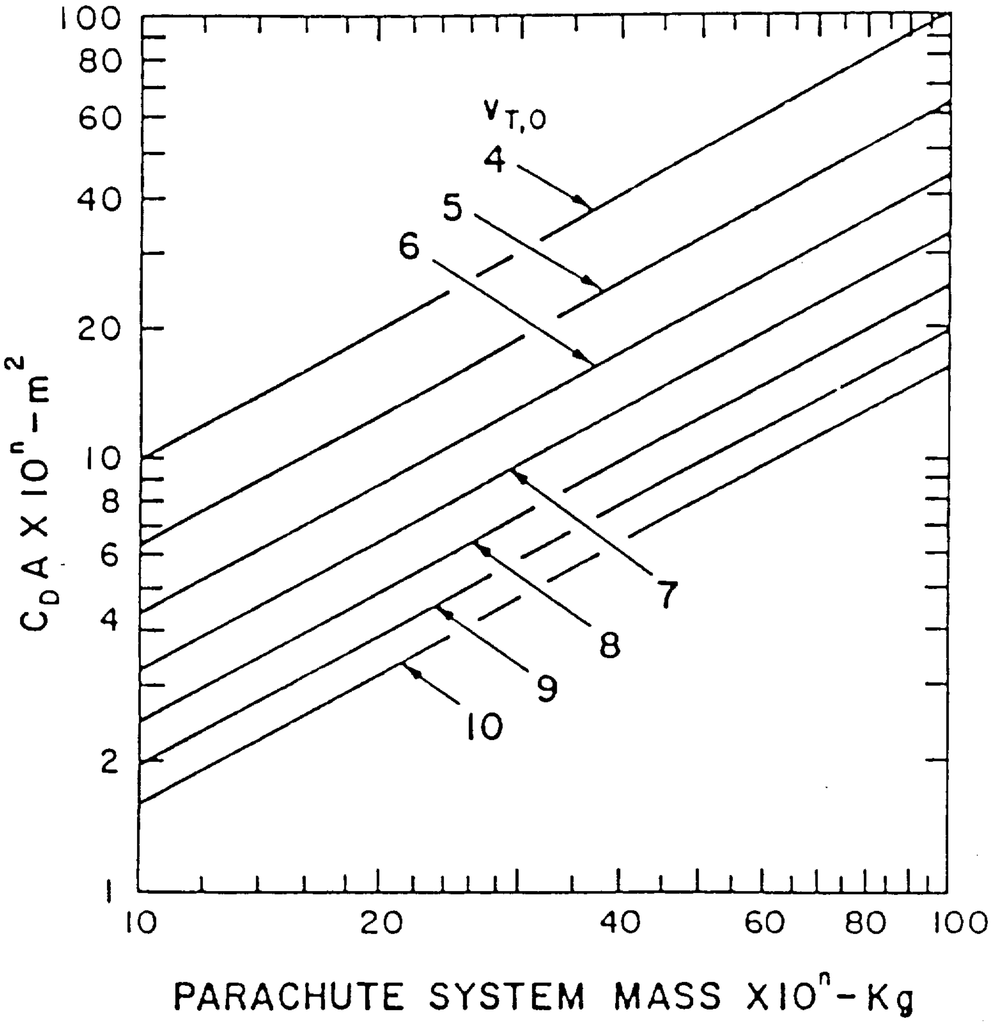

Figure 14. Sea Level Terminal Velocity of a Parachute as a Function of Parachute System Mass and the Product of Parachute Area and Drag Coefficient (Numbers on the abscissa and ordinate maybe concurrently multiplied by any factor 10^n to cover all non-zero values.) (2)

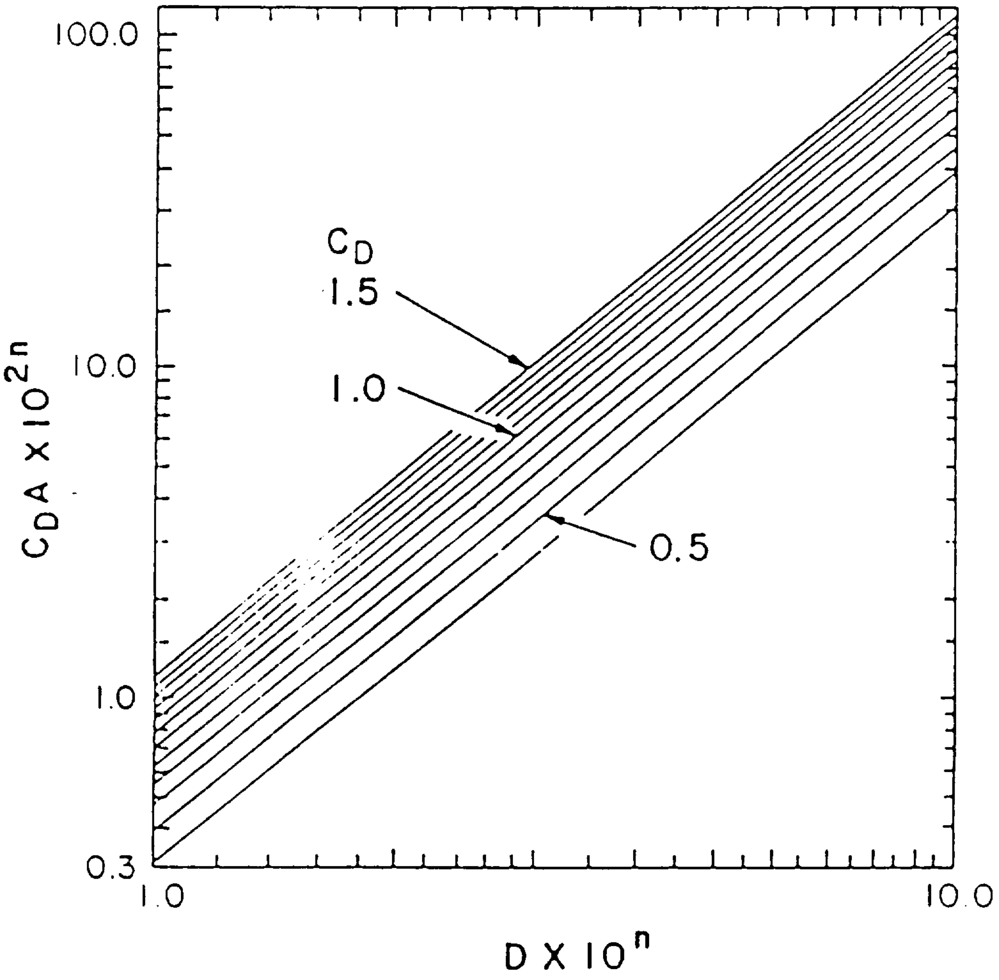

Figure 15. Nominal Diameter of a Parachute as a Function of Area and Drag Coefficient. (Numbers on the ordinate maybe multiplied by 10^{n} if numbers on the abscissa are concurrently multiplied by 10^{2n} to cover all non-zero values.) (2)

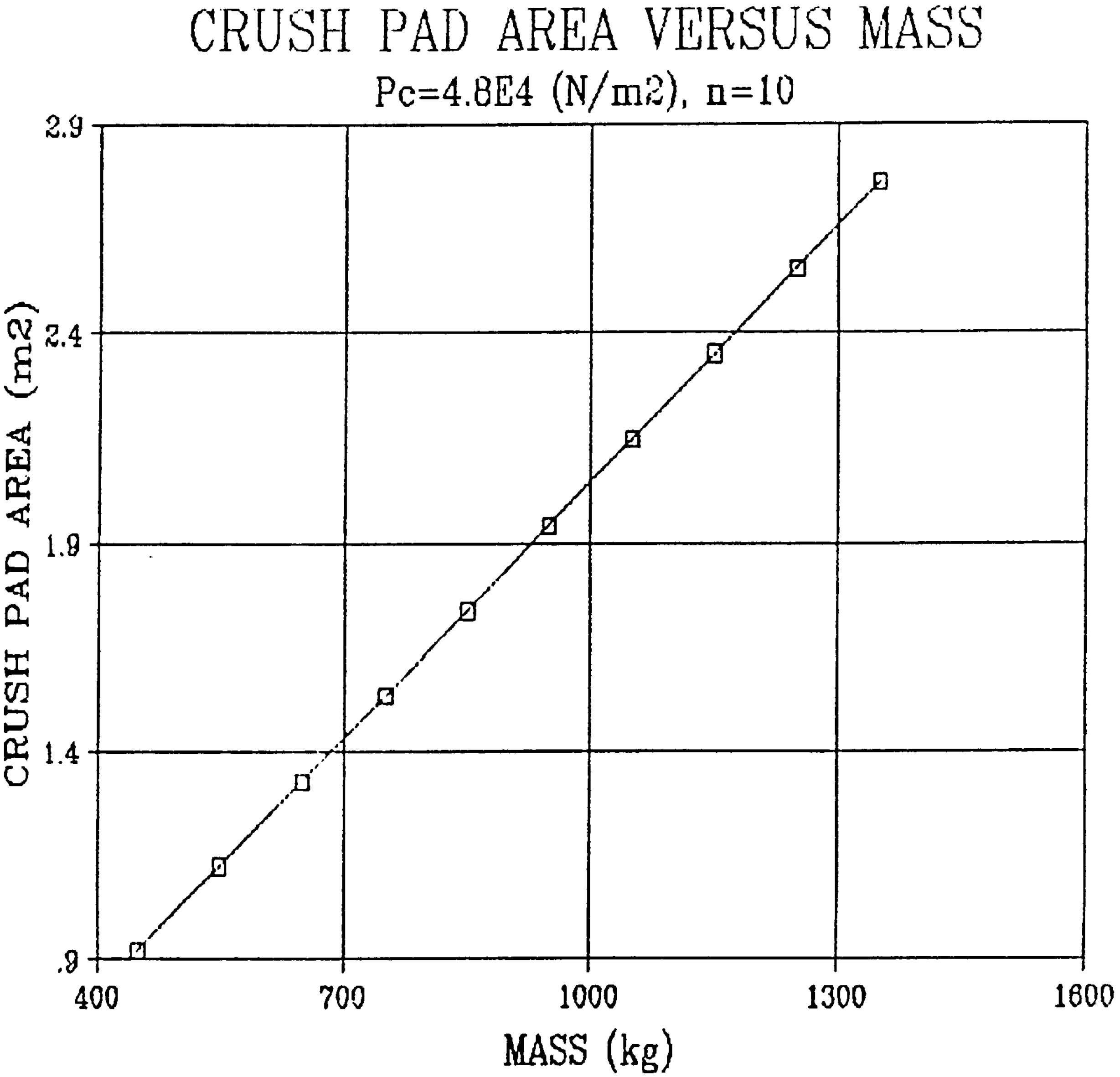

Figure 16. Crush Pad Area versus Payload Mass

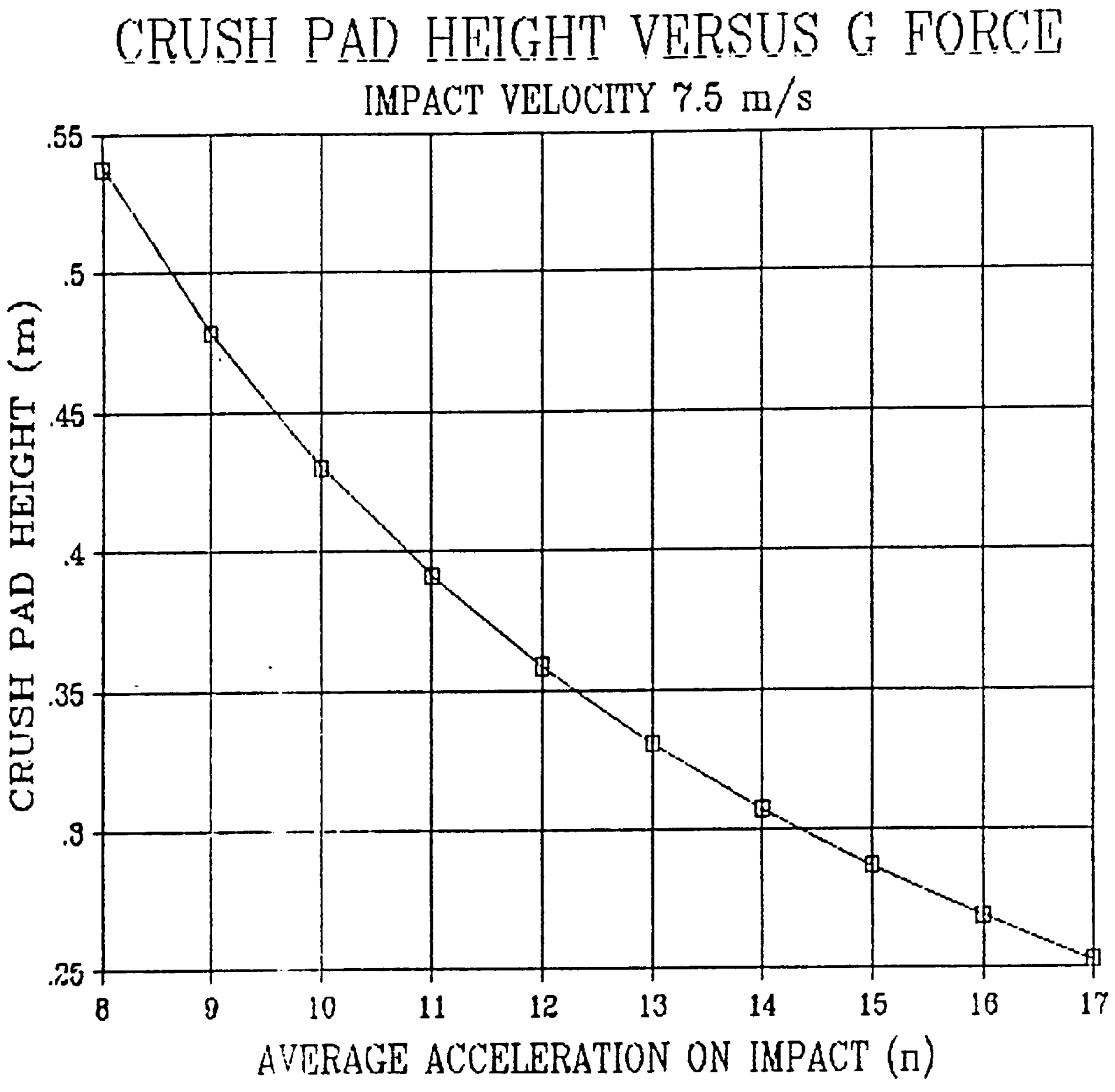

Figure 17. Crush Pad Height versus Average Acceleration on Impact

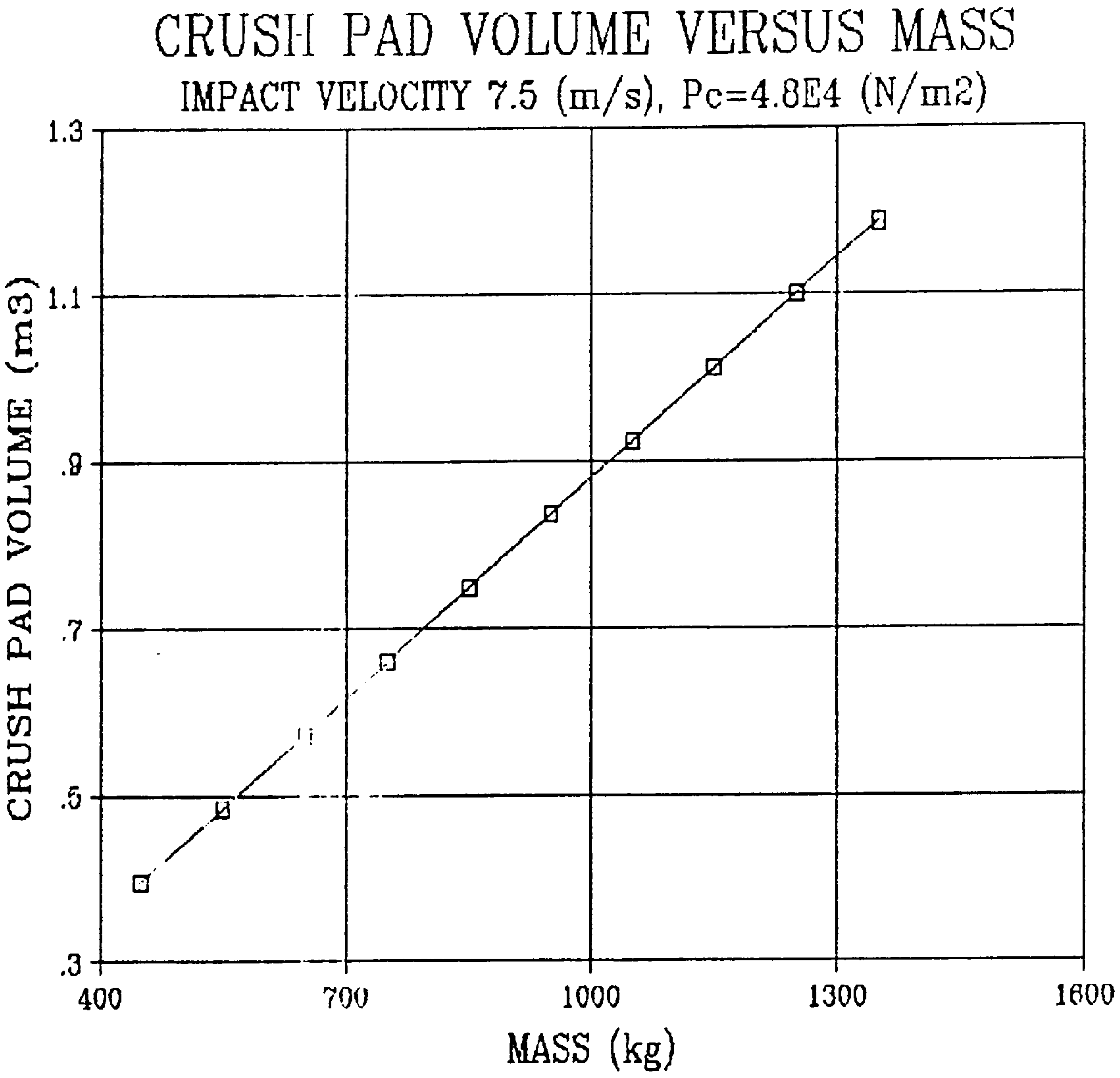

Figure 18. Crush Pad Volume versus Payload Mass

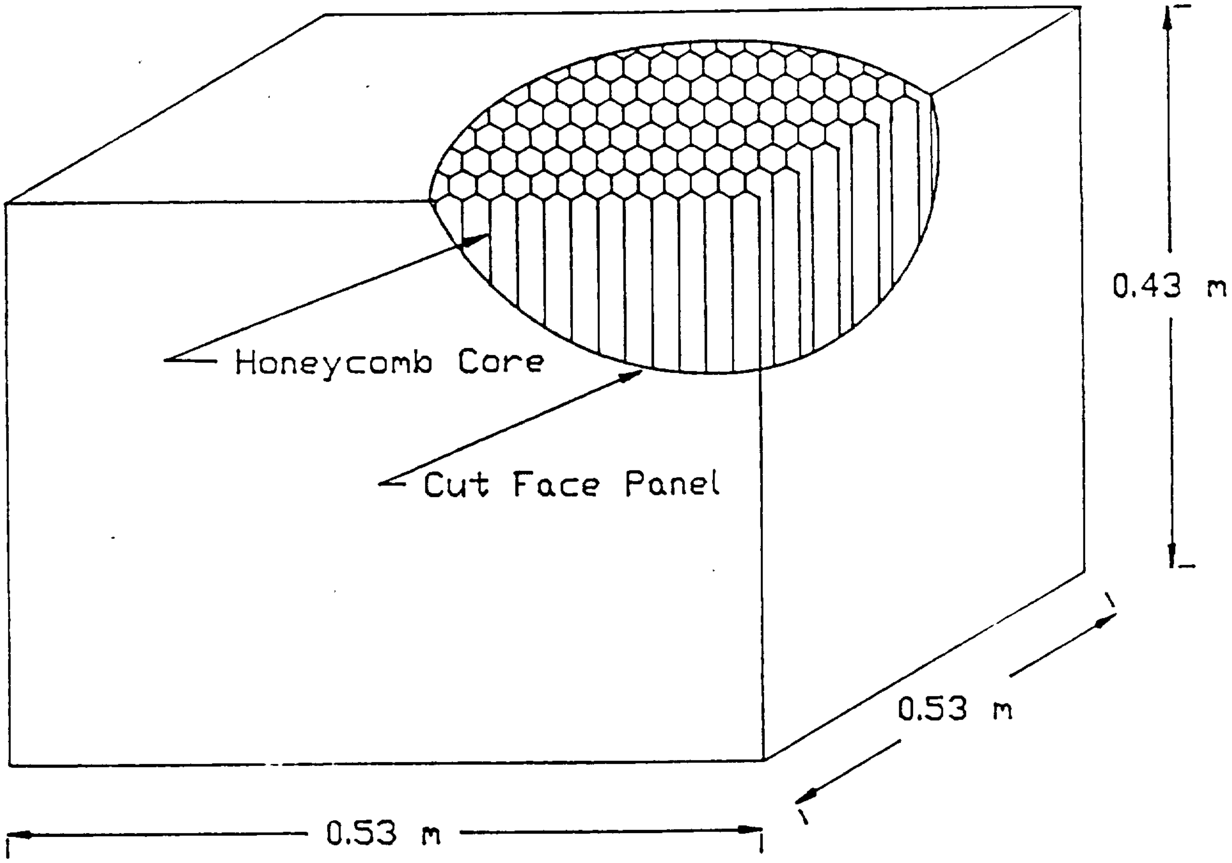

Figure 19. Schematic of the Crush Pad

APPENDIX A

(FORTRAN Program)

```
C**********************************************************************
C
C     PROGRAMMED BY:  TIMOTHY A. CAUTHEN
C                     LESLIE A. DANIEL
C                     STACEY G. ROCK
C
C     DATE:  MAR 06,1990
C
C**********************************************************************
C     THIS PROGRAM IS DESIGNED TO CALCULATE SMALL CHANGES IN THE
C     TEMPERATURE, VELOCITY, AND VOLUME OF THE HAORB.
C**********************************************************************
      DIMENSION PA(1201), TA(1201),ALT(1201)
      REAL MASS,MASSA,KF,KG
      OPEN(UNIT=54,FILE='HEATOUT.DAT',STATUS='OLD')
      OPEN(UNIT=64,FILE='COMP1.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=65,FILE='COMP2.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=66,FILE='COMP3.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=68,FILE='COMP4.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=70,FILE='COMP6.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=71,FILE='COMP7.DAT',STATUS='UNKNOWN')
C**********************************************************************
C
C     SYMBOL GLOSSARY
C
C     ACCEL = THE ACCELERATION OF THE HAORB
C     ACCELA = THE ACTUAL ACCELERATION WITH FANS
C     ALT = ALTITUDE FOR STANDARD ATMOSPHERE
C     AS = SURFACE AREA OF THE COOLING DUCTS
C     B = THE BOUYANT FORCE
C     BA = BOUYANT FORCE WITH FANS
C     CT = CHANNEL THICKNESS
C     AD = CROSS SECTIONAL AREA OF BALLOON WITH NO FANS
C     ADA = CROSS SECTIONAL AREA OF BALLOON WITH FANS
C     DIFF = TF - TG
C     DIFFA = TFA - TGA
C     DRAG = TOTAL DRAG OF BALLOON WITH NO FANS
C     DRAGA = TOTAL DRAG OF BALLOON WITH FANS
C     DT = THE TIME INCREMENT FOR INTEGRATION
C     FLOW = THE MASS FLOW REQUIRED BY THE FANS TO REMOVE Q1
C     HA = THE CONVECTION COEFFICIENT OF AIR
C     HG = THE NATURAL CONVECTION COEFFICIENT OF HELIUM
C     KF = THE FILM CONDUCTION HEAT TRANSFER COEFFICIENT
C     KG = THE GAS CONDUCTION HEAT TRANSFER COEFFICIENT
C     MASS = THE INITIAL CHARGE OF HELIUM IN BALLOON WITH NO FANS
C     MASSA = THE INITIAL CHARGE OF HELIUM IN BALLOON WITH FANS
C     PA = THE STANDARD ATMOSHERIC PRESSURE
C     PATM = PRESSURE AT ALTITUDE WITH NO FANS
C     PATMA = PRESSURE AT ALTITUDE WITH FANS
C     Q1A = THE ACTUAL HEAT TRANSFER TO THE GAS
C     Q1 = CONVECTION HEAT TRANSFER INSIDE THE BALLOON
C     Q2 = RATE OF ABSORBTION OF DIRECT AND REFLECTED SOLAR RADIATION
C     Q2A = RATE OF ABSORBTION WITH FANS
C     Q3 = RATE OF ABSORBTION OF INFRARED RADIATION
C     Q3A = RATE OF ABSORPTION OF INFRARED RADIATION WITH FANS
C     Q4 = RATE OF HEAT TRANSFER FROM THE ATMOSPHERE TO THE SKIN
C     Q4A = THE ACTUAL HEAT TRANSFER FROM THE ATM TO THE SKIN
C     Q5 = RATE OF RADIANT HEAT TRANSFER FROM THE SKIN
C     Q5A = RATE OF RADIANT HEAT TRANSFER FROM THE SKIN WITH FANS
C
C
C
```

```
C
C
C     QFANF = RATE OF HEAT TRANSFER FROM THE FILM BY THE FANS
C     QFANG = RATE OF HEAT TRANSFER FROM THE GAS BY THE FANS
C     QT = RATE OF HEAT TRANSFER TO THE BALLOON FILM
C     QTA = ACTUAL RATE OF HEAT TRANSFER TO THE BALLOON FILM
C     RG = THE GAS CONSTANT FOR HELIUM
C     RHOA = DENSITY AT ALTITUDE WITH NO FANS
C     RHOAA = DENSITY AT ALTITUDE WITH FANS
C     RHOG = DENSITY OF HELIUM AT ALTITUDE WITH NO FANS
C     RHOGA = DENSITY OF HELIUM AT ALTITUDE WITH FANS
C     TA = THE STANDARD ATMOSPHERIC TEMPERATURE
C     TATM = THE TEMPERATURE AT ALTITUDE WITH NO FANS
C     TATMA = THE TEMPERATURE AT ALTITUDE WITH FANS
C     TF = AVERAGE TEMPERATURE OF THE FILM
C     TFA = AVERAGE FILM TEMPERATURE WITH FANS
C     TG = UNIFORM TEMPERATURE OF THE HELIUM
C     TGA = UNIFORM TEMPERATURE OF THE HELIUM WITH FANS
C     THICK = THE THICKNESS OF THE BALLOON FILM
C     TIME = TIME ELAPSED
C     UA = VISCOSITY OF AIR
C     V = THE VELOCITY OF THE HAORB
C     VA = VELOCITY OF HAORB WITH FANS
C     VG = VOLUME OF THE HELIUM
C     VGA = VOLUME OF HELIUM WITH FANS
C     VFLOW = THE VOLUMETRIC FLOW RATE REQD OF THE FANS TO REMOVE Q1
C     VGMAX = THE MAXIMUM VOLUME OF THE FULLY INFLATED BALLOON
C     W = THE WEIGHT OF THE PAYLOAD AND THE BALLOON FILM
C     Z = ALTITUDE WITH NO FANS
C     ZA = ALTITUDE WITH FANS
C
C
C
C***********************************************************************
C     THIS CONFIGURATION IS FOR 4 TUBES ALONG THE SURFACE OF THE BALLOON
C***********************************************************************
      AS=1474.6*2.0
      CT=.0578
      KF=.19
      KG=.13
      HA=8.23*KF/(2.*CT)
      HG=126.665
      MASS=448.0
      MASSA=448.0
      TSUMFAN=0.0
      PI=3.14159
      RG=2077.2
      THICK=4.572E-4
      W=28468.
      WRITE(*,*)'READING IN DATA.'
      DO 100 I=1,1201
      READ(54,*) PA(I),TA(I),ALT(I)
100   CONTINUE
      WRITE(*,*)'CALCULATING VALUES.'
      WRITE(64,500)
      WRITE(65,550)
      WRITE(66,600)
      WRITE(68,700)
      WRITE(70,800)
      WRITE(71,850)
C     ASSUME INSTANTANEOUS CHANGE IN TEMPERATURES AT 24400 METERS
C     FILM TEMPERATURE IS 5 DEGREES HIGHER THAN ATMOSPHERIC
C     AND HELIUM TEMPERATURE IS 2.5 DEGREES HIGHER THAN ATMOSPHERIC
C
C
```

```
C
C
C
C     SET INITIAL CONDITIONS
C
      MM=1
      JJ=1
      TF=TA(1)+5.
      TFA=TA(1)+5.
      TG=TA(1)+2.5
      TGA=TA(1)+2.5
      ACCELA=0.0
      ACCEL=0.0
      VA=0.0
      V=0.0
      Z=26000.
      ZA=Z
      UA=143.83E-7
      VGMAX=467228.
      VG=MASS*RG*TGA/PA(1)
      VGA=VG
      IDT=1
      DT=1.0
C
C     INTEGRATION BEGINS HERE
C
      N=1
      DO 10 K=1,43200,IDT
      V=V+ACCEL*DT
      VA=VA+ACCELA*DT
      Z=Z+V*DT+.5*ACCEL*DT**2
      ZA=ZA+VA*DT+.5*ACCELA*DT**2
      IF(V.LT.0.) THEN
      JJ=1
      ENDIF
      DO 16 J=JJ,1200
      IF(VG.EQ.VGMAX) THEN
      GOTO 17
      ENDIF
      IF(Z.GE.ALT(J).AND.Z.LT.ALT(J+1))THEN
      PATM=(PA(J)+PA(J+1))/2.0
      TATM=(TA(J)+TA(J+1))/2.0
      GOTO 17
      ENDIF
   16 CONTINUE
   17 JJ=J
      IF(VA.LT.0.) THEN
      MM=1
      ENDIF
      DO 18 M=MM,1200
      IF(ZA.GE.ALT(M).AND.ZA.LT.ALT(M+1))THEN
      PATMA=(PA(M)+PA(M+1))/2.0
      TATMA=(TA(M)+TA(M+1))/2.0
      GOTO 19
      ENDIF
   18 CONTINUE
C
C
C
C
C
C     THE VALUES ARE COMPUTED EVERY SECOND, BUT WRITTEN
C     OUT EVERY 60 SECONDS
C
C
```

```
C
C
C
  19 MM=M
      RHOA=PATM/(287.05*TATM)
      RHOAA=PATMA/(287.05*TATMA)
      RHOG=PATM/(RG*TATM)
      RHOGA=PATMA/(RG*TATMA)
      IF(VG.GE.VGMAX)THEN
      GOTO 33
      ENDIF
      DIFF=TF-TG
      IF(DIFF.LE.0.)THEN
      DIFF=ABS(DIFF)
      Q1=-.628*VG**(2./3.)*KG*(DIFF)*((RHOG)**2*9.81*(DIFF)*.682/
     &(170.E-7)**2/TG)**(1./3.)
      GOTO 22
      ENDIF
      Q1=.628*VG**(2./3.)*KG*(DIFF)*((RHOG)**2*9.81*(DIFF)*.682/
     &(170.E-7)**2/TG)**(1./3.)
  22 Q2=322.9082*VG**(2./3.)+(247.61-.0693273*Z**(.5))*VG**(2./3.)
      Q3=171.46503*VG**(2./3.)
      Q4=.15471*VG**(1./3.)*(TF-TATM)*(1.+(509792607.4*RHOA**2*
     &VG*ABS(TF-TATM)/TATM)**.25)
      Q5=1.7641192E-07*VG**(2./3.)*TF**4.
      QT=Q2+Q3-Q1-Q4-Q5
      DELTF=QT*THICK/((PI*4.*KF)*(3.*VG/(4.*PI))**(2./3.))
      DELTG=Q1/((HG*4.*PI)*(3.*VG/(4.*PI))**(2./3.))
C
C     THE BELOW EQUATIONS ALLOW COMPUTATION OF REQUIRED FAN SIZE (CFM)
C
C     FLOW=Q1/(1006.0*(TF-TATM)
C     VFLOW=FLOW*2118.88/RHOA
C
C     THE BELOW EQUATIONS ARE USED AFTER SETTING THE SIZE OF THE FANS
C
  33 CHECKA=TGA-TATMA
      CHECK=TFA-TATMA
      IF(CHECK.LT..1.OR.CHECKA.LT..1)THEN
         QFANF=0.0
         QFANG=0.0
         ELSE
         IF(VA.GT..27) THEN
           TSUMFAN=TSUMFAN+1.
           QFANF=HA*AS*((TATMA-TFA+.0001)/ALOG(.0001/(TFA-TATMA)))
           QFANG=HA*AS*((TATMA-TGA+.0001)/ALOG(.0001/(TGA-TATMA)))
           GOTO 13
         ELSE
         IF(VA.LT..20) THEN
           QFANF=0.0
           QFANG=0.0
           GOTO 13
         ENDIF
           IF(ACCELA.LT.0.) THEN
              QFANF=HA*AS*((TATMA-TFA+.0001)/ALOG(.0001/(TFA-TATMA)))
              QFANG=HA*AS*((TATMA-TGA+.0001)/ALOG(.0001/(TGA-TATMA)))
              TSUMFAN=TSUMFAN+1.
              GOTO 13
           ELSE
              QFANF=0.0
              QFANG=0.0
C
C
C
C
```

```
C
C
C
C
           ENDIF
         ENDIF
      ENDIF
   13 DIFFA=TFA-TGA
      IF(DIFFA.LT.0.)THEN
      DIFFA=ABS(DIFFA)
      Q1A=-.628*VGA**(2./3.)*KG*(DIFFA)*((RHOGA)**2*9.81*(DIFFA)*.682
     &/(170.E-7)**2/TGA)**(1./3.)
      GOTO 23
      ENDIF
      Q1A=.628*VGA**(2./3.)*KG*(TFA-TGA)*((RHOGA)**2*9.81*(TFA-TGA)
     &*.682/(170.E-7)**2/TGA)**(1./3.)
   23 Q2A=322.9082*VGA**(2./3.)+(247.61-.0693273*ZA**(.5))*VGA**(2./3.)
      Q3A=171.46503*VGA**(2./3.)
      Q4A=.15471*VGA**(1./3.)*(TFA-TATMA)*(1.+(509792607.4*RHOAA**2*
     &VGA*ABS(TFA-TATMA)/TATMA)**.25)
      Q5A=1.7641192E-07*VGA**(2./3.)*TFA**4.
      QTA=Q2A+Q3A-Q5A-Q4A-Q1A-QFANF
      DELTFA=QTA*THICK/((PI*4.*KF)*(3.*VGA/(4.*PI))**(2./3.))
      DELTGA=(Q1A-QFANG-QFANF)/((HG*4.*PI)*(3.*VGA/(4.*PI))**(2./3.))
      TIME=FLOAT(K-1)/60.
      IF(K.EQ.1)THEN
      GOTO 210
      ENDIF
      IF(N.EQ.61)THEN
      N=1
      TSUM=TSUMFAN/60.
  210 WRITE(64,501)TIME,Z,ZA,V,VA
      WRITE(65,551)TIME,ACCEL,ACCELA,Q1,Q1A
      WRITE(66,601)Z,ZA,VG,VGA
      WRITE(68,701)TIME,Q1,Q1A,QT,QTA
      WRITE(70,801)TIME,QFANF,QFANG,TSUM
      WRITE(71,851)TIME,TG,TGA,TF,TFA
      ENDIF
      N=N+1
      IF(K.EQ.500.OR.K.EQ.1000.OR.K.EQ.1500)THEN
      PRINT*,K
      ENDIF
      IF(K.EQ.2000.OR.K.EQ.2500.OR.K.EQ.3600)THEN
      PRINT*,K
      ENDIF
      IF(K.EQ.5000.OR.K.EQ.7500.OR.K.EQ.10000)THEN
      PRINT*,K
      ENDIF
      IF(K.EQ.15000.OR.K.EQ.20000.OR.K.EQ.25000)THEN
      PRINT*,K
      ENDIF
      IF(K.EQ.30000.OR.K.EQ.35000.OR.K.EQ.40000)THEN
      PRINT*,K
      ENDIF
      IF(VG.LT.VGMAX)THEN
      TF=TF+DELTF
      TG=TG+DELTG
      VG=MASS*RG*TG/PATM
      AD=PI*(3.*VG/4./PI)**(2./3.)
      DRAG=.5*.3*RHOA*AD*V*V
C
C
C
C
C
```

```
C
C
C
C
      IF(V.LT.0.) THEN
      DRAG=-DRAG
      ENDIF
   44 B=RHOA*VG*9.81*(1.0-RHOG/RHOA)
      ACCEL=(B-W-DRAG)/W/9.8
      ENDIF
      TFA=TFA+DELTFA
      TGA=TGA+DELTGA
      VGA=MASSA*RG*TGA/PATMA
      ADA=PI*(3.*VGA/4./PI)**(2./3.)
      DRAGA=.5*.3*RHOAA*ADA*V*V
      IF(V.LT.0.) THEN
      DRAGA=-DRAGA
      ENDIF
   45 BA=RHOAA*VGA*9.81*(1.0-RHOGA/RHOAA)
      ACCELA=(BA-W-DRAGA)/W/9.8
      IF(VG.GT.VGMAX) THEN
      VG=VGMAX
      ACCEL=0.
      V=0.
      ENDIF
      IF(VGA.GT.VGMAX) THEN
      GOTO 200
      ENDIF
   10 CONTINUE
500   FORMAT(/,'  TIME',3X,'BALLOON ALT.',3X,'HAORB ALT.',3X,'BALLOON VE
     &L.',3X,'HAORB VEL.',/)
550   FORMAT(/,'  TIME',3X,'BALLOON ACC.',3X,'HAORB ACC.',5X,'Q1',5X,'Q1
     &FAN',/)
600   FORMAT(/,3X,'BALLOON ALT.',3X,'HAORB ALT.',3X,'BALLOON VOL.',4X,'H
     &AORB VOL.',/)
700   FORMAT(/,'  TIME',3X,'Q1',7X,'Q1 FAN',8X,'QT',7X,'QT FAN',/)
800   FORMAT(/,'  TIME',3X,'Q FANF',8X,'Q FANG',5X,'FAN RUNTIME',/)
850   FORMAT(/,'  TIME',3X,'TG BALLOON',3X,'TG HAORB',3X,'TF BALLOON',3X
     &,'TF HAORB',/)
501   FORMAT(1X,F6.1,3X,F7.1,3X,F7.1,3X,F7.4,3X,F7.4)
551   FORMAT(1X,F6.1,3X,F7.5,3X,F7.5,3X,F8.1,3X,F8.1)
601   FORMAT(1X,F7.1,3X,F7.1,3X,F8.0,3X,F8.0)
701   FORMAT(1X,F6.1,3X,F8.1,3X,F10.1,3X,F10.1,f10.1)
801   FORMAT(1X,F6.1,3X,F8.1,3X,F7.1,3X,F6.1)
851   FORMAT(1X,F6.1,3X,F7.3,3X,F7.3,3X,F7.3,3X,F7.3)
200   STOP
      END
```