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PRELIMINARY ANALYTICAL INVESTIGATION OF BOOSTER RECOVERY BY USE OF A HOT-AIR BALLOON FOR BOTH DECELERATION AND FINAL RECOVERY

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SUMMARY

An analytical investigation has been made of the flight mechanics, aerodynamic heating, and system weight for a booster recovery system in which a single large balloon is used as both a decelerator for reentry and a buoyant device for final recovery. The balloon was assumed to use ram air for maintenance of inflation and to use burners to heat the internal air to provide buoyancy in the atmosphere at low altitude for final recovery. The specific application of the system investigated was for the recovery of the Saturn S-1C booster.

The study indicated that a balloon made of conventional glass-fiber cloth, treated by a relatively inexpensive process to provide added heat resistance, could withstand the conditions encountered during both the deceleration and the buoyant phases, and that the deceleration levels were within acceptable levels for the booster. A balloon diameter of 275 feet (84 meters), or possibly less, was adequate for the task, and the total recovery-system weight was of the order of 45 000 to 50 000 pounds (20 412 to 22 680 kilograms). The use of a recovery system of this weight would result in a reduction in mission payload weight of about 3.5 percent. Although the subject recovery system appears feasible from the standpoint of factors studied in this investigation, there are many possible problem areas, particularly in the area of flight mechanics, that would have to be investigated before it could be considered feasible.

INTRODUCTION

One of the concepts studied during an exploratory analytical investigation (results unpublished) of the recovery of the Saturn S-1C booster by means of aerodynamic decelerators and a hot-air balloon consisted of using a single large balloon as both a decelerator during reentry and a buoyant device for final recovery. The balloon was considered to be constructed of metal fabric with a sealant coating and was capable of withstanding the aerodynamic heating during reentry. It was considered to be inflated near apogee, and inflation was maintained by ram air during reentry. After the system had reached low speeds and altitudes it was to be converted to a hot-air balloon configuration to provide buoyancy for final recovery. The exploratory work indicated that such a system appeared reasonable from a weight standpoint, depending on the payload penalty that can be tolerated, but pointed out that a number of developments in various areas, including the materials area, would be required before such a system could be made feasible. In the materials area, the developments required would include either a very large reduction in the cost of metal fabric, the development of a low-cost heat-resistant fabric such as high-temperature glass cloth to work in the 1000° F (811° K) temperature range, or the development of low-temperature ablative coatings to be used with fabrics such as nylon derivatives treated to provide greater resistance to heat than that of nylon.

In the present investigation, some recent experimental test data on promising treated glass fabric are applied, and system performance studies are made. Balloon diameters of 275 feet (84 meters) and 300 feet (91 meters) were considered. Flight trajectories, aerodynamic heating, decelerations, fabric stresses, and system weight aspects were evaluated.

SYMBOLS

Measurements of this investigation were taken in U.S. Customary Units. Equivalent values are also indicated in the International System (SI). Details of the SI system together with conversion factors can be obtained from reference 1.

a_o reservoir speed of sound, ft/sec (m/sec)

$C_{D,b}$ drag coefficient of booster, $\frac{F_D \text{ on booster}}{qS_b}$

$C_{D,c}$ drag coefficient of sphere, $\frac{F_D \text{ on balloon}}{qS_c}$

C_p pressure coefficient, $\frac{p_l - p}{q}$

c_p specific heat of air, $\frac{\text{Btu-ft}}{\text{lbf-sec}^2\text{-}^{\circ}\text{R}}$ $\left(\frac{\text{J}}{\text{kg-}^{\circ}\text{K}}\right)$

D diameter, ft (m)

F force, lbf (N)

g acceleration due to gravity, ft/sec^2 (m/sec^2)

g_o	acceleration due to gravity at sea level, ft/sec^2 (m/sec^2)
h	heat-transfer coefficient, $\frac{Btu}{ft^2\text{-}sec\text{-}^{o}R}$ $\left(\frac{J}{m^2\text{-}sec\text{-}^{o}K}\right)$
h_e	altitude above sea level, ft (m)
J	mechanical equivalent of heat, 778 ft-lbf/Btu (1 m-N/J)
M	Mach number
m	mass, $\frac{lbf\text{-}sec^2}{ft}$ (kg)
N_{Pr}	Prandtl number
p	static pressure, lbf/ft^2 (N/m^2)
q	dynamic pressure, lbf/ft^2 (N/m^2)
R	gas constant, $\frac{Btu\text{-}ft}{lbf\text{-}sec^2\text{-}^{o}R}$ $\left(\frac{J}{kg\text{-}^{o}K}\right)$
r	radius of earth, ft (m)
S_b	reference area of booster, ft^2 (m^2)
S_c	reference area of sphere, ft^2 (m^2)
T	static temperature, ^{o}Rankine (^{o}Kelvin)
t	time, sec
u	velocity at edge of boundary layer, ft/sec (m/sec)
V	velocity of vehicle, ft/sec (m/sec)
v	volume, ft^3 (m^3)
x	surface distance, ft (m)
γ	flight-path angle, measured positive up from local horizontal, deg or rad

γ_1 ratio of specific heats

ϵ emissivity

θ surface arc angle from stagnation point, deg

μ viscosity, $\frac{\text{lbf-sec}}{\text{ft}^2}$ $\left(\frac{\text{N-sec}}{\text{m}^2}\right)$

ρ density, $\frac{\text{lbf-sec}^2}{\text{ft}^4}$ $\left(\frac{\text{kg}}{\text{m}^3}\right)$

σ Stefan-Boltzmann constant, $\frac{\text{Btu}}{\text{ft}^2\text{-sec-}^{\circ}\text{R}^4}$ $\left(\frac{\text{J}}{\text{m}^2\text{-sec-}^{\circ}\text{K}^4}\right)$

ψ range angle, rad

Subscripts:

D drag

e edge of boundary layer

i internal

L laminar

l local

max maximum

T turbulent

t stagnation

w wall

A dot over a quantity indicates rate with respect to time in seconds.

CALCULATIONS

Methods

Flight trajectories and aerodynamic-heating aspects were calculated by means of the equations presented in appendix A. Basically the equations of motion used are two-dimensional point-mass equations. Provisions are added for calculating the temperature and pressure conditions inside the balloon in which inflation is maintained by ram air, and for calculating the consequent buoyant effect on the trajectory. The external temperatures on the balloon surface at various places around the periphery and the differential pressure on the fabric at corresponding places were determined as shown in appendixes A and B, respectively. These results were used in selecting the fabric weight (or strength) for the various areas of the balloon by the procedure discussed in appendix B.

The calculations were made with an electronic digital data processing machine, starting from stage separation. It was assumed for each trajectory that satisfactory inflation of the balloon was accomplished in the thin atmosphere before or near apogee and that ram air was used to maintain inflation as the reentry trajectory was traversed. Time histories were obtained of the flight variables, including altitude, velocity, flight-path angle, dynamic pressure, fabric temperatures, range, and so forth, from stage separation.

Inputs to Calculations

The flight conditions used approximated those for the S-1C booster at stage separation in the most demanding of three typical missions, on the basis of available information. These were the initial flight conditions which resulted in the highest temperatures and decelerations during reentry, and were: altitude, 225 000 feet (68.6 km); velocity, 8240 ft/sec (2512 m/sec); flight-path angle, 26.2°.

It would be expected from related experience with free balloons and drag balloons that the proper shape of the balloon for the subject recovery system would be somewhere between spherical and conical and would probably include an inflatable separation fence for stability. In most cases in this study, however, the balloon is treated as though it were spherical to simplify the analysis. Balloon diameters of 275 and 300 feet (84 and 91 meters) were assumed.

A range of weights of glass fabric was used, considered as representing possible fabrics based on test results obtained from a manufacturer and shown in figure 1. The fabric strength was scaled from the values shown in this figure as a direct function of fabric weight to estimate the strengths of fabrics of various weights. The particular fabric assumed is one of the best of a number of glass fabrics, treated to provide added heat resistance, which have been tested (results unpublished) for strength, flexibility, and abrasion resistance before, during, and after exposure to pertinent high-temperature environments. The fabric test data show that the strength of the treated glass cloth was not significantly degraded by its having been folded and compacted as would be required in packaging a recovery device. All fabric weights used in the present study were less than or equal to the 23.6 oz/yd^2 (0.8 kg/m^2) material tested and were assumed to have the same strength-to-weight ratio and the same percentage degradation with temperature. A safety factor of 2.0 was applied in selecting fabric weights (appendix B) for various zones on the periphery of the drag balloon. A high-temperature film 0.001 inch (0.025 mm) thick was assumed as sealant material for the balloons. This film was assumed to carry no stress and would weigh 0.526 oz/yd^2 (0.0178 kg/m^2). For a 300-foot-diameter (91-meter) sphere, such film would weigh 1030 pounds (467 kg). Adhesive for bonding the film to the glass-fabric sphere would add about another 0.26 oz/yd^2 (0.009 kg/m^2).

For purposes of estimating the suspension-system weight, the load lines were considered to be glass tapes reinforcing the fabric in the balloon. The tapes were assumed to run from the booster up each seam between the gores of the balloon. Such tapes would extend approximately up to the equator of the balloon in order to spread the large deceleration loads of the suspended booster over the surface of the balloon envelope. Several approaches to the estimation of suspension-system weight were used and one estimate was obtained from a balloon manufacturer. None of these efforts were rigorous, but each indicated a suspension-system weight of the order of 10 000 pounds (4536 kg), the value used in this study.

The variation of drag coefficient with Mach number used in the calculations for the fully inflated balloon and for the booster are presented in figures 2 and 3, respectively. The booster drag coefficients are based on the assumption that the booster will be engine-end first as it reenters the atmosphere, with the balloon trailing it. Between the time of stage separation and the time of inflation of the balloon, changes in booster attitude would, in themselves, have little effect on the trajectories because of the low dynamic pressure.

Scope of Calculations

On the basis of the (unpublished) results of the exploratory analysis mentioned previously, total reentry-configuration weights of 350 000, 375 000, and 400 000 pounds (158 757, 170 097, and 181 437 kg) were considered to cover the range of interest. These weights include 288 000 pounds (130 635 kg) as the estimated dry weight of the booster. The weights of other components will be given later as they become pertinent to the analysis and presentation of the data.

All trajectories were calculated on the assumption that inflation of the balloon took place near apogee, above 350 000 feet (106.7 km). At these altitudes, the drag of the balloon would be so low that it would have no appreciable effect on the trajectory.

RESULTS AND DISCUSSION

The results of the investigation will be presented and discussed under the following headings: Trajectories and Decelerations, Aerodynamic Heating on Surface of Balloon and Fabric Stresses, Internal Balloon Conditions and Buoyant Effect, Recovery-System Weight, and System Considerations.

Trajectories and Decelerations

Some results of the trajectory calculations are presented in table I, and time histories of flight conditions for a typical calculated trajectory are shown in figure 4. The maximum deceleration values in the table indicate that booster loads due to deceleration are well within the booster tolerance, inasmuch as it has been indicated that the S-1C booster can withstand 10g to 12g axial loads during reentry after burnout and stage separation.

Aerodynamic Heating on Surface of Balloon and Fabric Stresses

Tables II and III present some pertinent results of aerodynamic-heating calculations, specifically the maximum external-surface temperatures on various parts of the drag balloon during reentry for the assumed fabric weights. The range of fabric weights was used because it was not known at the time the calculations were made what strength fabric would be required, and these results were to be applied as inputs in making that determination. Some typical time histories of these temperatures, showing more than just the maximum values, are presented in figure 5. These temperature curves are for the trajectory shown in figure 4. As shown in figure 5, increasing the fabric weight results in lower maximum temperatures, occurring later in time along the trajectory.

The temperatures calculated for turbulent flow conditions (table III) were higher than those for laminar flow (table II), and these higher temperatures were used in determining the fabric weights necessary to provide the required strengths. More detailed studies of flow conditions over a balloon recovery device, however, might show some areas where laminar flow would be present, and thus enable the use of somewhat lighter weight fabric in those areas.

The temperatures in a practical balloon cannot be determined solely from the results of the heating calculations presented in tables II and III since the temperature is a function of fabric weight, and the fabric weight required is in turn a function of fabric stress and fabric strength at the pertinent temperature. As a matter of interest, it was observed that, in general, for lighter weight fabrics, peak surface temperatures acting on the balloon fabric on a given zone occurred between 1 and 3 seconds before the occurrence of peak stress ($\Delta pD/4$) on that zone. Some typical curves showing these trends for a given balloon skin zone are shown in figure 6. As may be seen, the use of a heavier fabric results in a lower maximum temperature, occurring later in time along the trajectory. For the heaviest weight fabric used – 23.6 oz/yd^2 (0.8 kg/m^2) – peak surface temperatures occurred in some zones as late as 3 seconds after the occurrence of peak fabric stress (not shown in fig. 6).

As pointed out in appendix B, the analysis included a consideration of pressure-temperature environments to which each zone was subjected, for each fabric weight used. This procedure permitted the determination, with applied fabric safety factor, of the minimum weight fabric that would suffice for each zone during each trajectory, that is, during the reentry for each of the six basic balloon-and-payload combinations. The actual fabric weights and temperatures finally determined for each zone of the balloons are presented in table IV for the various balloon sizes and reentry-system weights included in the analysis. These fabric weights then provided input to the subsequent determination of the weight of the entire recovery system, which is discussed subsequently.

Internal Balloon Conditions and Buoyant Effect

Figure 7 presents typical time histories of the weight, pressure, and temperature of the air inside the balloon (inflation maintained by ram air), and a time history of the buoyant force which ensued along the trajectory. These data are for the trajectory shown in figure 4, and the altitude and velocity curves from figure 4 are repeated in figure 7 for convenience. In general, at high altitudes the internal temperatures were quite high, but the density and pressure were so low that the buoyant force was very low. When lower altitudes were reached, the environment which created high external balloon skin temperatures (indicated in tables II and III, but not in fig. 7) was past, but internal pressure and density (latter not shown) increased, and the internal temperature remained high enough to have an appreciable buoyant effect on the trajectory. The velocities from 30 000 feet (9.1 km) down to sea level, shown in table I, are greatly affected by the large buoyant forces. The buoyant forces at altitudes below 30 000 feet (9.1 km), as shown in table I, are of the order of 1/4 to 1/2 of the total system weight.

In order to determine whether complete momentary buoyancy could be obtained and what size balloons would be required to achieve it, some brief additional calculations were made for spheres of larger diameter. The results indicated that (momentary) atmospheric buoyancy would be achieved at about 20 700 feet (6.3 km) if a 428-foot-diameter (130-meter) balloon and a 375 000-pound (170 097-kg) total reentry weight were used. Also, buoyancy would be achieved at about 51 000 feet (15.5 km) if a 606-foot-diameter (185-meter) balloon and a 400 000-pound (181 437-kg) total reentry weight were used. Time histories of altitude, velocity, and buoyant force for these two cases are presented in figure 8. The buoyant condition is referred to as momentary because, although neglected in the analysis, there would obviously be some cooling of the air in the balloon and it would continue to sink at a slow rate unless auxiliary heat, such as from a hot-air burner, is supplied.

Generally, as was the case in reference 2, when the use of heated-air balloons has been considered for application in bringing a large booster to a condition of atmospheric buoyancy, the balloon deployment has been assumed to take place at low altitudes – 30 000 to 20 000 feet (9.1 to 6.1 km) – and subsonic velocities. System weight requirements for achieving buoyancy have then been determined in two parts, that is, air-heater and fuel weight requirements for maintaining buoyancy and the additional heater and fuel weight requirements for rapid initial heating to attain buoyancy. The significance of the phenomenon noted herein, the inherent buoyant effect which results from using ram air to maintain inflation during supersonic reentry, is that weight requirements for initial heating of the air to attain buoyancy are reduced or eliminated, and recovery-system weight is thereby reduced.

Recovery-System Weight

The information in table IV enables an interpretation of the results of the investigation to be made in terms of recovery-system weights, and a comparison of these weights can be made with results that have been obtained during previous related studies.

As may be seen in the third column of table IV, a glass-fabric balloon of the size considered here would weigh about 24 000 to 30 000 pounds (10 886 to 13 608 kg), a safety factor of 2.0 being used in selecting fabric weights. Weights per square yard (square meter) of glass fabrics required in the various balloon zones as determined by the method of appendix B are also indicated, along with maximum temperatures that would act on these specific zones (on the basis of turbulent flow conditions). No attempt is made in this study to choose between the 275-foot (84-meter) and the 300-foot (91-meter) balloons. The results indicate that either can withstand the reentry environment and that balloon weight would be about the same. Numerous considerations and trade-offs would be involved in choosing an exact size, but from fabrication and operational viewpoints, it would seem desirable to use as small a balloon as possible; and it appears from the data of tables I and IV that a balloon 275 feet (84 meters) in diameter is not necessarily the smallest one that might be used.

Table V indicates internal-temperature requirements for atmospheric buoyancy at an altitude of 5 000 feet (1.5 km). The table shows that the air in the 275-foot-diameter (84-meter) balloon would have to be about 175° F (353° K) to 250° F (394° K) warmer (depending on total reentry weight) than the air in the 300-foot (91-meter) balloon. The balloon skin composed of glass fabric and film could withstand these temperatures and could, in fact, withstand the higher temperatures that would be required for a balloon somewhat smaller than 275 feet (84 meters) in diameter.

A greater rate of fuel usage (approximately 1.33 times as great) would be required for the 275-foot (84-meter) balloon than for the 300-foot (91-meter) one; the fuel difference would amount to about 2100 pounds (953 kg) per hour. The actual magnitude of fuel usage would depend on numerous unknowns such as heat loss through the balloon skin, openings in the balloon, and so forth, which have not been established. In either case, however, the fuel for maintaining buoyancy is presumed to come from onboard residual fuel, and is not considered as recovery-system weight. This assumption was also made in the recovery-system studies of references 2 and 3. With respect to this assumption, current plans for typical S-1C missions indicate that there will be an estimated 17 350 pounds (7 870 kg) of unburned RP-1 fuel on board at the time of engine cutoff. Of this amount, an estimated 6550 pounds (2971 kg) will be in the engines, whereas the remaining 10 800 pounds (4 899 kg) will be in the tank and in the fuel flow lines. It is realized that there may be reasons why even the latter amount of residual fuel cannot be made available for use in the air-heating burners: for example, technical problems in accomplishing fuel transfer, or a reduction of residual fuel which may result from preflight mission optimization procedures. If such be the case, it will be necessary to carry along special fuel for the air-heater burners and to charge the recovery system with the weight of this fuel at the rate of about 3000 pounds (1361 kg) for initial heating and about 5000 pounds (2268 kg) for every hour of buoyancy desired. (See ref. 2.)

The recovery-system weight, as specified in the fourth column of table IV, includes the weight of the glass-fabric balloon with 21 000 pounds (9 525 kg) added to account for the following four items:

	lb	kg
Air heaters (ref. 2)	7 500	3402
Reaction-control system (ref. 3)	2 000	907
Balloon inner liner (film) and adhesive	1 500	680
Load-line system	10 000	4536

The second item listed, a system for controlled booster turnaround to engine-end-first reentry attitude after stage separation, may not be necessary because the balloon may provide all the stability that is needed.

Figure 9 is a plot of some of the weights shown in table IV and was prepared to aid in interpretation of these data. This figure shows that if all of the residual fuel and oxidizer in the booster were retained, the total reentry weight would be about 388 000 pounds (175 994 kg), and the weight of the recovery system added to the basic booster would be 50 000 pounds (22 680 kg). Likewise, it shows that if all the residual fuel and oxidizer were jettisoned, except the 13 000 pounds (5 897 kg) of fuel required to provide 2 hours' buoyancy, the total reentry weight would be about 346 000 pounds (156 943 kg) and the recovery-system weight would be about 45 000 pounds (20 412 kg).

These recovery-system weights – 45 000 and 50 000 pounds (20 412 and 22 680 kg) – compare favorably with a 43 000-pound (19 505-kg) water-impact recovery system which evolved from the studies reported in reference 3.

The total recovery-system weight determined herein is less than 1 percent of the 6 000 000-pound (2 721 554-kg) launch weight of the advanced Saturn system. In terms of payload degradation, the data of figure 10 indicate reductions of 3500 pounds (1588 kg) and of 9000 pounds (4082 kg) for two typical planned missions. These results were obtained from unpublished trajectory-optimization studies. The values represent about 3.5 percent of the mission payloads for both cases.

System Considerations

As stated earlier, one of the primary factors that would prohibit the use of metal fabric in a large hypersonic drag balloon is the high cost of the metal fabric that would be required. No exact figures regarding the cost of appropriate glass fabric are available, but the material considered herein is conventional glass-fiber cloth treated to provide added heat resistance, by a process which adds only a small percentage to the cost of the fabric.

Many problem areas not considered in this investigation would have to be studied carefully before a booster-recovery system such as that described herein could be considered feasible. For example, these areas include the deployment and inflation of a large drag balloon at the high altitudes required, stability and control during turnaround between stage separation and reentry and during reentry, determination of proper inflated shape and maintenance of that shape by ram air and by a suitably designed balloon-booster interface suspension arrangement, and the effects of interference between booster and balloon on aerodynamic heating and drag. The effects of such factors as earth's rotation, winds, and apparent additional mass on the reentry trajectories, and hence possibly on system weights, would also have to be considered. In regard to effects of apparent additional mass, these are not known for the pertinent supersonic flight regime. However, preliminary estimates made with formulas applicable to subsonic conditions indicated that the effects are small and within the accuracy of the trajectory calculations of the study.

In the development of a recovery system, such as the one investigated herein, additional weight items not considered in the study would no doubt have to be included. On the other hand, it appears that a number of optimizing design approaches could be applied which could lead to weight reductions as compared with some of the weights estimated for this study. For example:

1. Laminar flow may be found to exist over portions of the balloon, and this condition would cause a reduction in the required fabric weight in those areas.

2. Differential local pressure loads occurring in the fabric surface can be reduced by shaping the balloon to be somewhat different than a sphere. Possibly, local curvatures and/or consideration of smaller areas than used herein in determining skin stresses and fabric weights – that is, more detailed tailoring of the balloon to meet local conditions – can result in lower weights. (The effects of reshaping of the balloon on overall aerodynamic drag coefficient would have to be studied.)

3. The specific heat of a balloon skin which is a composite of treated glass fabric, adhesive, inner liner, seams, and so forth, would be expected to be more than the value – 0.19 Btu/lbm-$^{\circ}$R (795 J/kg-$^{\circ}$K) – used in this study on the basis of available information for bare glass fabric. A higher specific heat should result in lessened temperatures and perhaps some reduction in fabric weight.

CONCLUSIONS

The following conclusions were drawn from the analysis of the recovery of the Saturn S-1C booster by means of a system in which a single large balloon with ram-air maintenance of inflation is used both as a decelerator during the reentry phase of recovery and as a buoyant device with air heating in the lower atmosphere for final recovery:

1. A balloon with a diameter of 275 or 300 feet (84 or 91 meters) – or perhaps less – is about the proper size for the task.

2. The maximum deceleration loads during reentry are of the order of 8.5g, which is within the tolerance of the booster.

3. The maximum surface temperatures of the balloon are about 800° to 850° F (700° to 727.8° K), which appear to be acceptable for conventional glass-fiber cloth, treated to provide added heat resistance.

4. The buoyancy that results from aerodynamic heating and compression of the air in the balloon during reentry has significant effects on the descent velocities at low altitudes; for example, 30 000 feet (9.1 km) and below.

5. The internal air temperatures required to achieve buoyancy at low altitude are within acceptable limits for the glass-fiber cloth.

6. The total recovery-system weight is of the order of 45 000 to 50 000 pounds (20 412 to 22 680 kg). The use of a recovery system of this weight would result in a reduction in mission payload weight of about 3.5 percent.

7. Many problem areas must be investigated before the subject recovery system could be pronounced feasible. These include such areas as balloon deployment and inflation in a near-space environment, booster turnaround before reentry, system stability during the supersonic phase of the reentry, determination of proper inflated shape and maintenance of that shape by ram air and by a suitably designed balloon-booster interface suspension arrangement, and the effects of booster-balloon interference on aerodynamic heating and drag.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 29, 1966,
124-07-03-06-23.

APPENDIX A

EQUATIONS OF MOTION AND EQUATIONS FOR AERODYNAMIC HEATING ASPECTS

Trajectories

The trajectories were calculated for the motion of a point mass acted upon by the gravitational force, aerodynamic drag force, and buoyant force as the body enters the earth's atmosphere. The "body" here includes the internal air mass, which for the large internal volumes considered in this investigation becomes a significant part of the mass of the body as reentry ensues. The earth was assumed to be spherical and nonrotating. The rates of change of velocity, flight-path angle, altitude, and range angle, and the total range, are given by the following equations:

$$\dot{V} = \frac{-F_D}{m + m_i} - g \sin \gamma + \frac{v g_o \rho}{m + m_i} \sin \gamma \tag{1}$$

$$\dot{\gamma} = -\frac{g \cos \gamma}{V}\left[1 - \frac{V^2}{g(r + h_e)}\right] + \frac{v g_o \rho}{V(m + m_i)} \cos \gamma \tag{2}$$

$$\dot{h}_e = V \sin \gamma \tag{3}$$

$$\dot{\psi} = \frac{V \cos \gamma}{r + h_e} \tag{4}$$

$$\begin{aligned} \text{Range} &= r\psi \\ &= 3954\psi \text{ statute miles} \\ &= 6363\psi \text{ km} \end{aligned} \tag{5}$$

The variation of acceleration due to gravity with altitude is given by

$$g = g_o\left(\frac{r}{r + h_e}\right)^2$$

The aerodynamic drag acting on the body is composed of the booster drag and the decelerator drag:

$$F_D = C_{D,b} \frac{\rho}{2} V^2 S_b + C_{D,c} \frac{\rho}{2} V^2 S_c$$

All drag coefficients were a function of Mach number. Mach number varied with velocity and altitude; altitude, air density, pressure, and temperature varied in accordance with the tables in reference 4.

APPENDIX A

Internal Air

The perfect-gas temperature and mass of air contained within the balloon were calculated by using the following assumptions and constraints:

1. The balloon was always inflated by ram air to an internal pressure of

$$p_i = p + \frac{1}{2}\rho V^2 \tag{6}$$

(See appendix B for pertinent treatment of internal-external pressure ratio.)

2. The air added to the balloon to maintain the prescribed pressure was at stream stagnation temperature.

3. The air within the balloon compressed isentropically as air was added and expanded isentropically as air was exhausted.

4. No heat was added to, or lost from, the system through the balloon wall.

Along the trajectory the computer program calculated the effect of a small step in internal pressure Δp_i, the internal temperature $T_i + \Delta T_i$, and the internal mass $m_i + \Delta m_i$. Since the internal mass and energy (temperature) of the system are assumed to result from the stagnation-temperature air taken on to maintain the prescribed pressure and from the compression of the internal air, it is reasoned that

$$c_p\left(m_i + \Delta m_i\right)\left(T_i + \Delta T_i\right) = c_p T_t \Delta m_i + c_p m_i\left(T_i + \Delta T_i\right)$$

and for isentropic compression of the gas,

$$\left(m_i + \Delta m_i\right)\left(T_i + \Delta T_i\right) = T_t \Delta m_i + m_i T_i\left(\frac{p_i + \Delta p_i}{p_i}\right)^{\left(\gamma_1 - 1\right)/\gamma_1}$$

or, rearranging,

$$T_t\left(m_i + \Delta m_i\right) = \left(m_i + \Delta m_i\right)\left(T_i + \Delta T_i\right) + T_t m_i - T_i m_i\left(\frac{p_i + \Delta p_i}{p_i}\right)^{\left(\gamma_1 - 1\right)/\gamma_1} \tag{7}$$

From the equation of state of the gas,

$$m_i + \Delta m_i = \frac{v\left(p_i + \Delta p_i\right)}{RJ\left(T_i + \Delta T_i\right)} \tag{8}$$

and equation (7) becomes

$$\frac{T_t v\left(p_i + \Delta p_i\right)}{RJ\left(T_i + \Delta T_i\right)} = \frac{v}{RJ}\left(p_i + \Delta p_i\right) + T_t m_i - T_i m_i\left(\frac{p_i + \Delta p_i}{p_i}\right)^{\left(\gamma_1 - 1\right)/\gamma_1}$$

Solving for the temperature at the end of the step in pressure,

$$T_i + \Delta T_i = \frac{\frac{T_t}{RJ}\left(p_i + \Delta p_i\right)}{\frac{p_i + \Delta p_i}{RJ} + \frac{m_i T_t}{v} - \frac{m_i T_i}{v}\left(\frac{p_i + \Delta p_i}{p_i}\right)^{(\gamma_1 - 1)/\gamma_1}} \tag{9}$$

For a pressure decrease (negative Δp_i) inside the balloon, the flow will reverse and leave the balloon, in which case the air temperature will be calculated from the expansion of the gas inside the balloon. Thus,

$$T_i + \Delta T_i = T_i\left(\frac{p_i + \Delta p_i}{p_i}\right)^{(\gamma_1 - 1)/\gamma_1}$$

The mass of internal air is given by equation (8).

Laminar Heat Transfer

The laminar stagnation-point heat-transfer coefficient was obtained from the following equation, which is based on the analysis of reference 5 and is for a perfect gas:

$$h_L = \frac{0.54\sqrt{2}}{N_{Pr}{}^{0.6}}\left(\frac{\rho_w \mu_w}{\rho_t \mu_t}\right)^{0.1} \sqrt{\rho V c_p} \sqrt{\frac{p_t}{p} \frac{\mu_t}{D}\left(\frac{T}{T_t}\right)^{0.5} \frac{1}{M} \frac{d(u/a_o)}{d(x/D)}} \tag{10}$$

For this calculation the following values were used:

$$\left(\frac{\rho_w \mu_w}{\rho_t \mu_t}\right)^{0.1} = 1 \qquad N_{Pr} = 0.7 \qquad \frac{d(u/a_o)}{d(x/D)} = 2.18$$

and

$$\mu = 0.0231 \frac{T^{3/2}}{T + 216}\left(10^{-6}\right) \frac{\text{lbf-sec}}{\text{ft}^2}$$

or

$$\mu = 0.0111 \frac{\left(\frac{5}{9} T\right)^{3/2}}{\frac{5}{9} T + 120}\left(10^{-4}\right) \frac{\text{N-sec}}{\text{m}^2}$$

The heat-transfer coefficient to various zones around the sphere was taken as the maximum heat-transfer coefficient in the particular zone. From the method of reference 6, the maximum zone heating was calculated as a percentage of the stagnation-point heating. These percentages and corresponding zones are as follows:

Zone	Angle of zone from stagnation point	Percentage of stagnation-point heat-transfer coefficient
1	0° to 20°	100
2	20° to 40°	95
3	40° to 60°	72
4	60° to 80°	40
5	80° to 180°	17.5

Turbulent Heat Transfer

The turbulent heat-transfer coefficient around the balloon was determined from the following equation, which is based on information given in reference 7:

$$h_T = 0.042\rho V c_p \left[\frac{d(u/a_o)}{d(x/D)}\right]^{0.8} \left(\frac{a_o}{V}\right)^{0.8} \left(\frac{\rho V D}{\mu}\right)^{-0.2} \left(\frac{\rho_e}{\rho}\right)^{0.8} \left(\frac{\mu_e}{\mu}\right)^{0.2} \left(\frac{x}{D}\right)^{0.6} N_{Pr}^{-2/3} \tag{11}$$

The values of density and velocity at the edge of the boundary layer (ρ_e and u) were obtained from the stream quantities, assuming a normal shock ahead of the balloon and an isentropic expansion from the stagnation-point pressure to the local Newtonian pressure $\left(C_p = C_{p,max}\cos^2\theta\right)$. The point of maximum turbulent heating on a sphere is about 40° to 45° away from the stagnation point, and this maximum value was determined in the calculations. Various percentages of this maximum value were used for the zones around the sphere. These percentages determined on the basis of equation (11) at a Mach number of 6 were used at all velocities. The percentages are shown in the following table:

Zone	Angle of zone from stagnation point	Percentage of maximum turbulent heat-transfer coefficient
1	0° to 20°	84
2	20° to 40°	100
3	40° to 60°	100
4	60° to 80°	78
5	80° to 180°	34

As in the laminar calculation, the stagnation-point velocity gradient $\frac{d(u/a_o)}{d(x/D)}$ was 2.18.

APPENDIX A

Wall Temperatures

Radiation equilibrium temperatures (listed under zero fabric weight in tables II and III) are

$$T_w^4 = \frac{h\left(T_t - T_w\right)}{\epsilon\sigma} \tag{12}$$

where h is the appropriate laminar or turbulent heat-transfer coefficient or a fraction thereof. These temperatures were computed from

$$T_w = \frac{1}{2}\left[-\sqrt{Z} + \sqrt{Z - 2\left(Z - \frac{b}{\sqrt{Z}}\right)}\right]$$

where

$$Z = \left(\frac{b^2}{2} + \sqrt{\frac{b^4}{4} + \frac{64a^3}{27}}\right)^{1/3} + \left(\frac{b^2}{2} - \sqrt{\frac{b^4}{4} + \frac{64a^3}{27}}\right)^{1/3}$$

and

$$a = \frac{hT_t}{\epsilon\sigma} \qquad b = \frac{h}{\epsilon\sigma}$$

This explicit solution of equation (12) is based on material presented in references 8 and 9, with errors in those sources corrected. It is practical to use this explicit solution only when an automatic computer is available; otherwise the trial-and-error method is more practical.

Temperatures of balloon walls of sufficient mass to cause the wall temperature to lag behind the equilibrium temperature are

$$T_w = T_o + \frac{1}{A}\int_0^t \left[h\left(T_t - T_w\right) - \epsilon\sigma T_w^4\right] dt \tag{13}$$

where h is the appropriate laminar or turbulent heat-transfer coefficient or fraction thereof, T_o is the initial material temperature before heating, and A is the product of the wall weight per unit area and the specific heat of the material. A value of 0.9 was used for ϵ, and a value of 0.19 Btu/lbm-^{o}R (795 J/kg-^{o}K) was used for the specific heat of the balloon wall material.

APPENDIX B

DETERMINATION OF DIFFERENTIAL PRESSURE AT POINTS ON BALLOON AND PROCEDURE FOR SELECTING FABRIC WEIGHTS

The coefficient of differential pressure at a given point on the balloon surface was determined from the equation

$$\Delta C_p = 1.8 \cos^2\theta - 1$$

The first term on the right-hand side is based on the assumed existence of Newtonian flow on the surface of the balloon, and figure 11, taken from reference 10, shows the pertinent curve of external pressure coefficient as a function of θ. The second term represents internal pressures as used in this investigation;[1] the tests of reference 11 indicated that such internal pressures were sufficient to keep decelerator models inflated. One means of achieving the prescribed internal pressure of $C_{p,i} = 1.0$ rather than $C_{p,i} = 1.8$ at the critical speed, $M \approx 4.5$, might be the use of a flush inlet on the surface. The location would be selected so that at the critical condition of q_{max}, the local static pressure would correspond to $C_p = 1.0$.

The forward part of the final balloon shape probably will not be spherical, as assumed here, but will tend toward a conical shape as in reference 11. The use of the spherical shape in the analysis is believed to be justified for the purpose of weight estimation, even though it results in a model with external pressure over the front greater than the internal pressure. However, in the actual situation the somewhat conical shape of the balloon and suspension of the booster ahead of the balloon should prevent collapse of the fabric.

As part of the procedure for selecting lighter-weight fabrics where possible for some areas of the balloon, the maximum external skin temperature (determined by the method of appendix A) and the maximum differential pressure which acts on any part of a given zone were assumed to act over the entire zone. However, these maximum values do not occur at the same time (as stated in the body of the paper) and the time between them varies with assumed balloon-zone fabric weight, weight of reentry system, and so forth. The time history of pressure-temperature environments for each balloon zone,

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[1]The internal pressure assumed in appendix A (see eq. (6)), expressed as a pressure coefficient, is:

$$C_{p,i} = \frac{p_i - p}{\frac{\rho}{2} V^2} = \frac{\left(p + \frac{\rho}{2} V^2\right) - p}{\frac{\rho}{2} V^2} = 1$$

for each assumed fabric weight, and for each basic trajectory was examined to determine, for each instant, the weight of fabric that would just break in each environment. In order to do this, the curve in figure 1 for 23.6 oz/yd^2 (0.8 kg/m^2) glass fabric was used. A weight representing a breaking-strength factor of 1.0 was obtained for each instant from the formula

$$\text{oz/yd}^2 = \frac{\text{Stress in assumed fabric}}{\text{Breaking stress of 23.6 oz/yd}^2\text{ fabric}} \times 23.6$$

or

$$\text{kg/m}^2 = \frac{\text{Stress in assumed fabric}}{\text{Breaking stress of 0.8 kg/m}^2\text{ fabric}} \times 0.8$$

at the pertinent temperature. From these instantaneous values of required weight a maximum value was taken and used as explained in the next paragraph.

A plot was made similar to the sample in figure 12, in which the maximum fabric weight required for a breaking-strength factor of 1.0, for each assumed fabric weight, was plotted against the ratio of assumed fabric weight to the fabric weight required for a breaking-strength factor of 1.0. The fabric weight that would be required in order for the aforementioned ratio to be 2.0 was then considered to be one-half the fabric weight necessary in the zone to provide a fabric safety factor of 2.0. Figure 13 was prepared from the information in figure 12 in order to show fabric weight required as a direct function of fabric safety factor.

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TABLE I.- RESULTS OF REENTRY TRAJECTORY CALCULATIONS

(a) U.S. Customary Units

No.	Balloon diam., ft	Reentry-system weight, lbm	Flight conditions when maximum dynamic pressure and maximum deceleration are reached						In vertical descent						Range at impact, statute miles
									30 000 ft		15 000 ft		Impact		
			t, sec	h_e, statute miles	V, ft/sec	γ, deg	q, lbf/ft^2	g units	V, ft/sec	Buoyant force, lbf	V, ft/sec	Buoyant force, lbf	V, ft/sec	Buoyant force, lbf	
1	275	350 000	281	26.3	4825.9	-31.81	65.09	-8.4	168	89 584	122	115 516	89	152 589	387.0
2	↓	375 000	281	26.1	4943.7	-31.74	70.47	-8.5	175	90 155	128	116 165	94	153 341	387.6
3	↓	400 000	282	25.5	4779.1	-31.98	75.92	-8.6	183	90 723	135	116 814	99	154 272	388.1
4	300	350 000	280	27.1	4817.6	-31.66	53.67	-8.2	146	114 758	104	148 223	72	196 454	385.8
5	↓	375 000	280	27.0	4936.0	-31.59	58.11	-8.3	154	115 411	110	148 960	78	197 029	386.3
6	↓	400 000	281	26.3	4778.3	-31.83	62.61	-8.4	161	116 070	116	149 706	83	198 042	386.9

(b) International System of Units

No.	Balloon diam., m	Reentry-system weight, kg	Flight conditions when maximum dynamic pressure and maximum deceleration reached						In vertical descent						Range at impact, km
									9.144 km		4.572 km		Impact		
			t, sec	h_e, km	V, m/s	γ, deg	q, N/m^2	g units	V, m/s	Buoyant force, N	V, m/s	Buoyant force, N	V, m/s	Buoyant force, N	
1	84	158 757.3	281	42.3	1470.9	-31.81	3116.5	-8.4	51.2	398 489	37.2	513 841	27.1	678 750	622.8
2	↓	170 097.1	281	42.0	1506.8	-31.74	3374.1	-8.5	53.3	401 029	39.0	516 728	28.7	682 095	623.8
3	↓	181 436.9	282	41.0	1456.7	-31.98	3635.1	-8.6	55.8	403 556	41.2	519 615	30.2	686 236	624.6
4	91	158 757.3	280	43.6	1468.4	-31.66	2569.7	-8.2	44.5	510 469	31.7	659 329	21.9	873 871	620.9
5	↓	170 097.1	280	43.5	1504.5	-31.59	2782.3	-8.3	46.9	513 374	33.5	662 607	23.8	876 429	621.7
6	↓	181 436.9	281	42.3	1456.4	-31.83	2997.8	-8.4	49.1	516 305	35.4	665 925	25.3	880 935	622.7

TABLE II.- MAXIMUM TEMPERATURES ON EXTERNAL BALLOON SURFACE DUE TO AERODYNAMIC HEATING IN LAMINAR FLOW

[Configuration numbers correspond to those in table I]

(a) U.S. Customary Units

	Max. temp., °F, for fabric wt of –					
	0 oz/yd^2	4 oz/yd^2	8 oz/yd^2	12 oz/yd^2	16 oz/yd^2	23.6 oz/yd^2
No.	Zone 1 ($0^\circ < \theta < 20^\circ$)					
1	580	573	544	497	450	376
2	590	583	555	509	462	388
3	599	592	565	521	474	399
4	548	539	504	454	407	---
5	557	549	515	466	418	---
6	565	558	526	477	430	358
No.	Zone 2 ($20^\circ < \theta < 40^\circ$)					
1	568	560	529	480	433	360
2	577	570	540	493	445	372
3	585	579	550	504	457	382
4	536	527	489	438	390	---
5	545	536	500	450	402	---
6	553	545	511	461	413	342
No.	Zone 3 ($40^\circ < \theta < 60^\circ$)					
1	503	491	448	393	346	---
2	512	501	458	404	357	---
3	520	512	469	415	367	300
4	473	459	409	353	308	---
5	481	468	420	364	318	---
6	489	477	430	374	328	267
No.	Zone 4 ($60^\circ < \theta < 80^\circ$)					
1	378	351	283	229	193	156
2	386	360	292	238	201	162
3	393	369	302	246	209	168
4	352	319	248	198	166	---
5	359	328	257	206	173	---
6	366	337	266	214	180	145
No.	Zone 5 ($80^\circ < \theta < 180^\circ$)					
1	228	161	94	68	58	---
2	235	169	101	73	62	---
3	241	177	108	78	66	59
4	207	132	72	51	43	---
5	213	140	78	55	47	---
6	218	148	84	60	51	48

(b) International System of Units

	Max. temp., °K, for fabric wt of –					
	0 kg/m^2	0.136 kg/m^2	0.271 kg/m^2	0.407 kg/m^2	0.542 kg/m^2	0.800 kg/m^2
No.	Zone 1 ($0^\circ < \theta < 20^\circ$)					
1	578	574	558	532	506	464
2	583	579	564	538	512	471
3	588	584	569	545	519	477
4	560	555	536	508	482	---
5	565	561	542	514	488	---
6	569	566	548	521	494	454
No.	Zone 2 ($20^\circ < \theta < 40^\circ$)					
1	571	567	549	522	496	456
2	576	572	556	529	503	462
3	581	577	561	536	509	468
4	553	548	527	499	472	---
5	558	553	533	506	479	---
6	563	558	539	512	485	446
No.	Zone 3 ($40^\circ < \theta < 60^\circ$)					
1	535	528	504	474	448	---
2	540	534	510	480	454	---
3	544	540	516	486	459	422
4	518	511	483	452	427	---
5	523	516	489	458	432	---
6	527	521	494	463	438	404
No.	Zone 4 ($60^\circ < \theta < 80^\circ$)					
1	466	451	413	383	363	342
2	470	456	418	388	367	346
3	474	461	423	392	372	349
4	451	433	393	366	348	---
5	455	438	398	370	352	---
6	459	443	403	374	356	336
No.	Zone 5 ($80^\circ < \theta < 180^\circ$)					
1	382	345	308	293	288	---
2	386	349	312	296	290	---
3	389	354	316	299	292	288
4	371	329	296	284	279	---
5	374	333	299	286	282	---
6	377	338	302	289	284	282

TABLE III.- MAXIMUM TEMPERATURES ON EXTERNAL BALLOON SURFACE DUE TO

AERODYNAMIC HEATING IN TURBULENT FLOW

[Configuration numbers correspond to those in table I]

(a) U.S. Customary Units

	Max., temp., °F, for fabric wt of –					
	0 oz/yd²	4 oz/yd²	8 oz/yd²	12 oz/yd²	16 oz/yd²	23.6 oz/yd²
No.	Zone 1 ($0° < \theta < 20°$)					
1	868	846	834	807	769	688
2	886	864	853	829	792	713
3	904	881	872	849	814	737
4	820	798	783	750	707	---
5	837	817	801	770	731	---
6	855	832	820	791	751	669
No.	Zone 2 ($20° < \theta < 40°$)					
1	901	899	889	869	836	762
2	919	917	909	890	860	788
3	937	935	928	910	882	812
4	852	849	838	811	774	---
5	869	867	857	832	797	---
6	887	885	875	853	818	743
No.	Zone 3 ($40° < \theta < 60°$)					
1	901	899	889	869	836	762
2	919	917	909	890	860	788
3	937	935	928	910	882	812
4	852	849	838	811	774	---
5	869	867	857	832	797	---
6	887	885	875	853	818	743
No.	Zone 4 ($60° < \theta < 80°$)					
1	855	824	811	781	740	657
2	872	841	830	803	764	682
3	890	859	848	823	786	705
4	807	776	759	723	678	---
5	824	794	778	745	701	---
6	841	810	796	765	723	639
No.	Zone 5 ($80° < \theta < 180°$)					
1	709	596	550	489	433	---
2	725	611	569	509	453	---
3	741	627	587	529	473	390
4	666	553	500	436	382	---
5	682	569	518	455	400	---
6	697	584	536	474	418	341

(b) International System of Units

	Max. temp., °K, for fabric wt of –					
	0 kg/m²	0.136 kg/m²	0.271 kg/m²	0.407 kg/m²	0.542 kg/m²	0.800 kg/m²
No.	Zone 1 ($0° < \theta < 20°$)					
1	738	726	719	704	683	638
2	748	736	730	716	696	652
3	758	745	740	727	708	665
4	711	699	691	672	648	---
5	721	710	701	683	662	---
6	731	718	711	695	673	627
No.	Zone 2 ($20° < \theta < 40°$)					
1	756	755	750	738	720	679
2	766	765	761	750	733	693
3	776	775	771	761	746	707
4	729	727	721	706	686	---
5	738	737	732	718	698	---
6	748	747	742	730	710	668
No.	Zone 3 ($40° < \theta < 60°$)					
1	756	755	750	738	720	679
2	766	765	761	750	733	693
3	776	775	771	761	746	707
4	729	727	721	706	686	---
5	738	737	732	718	698	---
6	748	747	742	730	710	668
No.	Zone 4 ($60° < \theta < 80°$)					
1	731	713	706	689	667	621
2	740	723	717	702	680	634
3	750	733	727	713	692	647
4	704	687	677	657	632	---
5	713	697	688	669	645	---
6	723	706	698	681	657	611
No.	Zone 5 ($80° < \theta < 180°$)					
1	649	587	561	527	496	---
2	658	595	572	538	507	---
3	667	604	582	549	518	472
4	626	563	533	498	468	---
5	634	572	543	508	478	---
6	643	580	553	519	488	445

TABLE IV.- RESULTS IN TERMS OF SYSTEM WEIGHTS AND MAXIMUM BALLOON SURFACE TEMPERATURES

(a) U.S. Customary Units

Balloon diam., ft	Assumed reentry weight,[a] lbm	Glass-fabric balloon weight,[b] lbm	Recovery-system weight,[c] lbm	Fuel for providing buoyancy,[d] lbm	Weight remainder,[e] lbm	Glass-fabric weight and maximum temperature									
						Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
						Wt,[f] oz/yd^2	T, ^{o}F	Wt, oz/yd^2	T, ^{o}F	Wt, oz/yd^2	T, ^{o}F	Wt, oz/yd^2	T, ^{o}F	Wt oz/yd^2	T, ^{o}F
275	350 000	25 000	46 000	13 000	3 000	16.8	760	15.8	839	15.2	843	17.9	719	13.9	460
↓	375 000	27 000	48 000	↓	26 000	18.7	763	17.7	845	17.1	850	19.7	725	15.1	465
↓	400 000	30 000	51 000	↓	48 000	20.4	770	19.8	848	19.1	854	21.5	726	16.3	469
300	350 000	24 000	45 000	↓	4 000	13.9	729	12.5	808	12.0	811	14.8	690	12.6	426
↓	375 000	28 000	49 000	↓	25 000	15.3	738	14.1	814	13.5	819	16.2	700	13.7	430
↓	400 000	30 000	51 000	↓	48 000	16.9	740	15.6	822	15.1	826	17.9	701	14.8	435

(b) International System of Units

Balloon diam., m	Assumed reentry weight,[a] kg	Glass-fabric balloon weight,[b] kg	Recovery-system weight,[c] kg	Fuel for providing buoyancy,[d] kg	Weight remainder,[e] kg	Glass-fabric weight and maximum temperature									
						Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
						Wt,[f] kg/m^2	T, ^{o}K	Wt, kg/m^2	T, ^{o}K	Wt, kg/m^2	T, ^{o}K	Wt, kg/m^2	T, ^{o}K	Wt, kg/m^2	T, ^{o}K
84	158 757	11 340	20 865	5 897	1 361	0.570	678	0.536	722	0.515	724	0.607	655	0.471	511
↓	170 097	12 247	21 772	↓	11 793	.634	679	.600	725	.580	728	.668	658	.512	514
↓	181 437	13 608	23 133	↓	21 772	.692	683	.671	727	.648	730	.729	659	.553	516
91	158 757	10 886	20 412	↓	1 814	.471	661	.424	705	.407	706	.502	639	.427	492
↓	170 097	12 701	22 226	↓	11 340	.519	666	.478	708	.458	711	.549	644	.465	494
↓	181 437	13 608	23 133	↓	21 772	.573	667	.529	712	.512	715	.607	645	.502	497

[a]Includes dry booster weight of 288 000 lbm (130 635 kg), weight of a recovery system, and weight of residual and trapped fuel and oxidizer (which normally totals 50 500 lbm (22 906 kg) if none is jettisoned).

[b]Derived by method of appendix B.

[c]Weight of fabric in balloon plus 21 000 lbm (9 525 kg) allowance for film liner and adhesive, load-line system, reaction-control system, and air heaters. A breakdown of this weight allowance and the sources of component weight estimates are given in the text.

[d]According to ref. 2, this amount of residual fuel will provide buoyancy in the lower atmosphere for approximately 2 hr. This is part of the 50 500-lbm (22 906-kg) value noted in footnote a, and leaves 37 500 lbm (17 009 kg) of this weight to be otherwise accounted for.

[e]Weight within the assumed reentry weight that is not accounted for in previous columns as part of the necessary system weight.

[f]Weight of fabric per unit area is a function of differential pressure as well as of temperature indicated (see appendix B); weights shown are for fabric safety factor of 2.0.

TABLE V.- INTERNAL BALLOON TEMPERATURES

REQUIRED FOR BUOYANCY

(a) At 5000-foot altitude (U.S. Customary Units)

Balloon diam., ft	Temperature, ^{o}F, for system weight of –		
	350 000 lbm	375 000 lbm	400 000 lbm
275	518	589	672
300	342	378	418

(b) At 1.5-km altitude (International System of Units)

Balloon diam., m	Temperature, ^{o}K, for system weight of –		
	158 757 kg	170 097 kg	181 437 kg
84	543	583	629
91	446	466	488

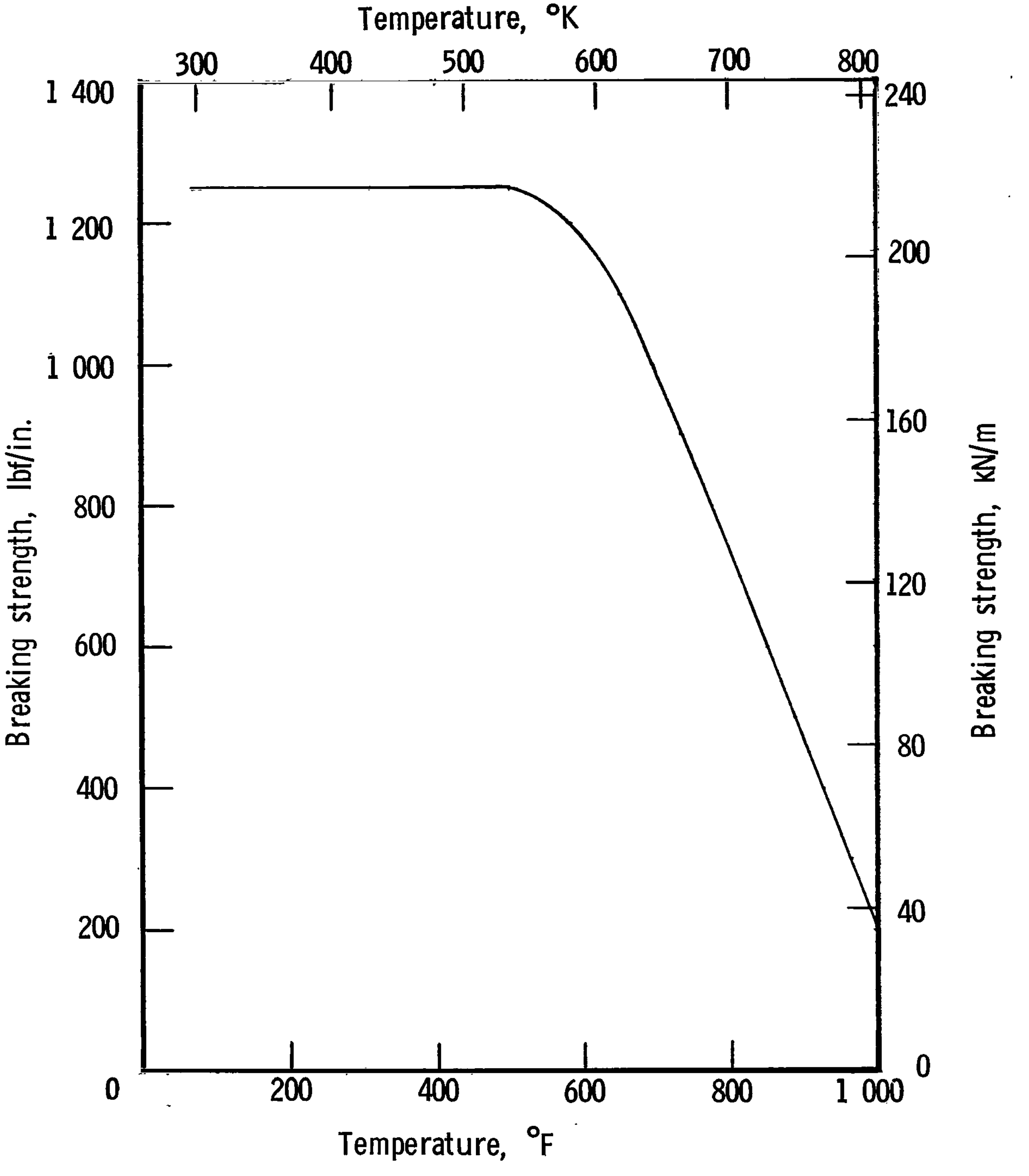


Figure 1.- Variation of breaking strength with temperature for 23.6 oz/yd^2 (0.8 kg/m^2) glass fabric (herringbone weave).

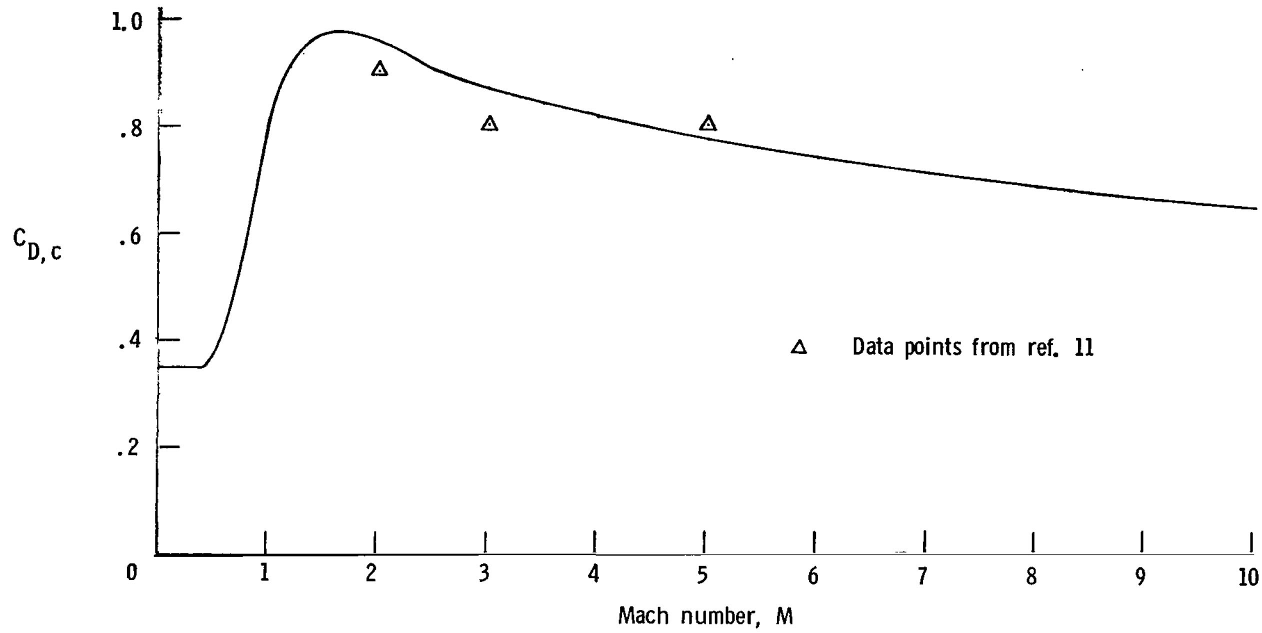


Figure 2.- Variation of balloon drag coefficient with Mach number (subsonic portion based on typical existing data for spheres.)

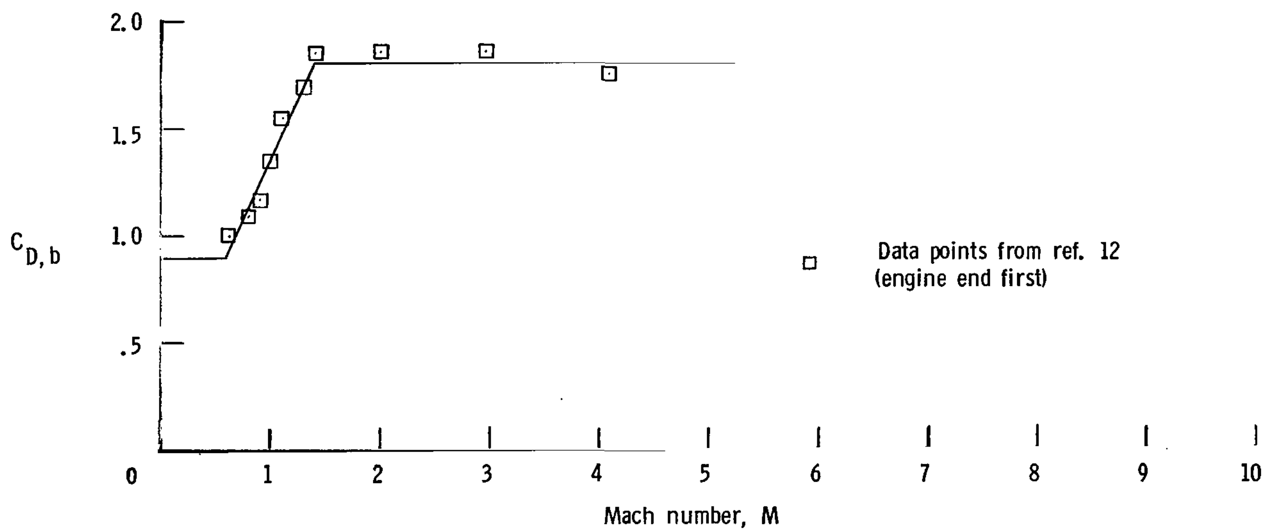
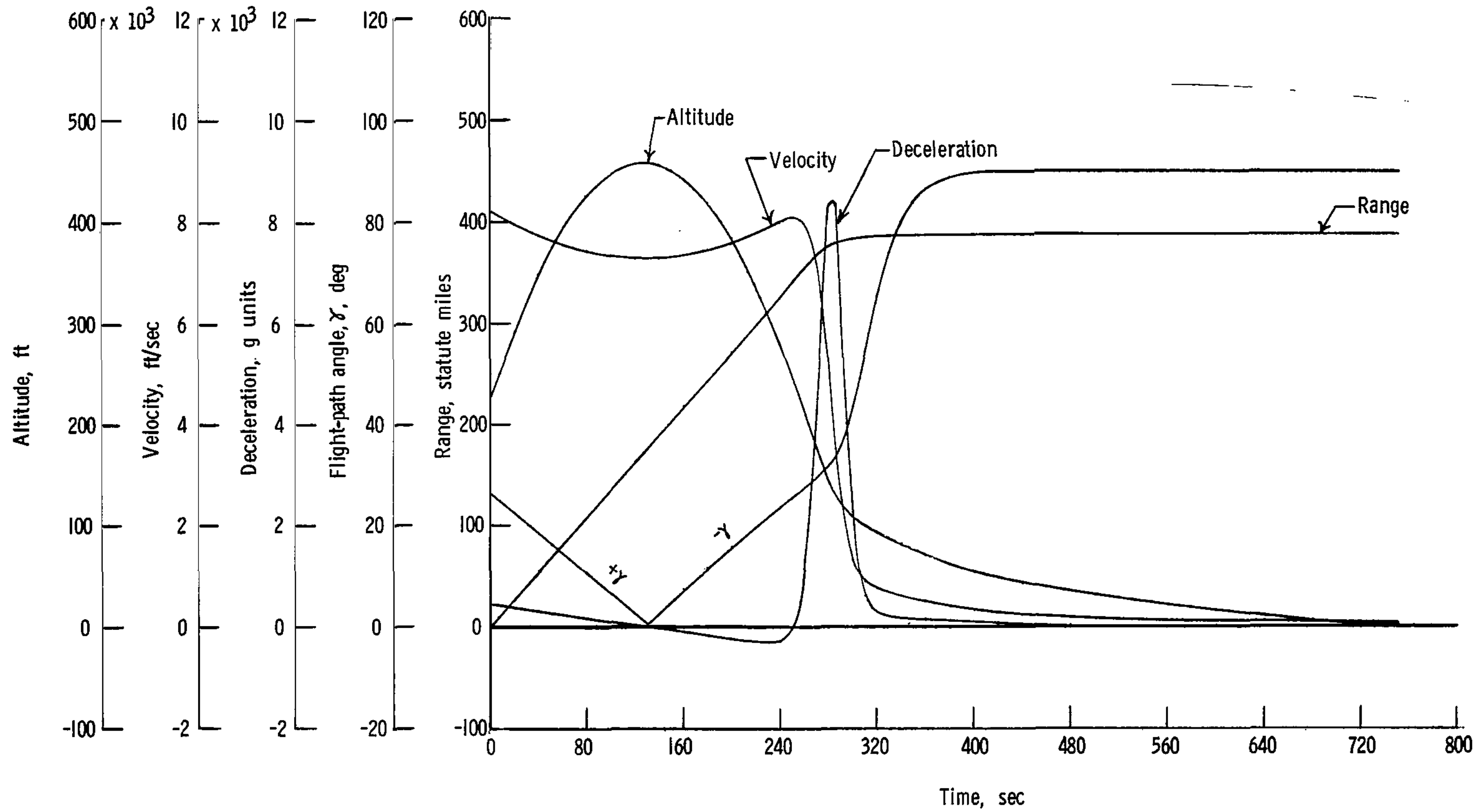
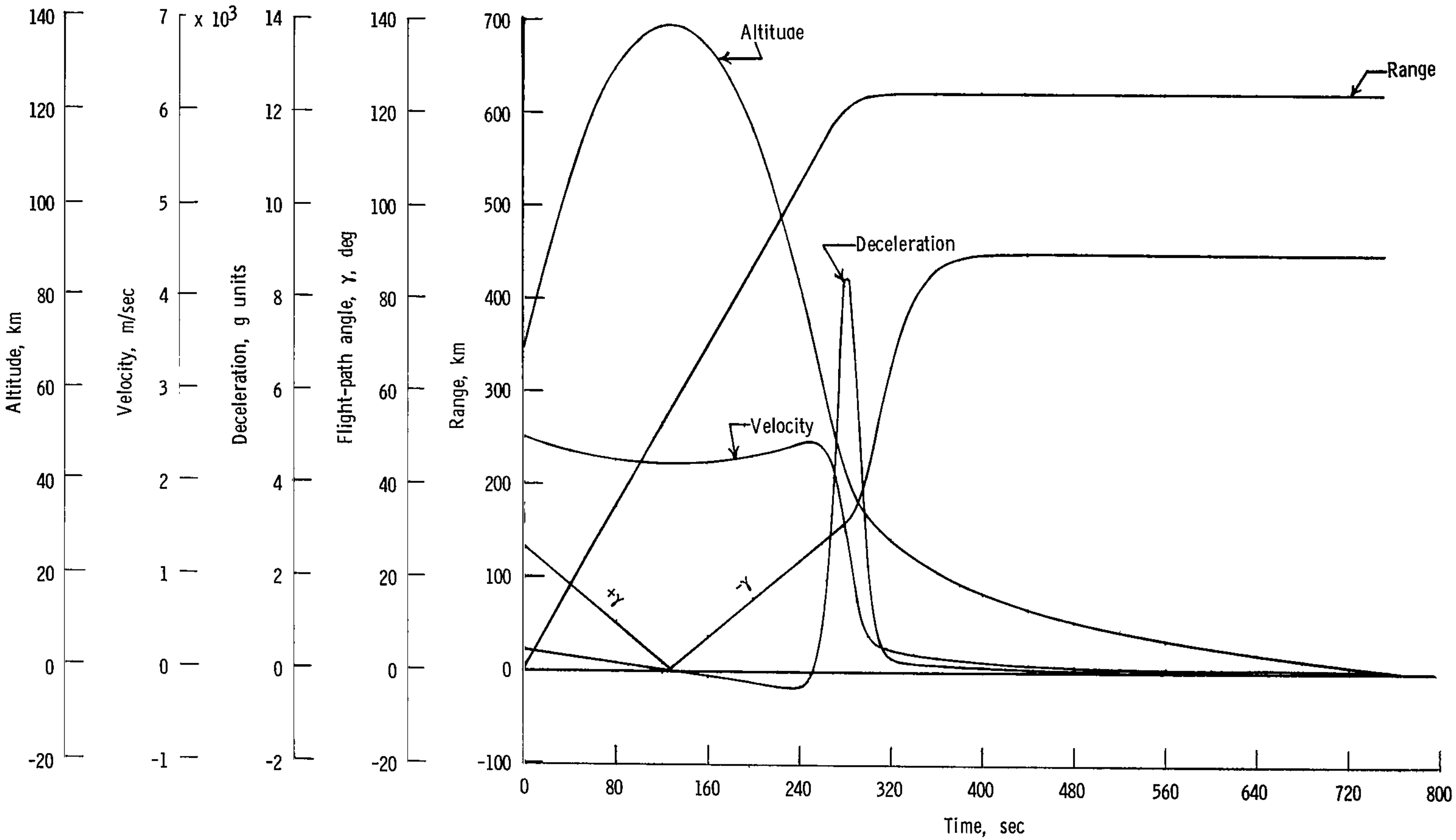


Figure 3.- Variation of booster drag coefficient with Mach number. $S_b = 855\ ft^2$ $(79\ m^2)$.



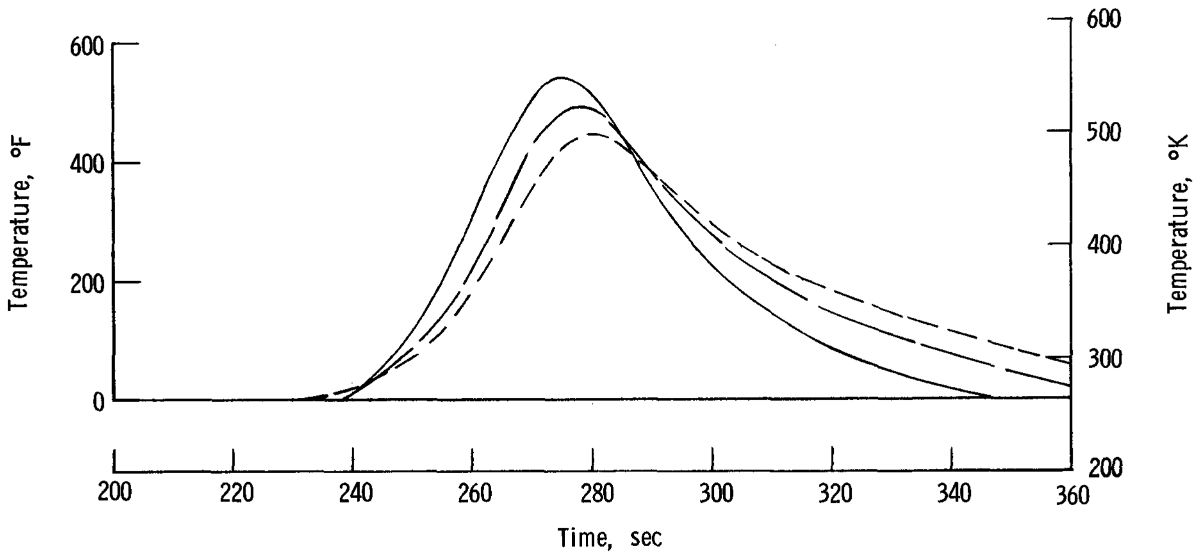
(a) U.S. Customary Units. Reentry system weight, 350 000 pounds; balloon diameter, 275 feet; corresponds to line 1 in table I(a).

Figure 4.- Typical time history of some flight values.

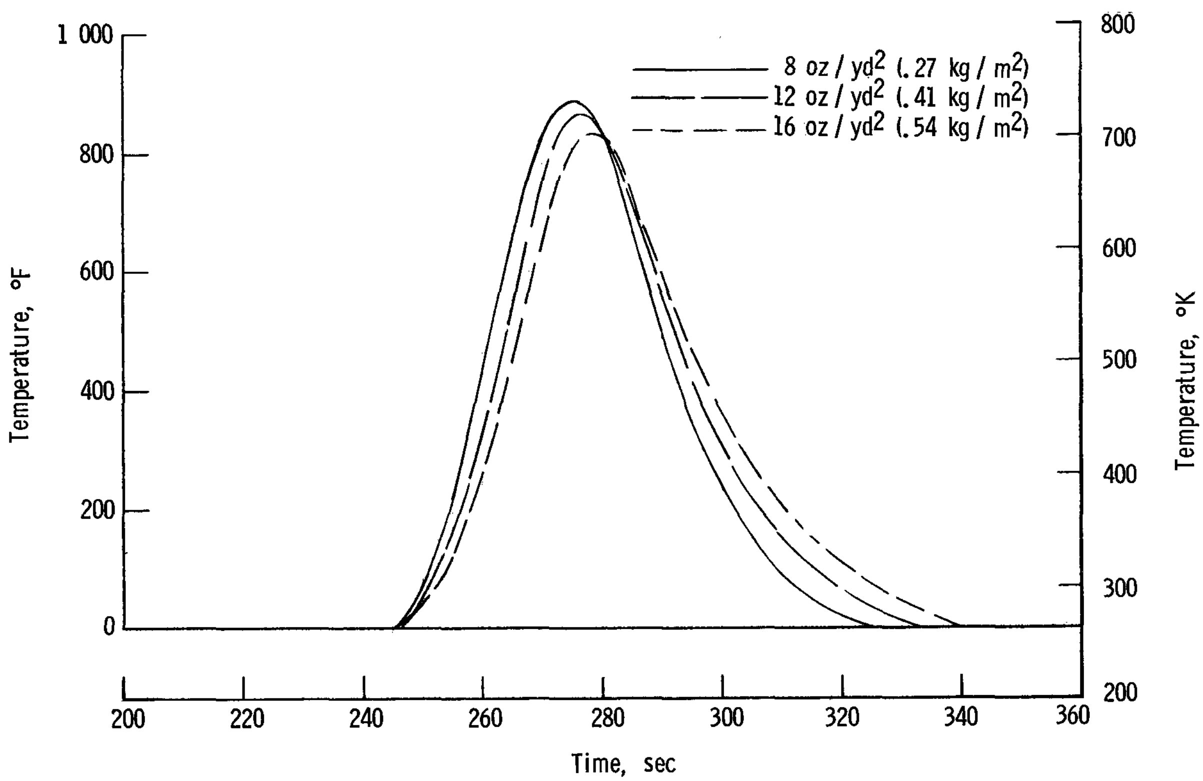


(b) International System of Units. Reentry system weight, 158 757 kilograms; balloon diameter, 84 meters; corresponds to line 1 in table I(b).

Figure 4.- Concluded.



(a) Laminar flow (zone 1 on balloon).



(b) Turbulent flow (zones 2 and 3 on balloon).

Figure 5.- Typical time histories of temperature on surface of drag balloon. Reentry system weight, 350 000 pounds (158 757 kilograms); balloon diameter, 275 feet (84 meters).

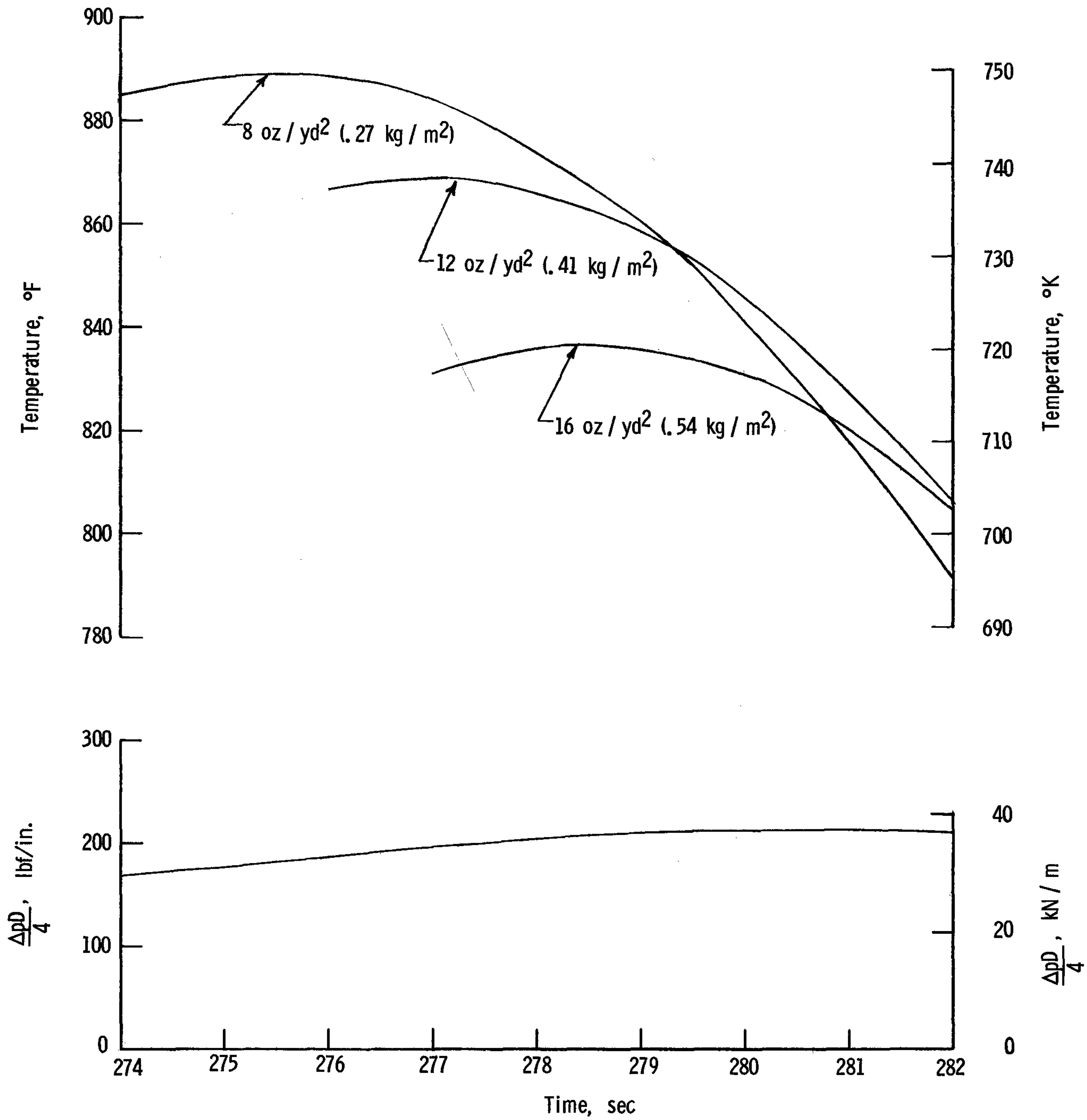
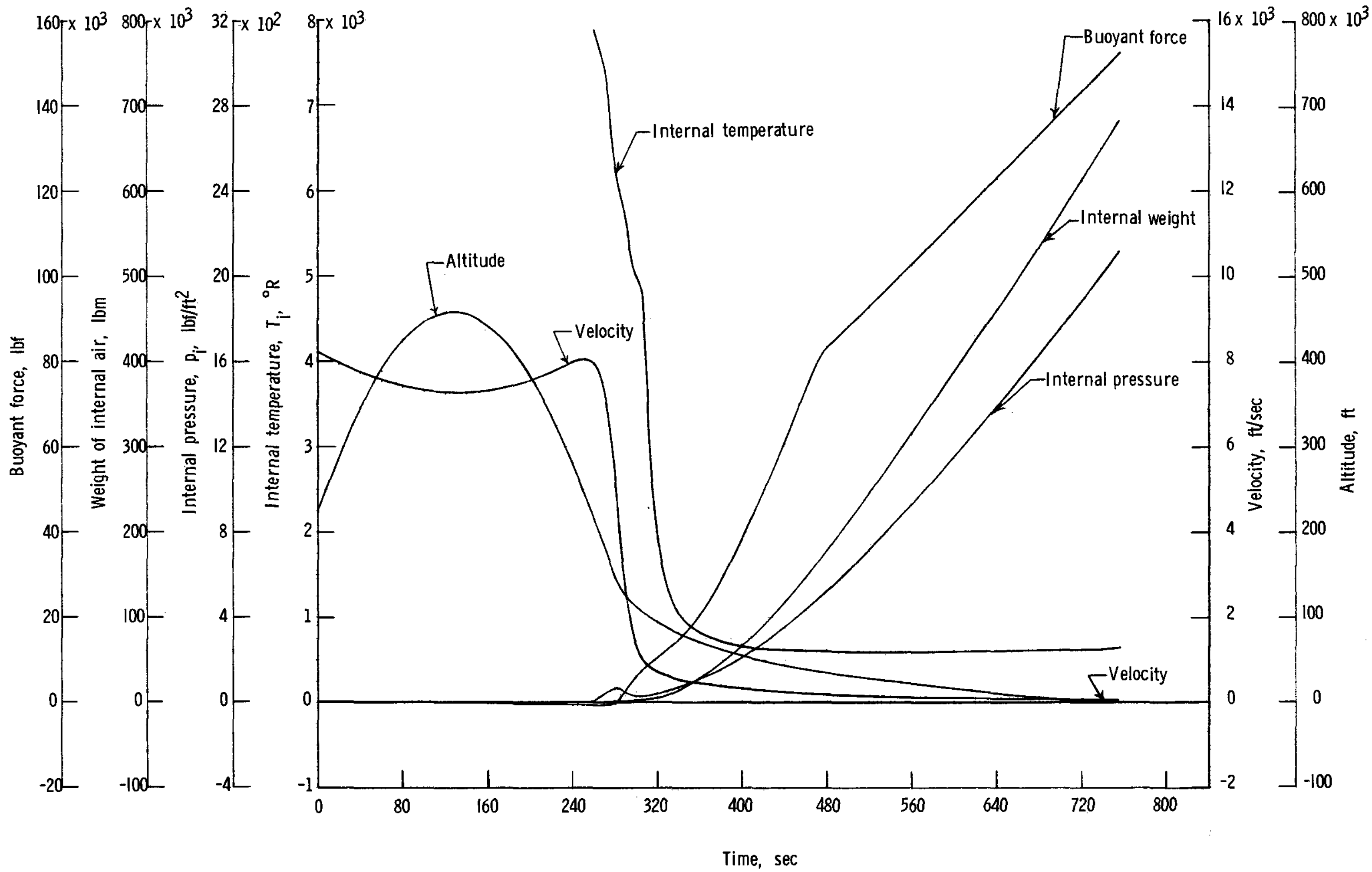
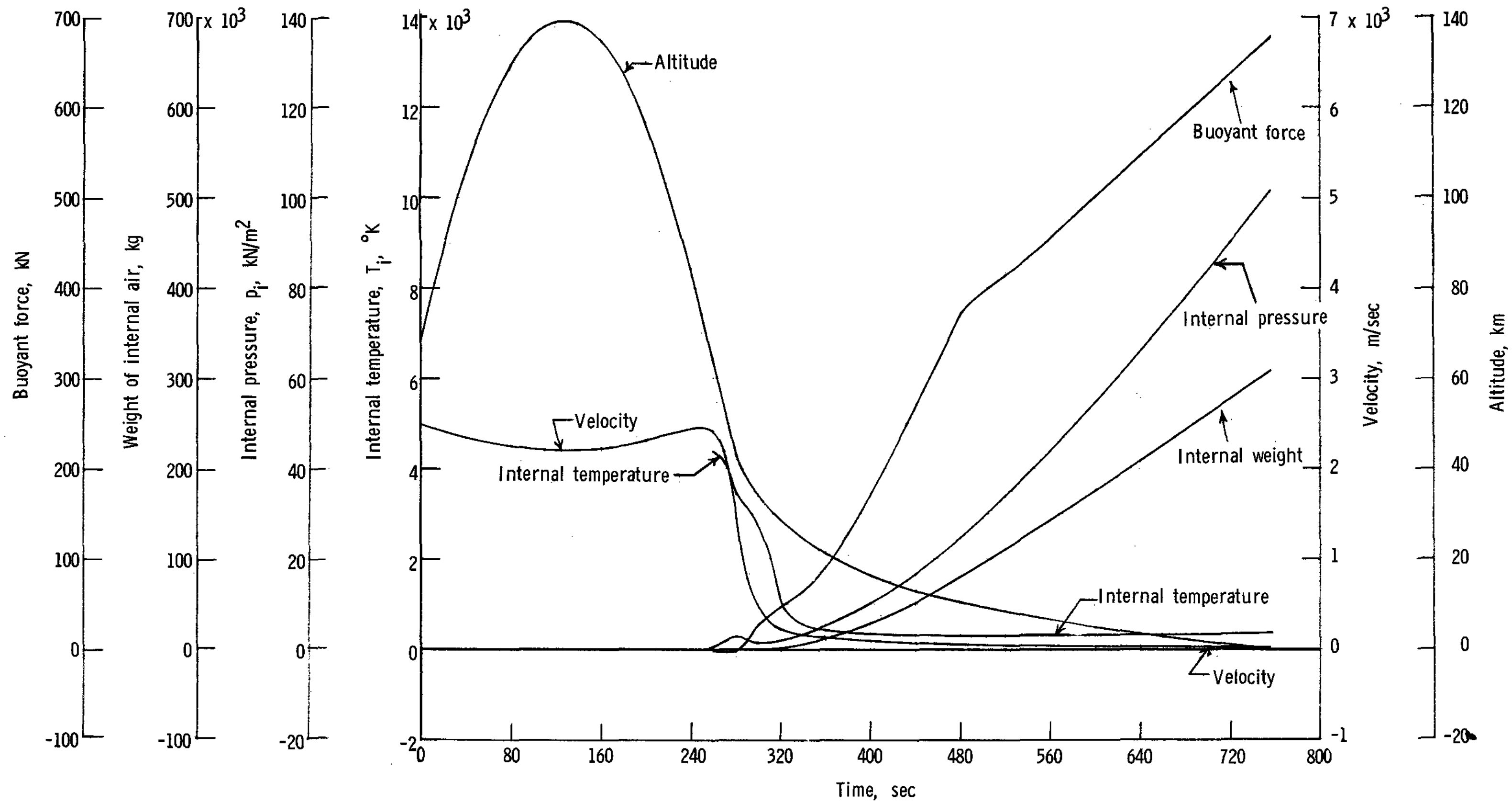


Figure 6.- Typical time histories of temperature and fabric stress in balloon skin. Reentry system weight, 350 000 pounds (158 757 kilograms); balloon diameter, 275 feet (84 meters); zone 2 on balloon; turbulent-flow data.



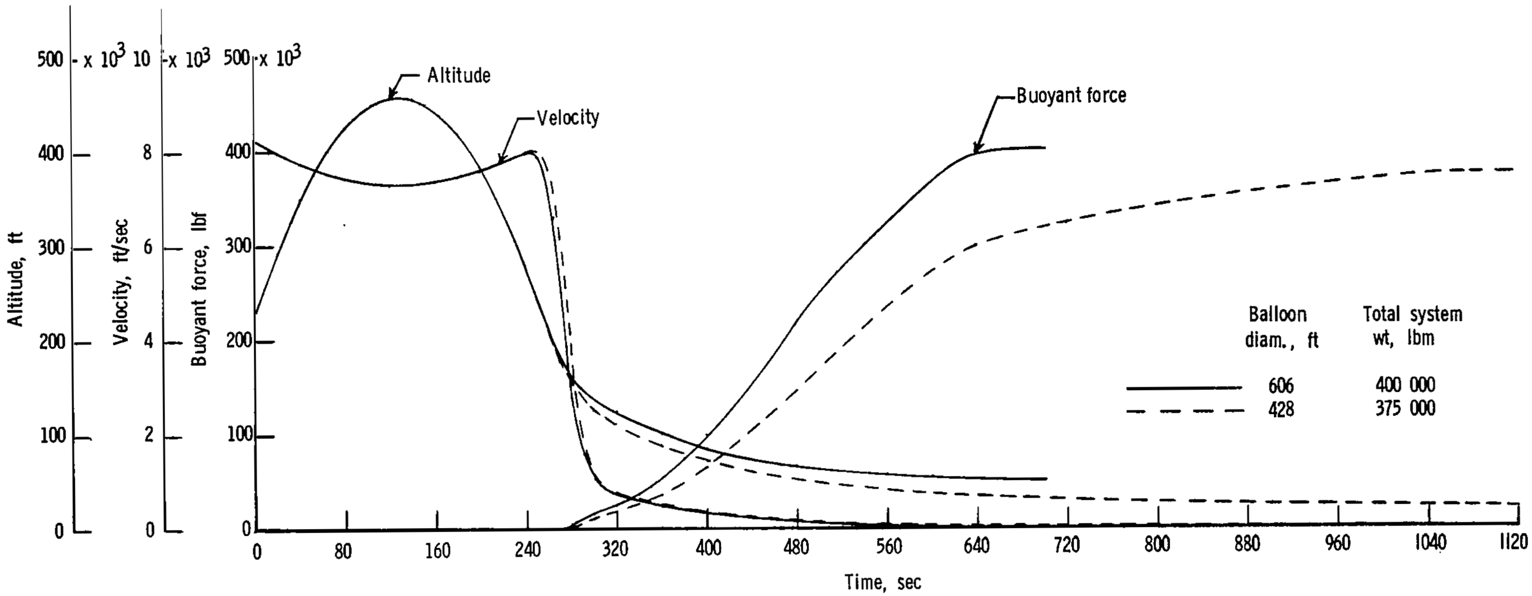
(a) U.S. Customary Units. Reentry-system weight, 350 000 pounds; balloon diameter, 275 feet.

Figure 7.- Typical time-histories of air-mass weight, pressure, and temperature inside balloon, and buoyant force.



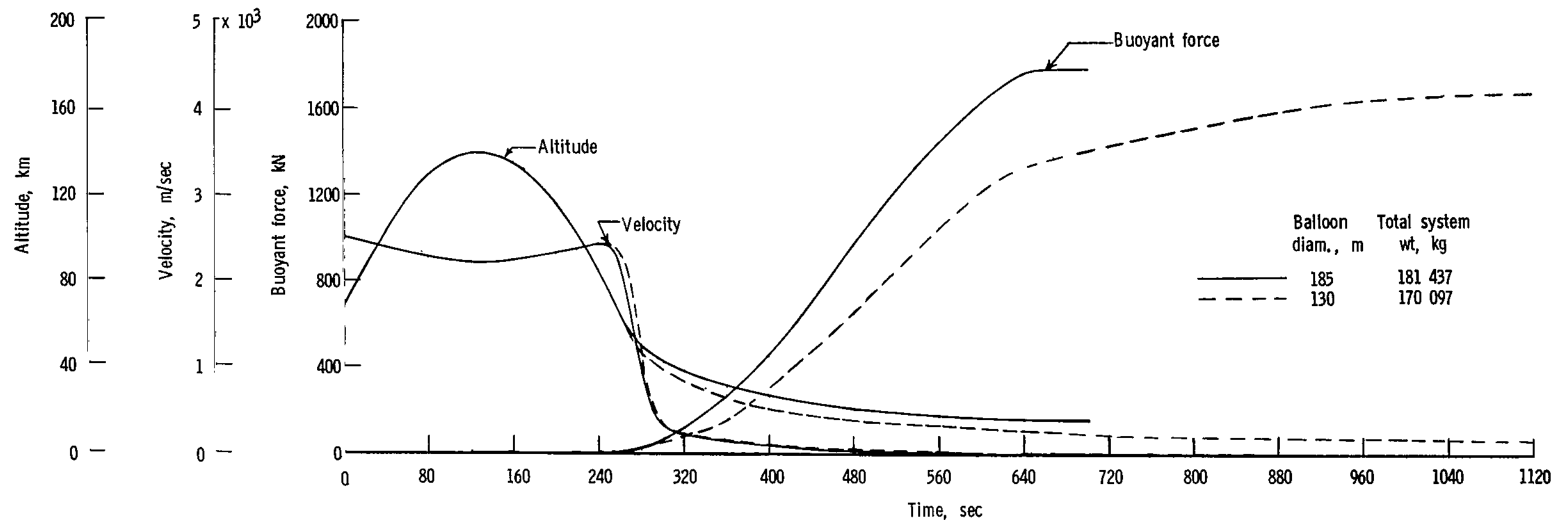
(b) International System of Units. Reentry-system weight, 158 757 kilograms; balloon diameter, 84 meters.

Figure 7.- Concluded.



(a) U.S. Customary Units.

Figure 8.- Time history of altitude, velocity, and buoyant force for two balloons.



(b) International System of Units.

Figure 8.- Concluded.

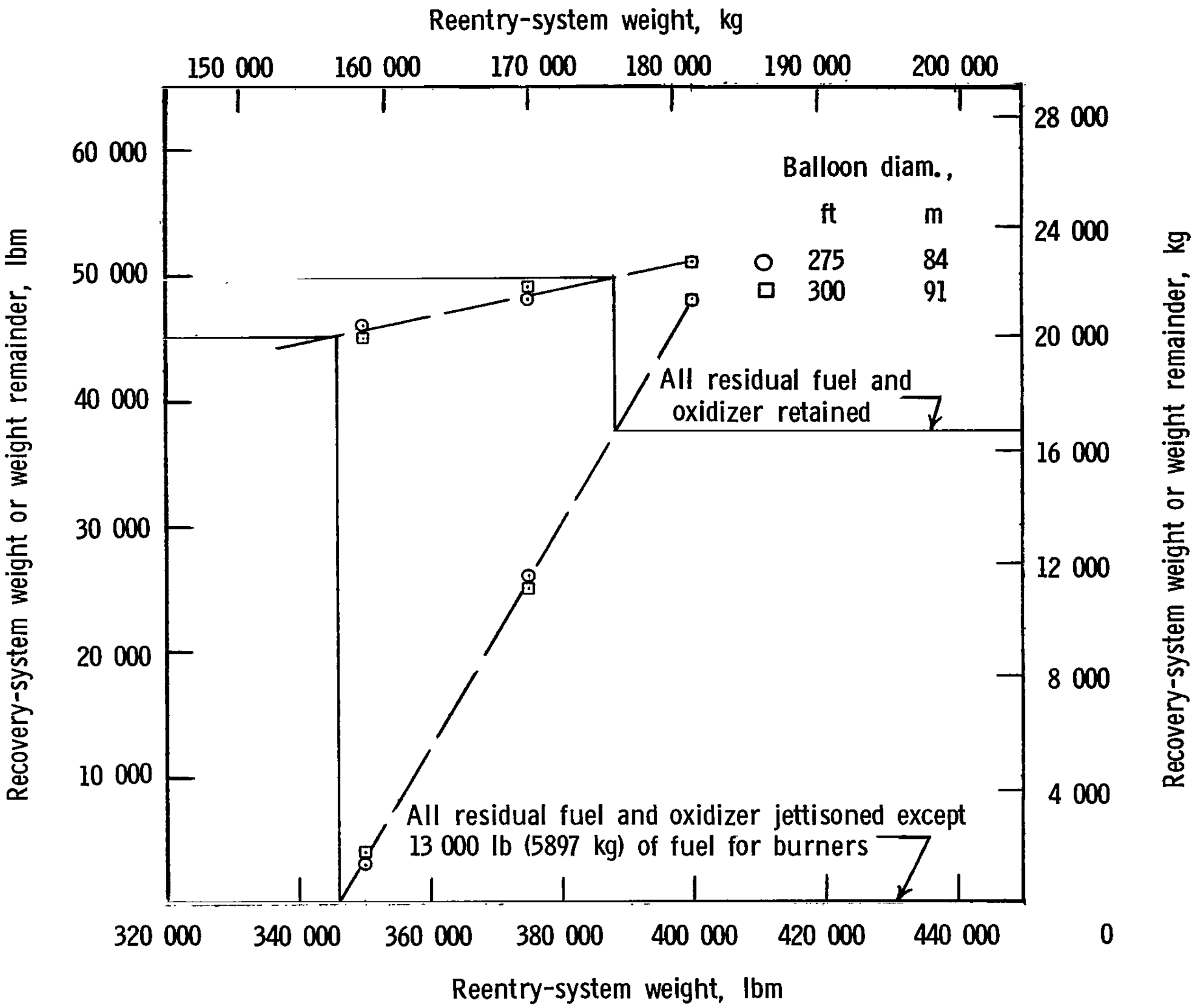


Figure 9.- Graph for determination of recovery-system weight.

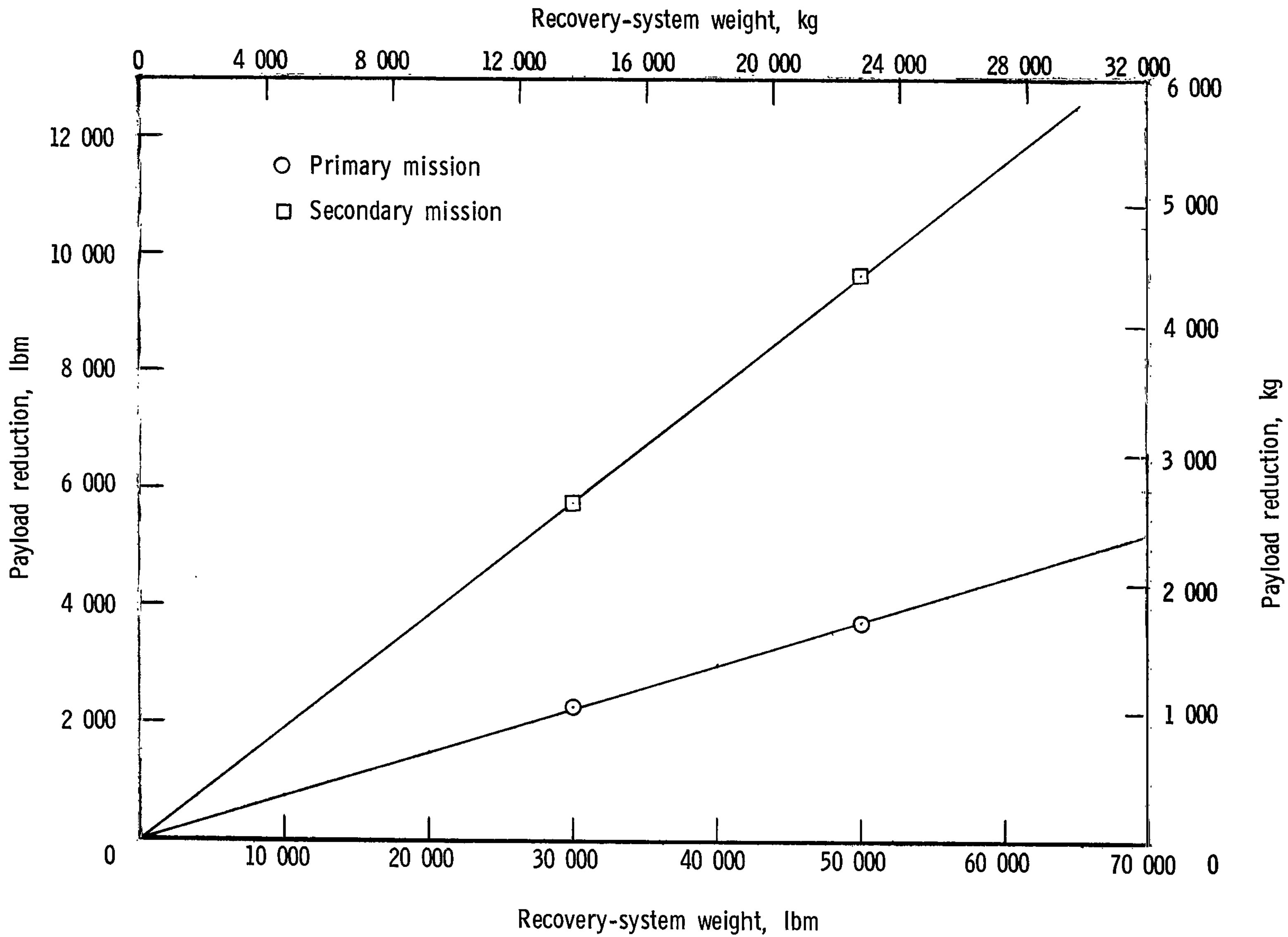


Figure 10.- Payload reduction as a function of S-1C recovery-system weight.

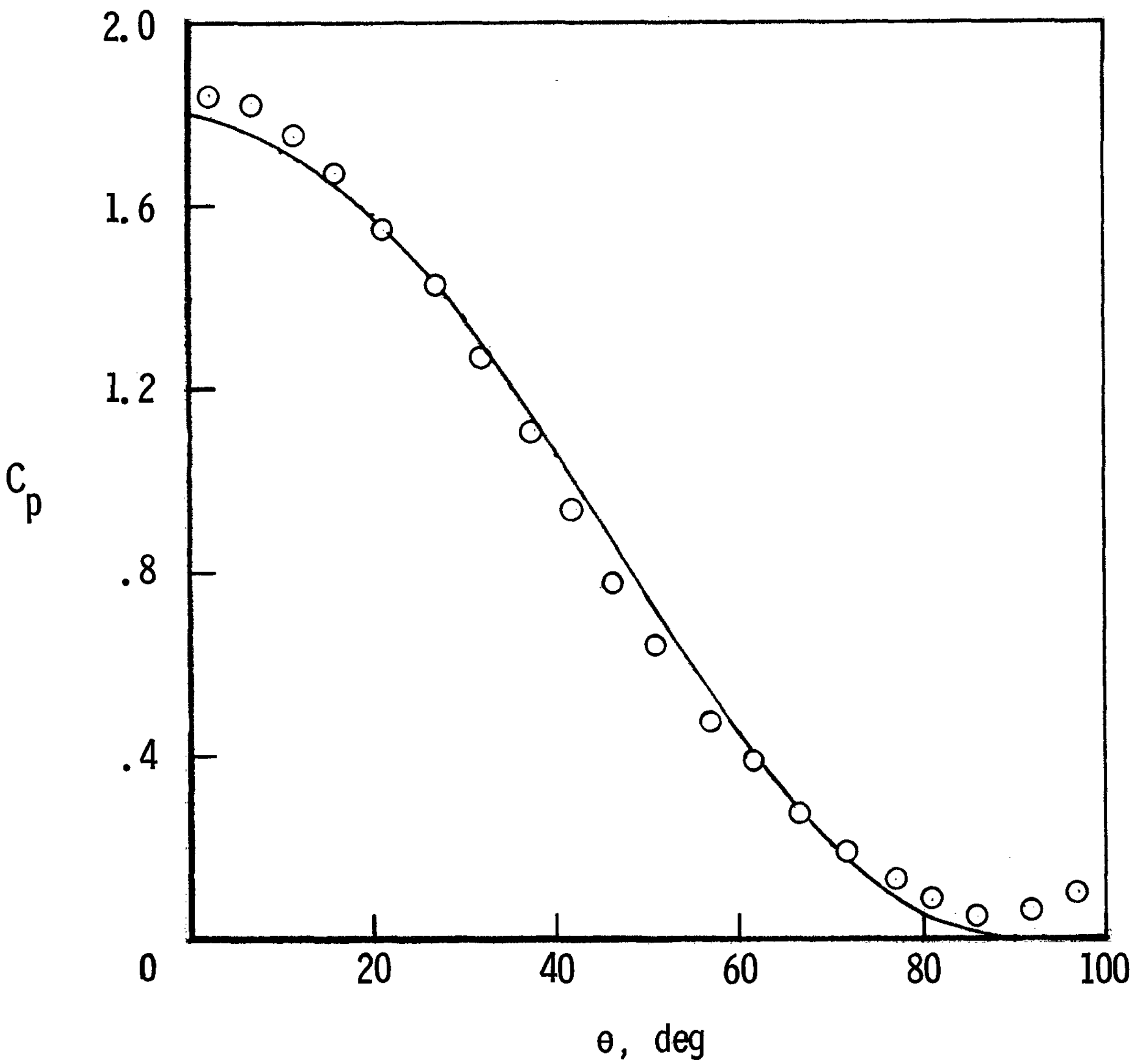


Figure 11.- External pressure coefficient on drag balloon as a function of θ. (From tests on a sphere reported in ref. 10.)

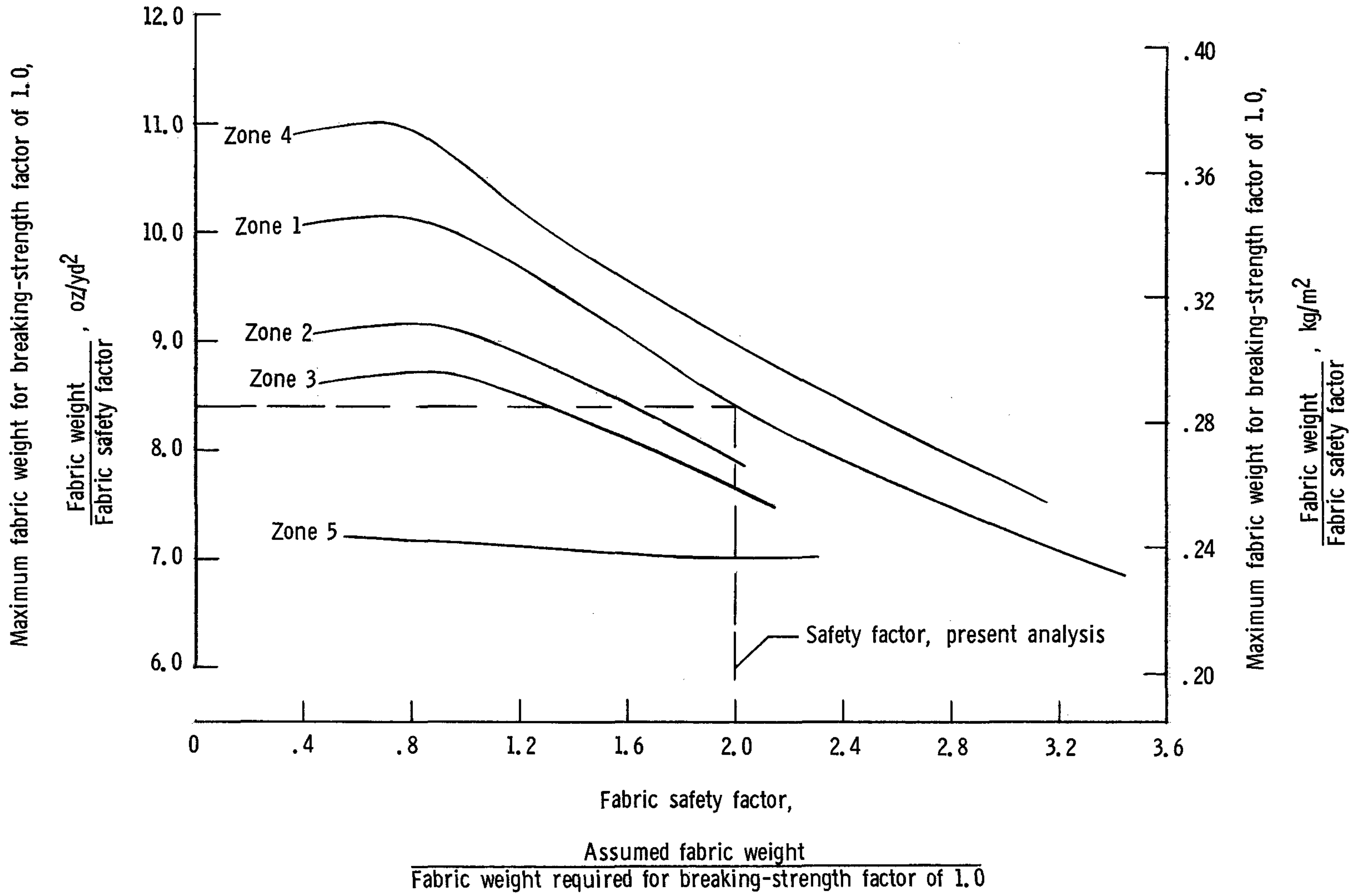


Figure 12.- Typical plot showing variation of material weight required for a breaking-strength factor of 1.0 as a function of safety factor. Reentry-system weight, 350 000 pounds (158 757 kilograms); balloon diameter, 275 feet (84 meters); turbulent flow assumed.

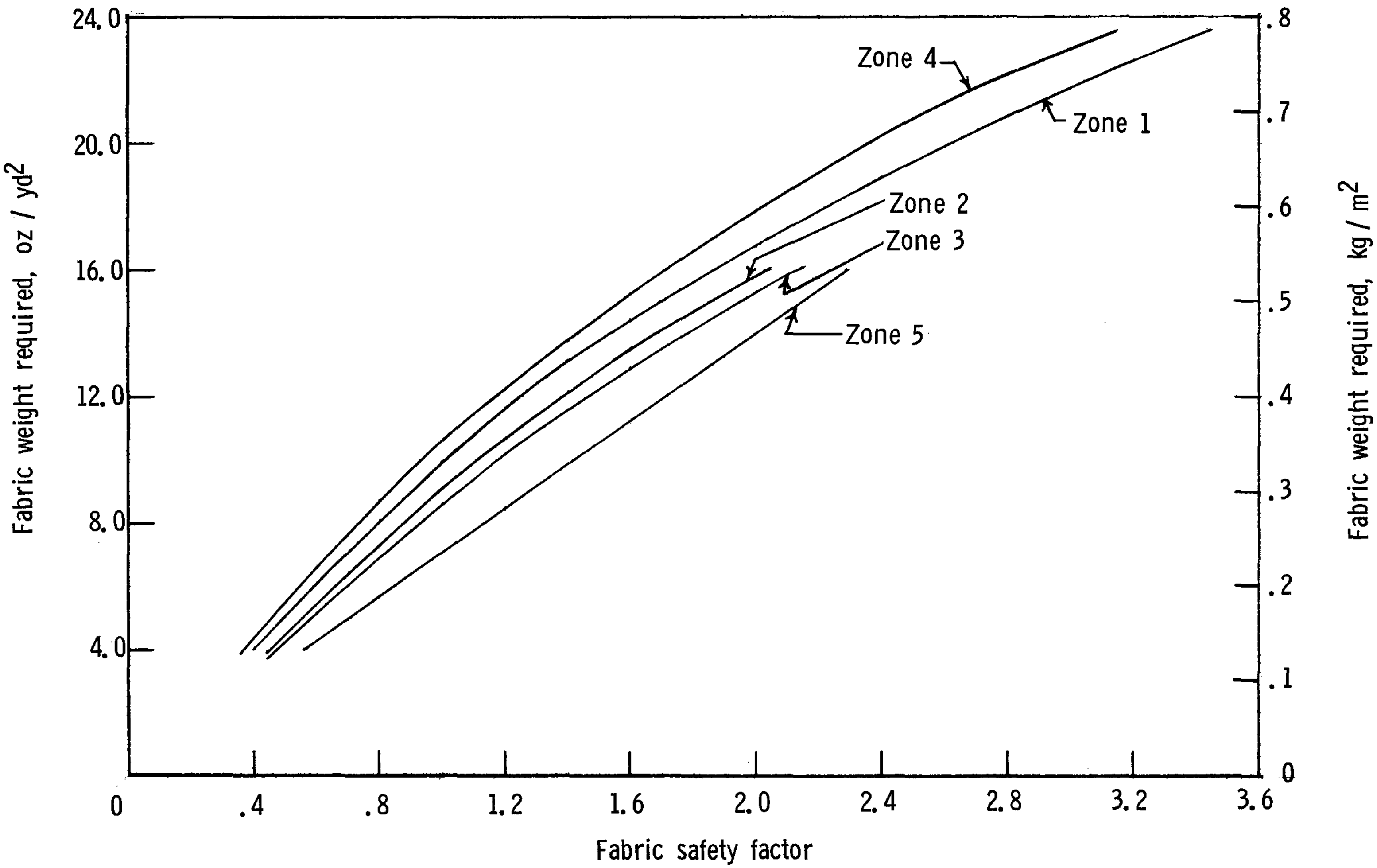


Figure 13.- Typical plot showing variation of fabric weight required in various zones on balloon as a function of fabric safety factor. Based on figure 12.

NASA-Langley, 1966 L-5096

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