EXPLORATORY INVESTIGATIONS OF THE RECOVERY OF A LARGE BOOSTER BY MEANS OF AERODYNAMIC DECELERATORS AND A HOT-AIR BALLOON

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INTRODUCTION

The NASA research organizations do generalized research on many recovery systems to provide basic information, and this paper deals with one such piece of generalized research. The scheme investigated is one which has become of increased interest for possible application to large boosters. It involves the use of a large hot-air balloon to provide buoyancy in the lower atmosphere with a subsequent dry recovery. Such a recovery system is shown in figure 1. It consists of a balloon with an open mouth at the bottom, with a burner beneath this mouth to keep the air in the balloon heated to provide buoyancy in the lower atmosphere. This system, of course, could conceivably be applied to the recovery of other space systems besides boosters, but this paper is limited to the case of booster recovery. It should not be inferred, however, that NASA necessarily considers this type of system as being among the best possible recovery systems for boosters; and other systems are also under consideration.

This paper describes two first-cut feasibility studies of the subject type of recovery system. First, an analytical investigation of some system performance factors. And second, an experimental study to see whether the balloon can be deployed and inflated with ram air entering its mouth.

ANALYTICAL INVESTIGATION

In the analytical investigation two means of using the hot-air balloon were explored. The two systems are illustrated in figure 2. In one system, called the balloon-alone system, a single large balloon is used both as the decelerator for reentry and as a buoyant device in the lower atmosphere. In this case, the balloon must be able to withstand the aerodynamic heating on reentry. The other system is called the decelerator plus balloon system, and in it smaller decelerators are used for the reentry phase and a large nonheat-protected balloon is deployed at relatively low velocities for buoyancy in the lower atmosphere. The analytical investigation explored feasibility from the standpoint of the three factors noted in figure 3. First, deceleration; that is, whether the decelerations can be kept low enough so that the booster will not break up. Second, aerodynamic heating; that is, whether the aerodynamic heating can be kept within levels that the fabric decelerator can withstand. And third, weight; or, whether the weight of the recovery system is reasonable in terms of payload degradation. The study was not an elaborate one [redacted]

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might be made to optimize a well-defined system, but was a first-cut look at a new system to see whether it was worth more serious study. This work is considered to be an example of how to apply calculation techniques for use in preliminary feasibility studies.

Balloon-Alone System

Decelerations.- Initially, to investigate deceleration levels, reentry trajectories were calculated. Simple two-dimensional point-mass equations of motion based on the assumption of a spherical, nonrotating earth were used. The equations were solved using a digital computer, and provision was made for various timings of the decelerator inflation sequence. A number of assumptions had to be made regarding inputs to the equations of motions, however, and some of these assumptions will now be discussed.

The trajectories were calculated starting from stage separation, and figure 4 shows assumed starting conditions. As shown, three different typical sets of conditions at stage separation were used. Altitudes, velocities, and flight-path angles, all referenced to the earth, are listed. Most of the analysis that will be discussed later will be based on trajectories starting from the conditions for the secondary 2 mission, because resulting decelerations and aerodynamic heating during reentry reached highest magnitudes after starting from that condition. It was assumed that inflation of the balloon was accomplished in the thin atmosphere before or near apogee and that the balloon might be inflated either by ram air or by a gas inflation system; it did not matter which in this analysis since it takes only about 400 pounds of gas to inflate the balloon in the very rarefied atmosphere near apogee. It was also assumed that ram air was used to maintain inflation as the reentry trajectory was traversed, and this assumption was important from a weight standpoint.

In making the trajectory calculations a weight was assumed for the total system recovered - the booster plus the recovery system. Since the booster weighs approximately 330,000 pounds at stage separation, a total reentry weight of 400,000 pounds was assumed on the basis of related experience with recovery systems - and this weight was varied ±5 percent.

Another area in which it was necessary to define the characteristics of the system for the trajectory calculations was with respect to drag. The proposed hot-air recovery balloons are somewhere between spherical and conical in shape, and a spherical shape with an inflatable transition strip for stability was chosen as being representative from a drag standpoint. Figure 5 shows the variation of drag coefficient with Mach number used for the balloon. The drag coefficient is based on the balloon cross-sectional area, and the data points indicated were obtained in the Langley Unitary wind tunnel (ref. 1). The subsonic portion shown is based on typical existing data for spheres. The dashed lines indicate arbitrary variations of ±10 percent which were also used in the calculations. A balloon diameter of 350 feet was selected on the basis of its being the minimum size which would provide buoyancy in the lower atmosphere with an air-heating system operating, on the basis of data from reference 2.

[redacted]

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Booster drag was used in the calculations but was quite small compared to the drag of the deployed balloon. It was assumed that the booster was at 180° angle of attack, that is, going engine-end first, as it reentered the atmosphere with the balloon trailing it. This was the attitude in which it could withstand the greatest decelerations.

Some of the deceleration results from the balloon-alone recovery-system study will be considered next. Typical time histories from one calculated trajectory are shown in figure 6. Plotted are altitude, velocity, range, flight-path angle, and deceleration in units of g. The balloon inflated over the time period indicated. Note the peak deceleration which occurs as the dense atmosphere is reentered.

When the basic drag coefficient versus Mach number data for the balloon was used, and the balloon was deployed and inflated over an arbitrary 60-second interval of time starting 50 seconds after stage separation, as was the case for this sample trajectory, maximum deceleration during reentry was about 8.0g.

It has been indicated that boosters of the S-1C class can withstand axial deceleration of 10g to 12g during reentry following burnout and stage separation, that is, with nearly empty tanks, so the 8g booster loads appear tolerable.

Inflation periods of 30 seconds as well as of 60 seconds, and starting as early as 3 seconds after stage separation were also investigated. The results indicated no appreciable effect on maximum deceleration. This lack of effect of inflation time, for inflation prior to apogee, results from the fact that the dynamic pressure drops off very rapidly after stage separation, so that there is no significant deceleration acting regardless of whether the balloon is fully inflated. Even larger inflation times than 60 seconds could be used with little effect on deceleration because of the low dynamic pressure environment near apogee.

Increases or decreases of about 10 percent in balloon drag coefficient at Mach numbers between 1.5 and 10 had only small effects on results obtained, and the trends were as expected.

Aerodynamic heating.- Inasmuch as the trajectory calculations had shown that deceleration levels were well within the limits of the booster, the next step was to examine the problem of aerodynamic heating of the decelerator. The heating characteristics were based on the trajectories already calculated.

Figure 7 lists some of the factors considered with respect to determination of aerodynamic heating of the inflated balloon. As shown, turbulent flow was assumed in the analysis because it was felt certain that the boundary layer would be largely turbulent on such a large body. An emissivity factor of 0.9 was assumed on the basis of measured characteristics of a representative sample of material with an appropriate heat-resistant coating. Account was taken of altitude and velocity using the previously calculated trajectories, and account was also taken of the radius of the nose of the balloon and the presence of the booster. Methods used in reference 3 were employed.

The results of the aerodynamic heating calculations are summarized in figure 8. These data show that the maximum balloon temperature varied from about 800° F for the primary mission to nearly 1,000° F for some of the perturbations on the secondary 2 mission. All of these temperatures are considered too high for the textile fabrics available - even heat resistant ones such as Nomex. They are, however, well within the capability of the next fabric material up the line of heat resistance - René 41 woven wire cloth.

Figure 9 describes some of the characteristics of René 41 metal cloth. The important things to note are the relatively high strength, the fact that the material retains full strength up to 1,100° F which is above the heating levels calculated, and the fact that a sealant is required to make the balloon gas tight. There are suitable flexible heat-resistant sealant materials available - materials such as silicon elastomers.

One factor which was left off of figure 9 is the price of the material. At present, René 41 cloth is prohibitively expensive for use in such a large balloon, but the investigation was continued to examine other aspects of system feasibility because of the possibility that future developments may result in greatly reduced costs for woven wire fabric or in the development of other suitably heat-resistant materials - and there appear to be such developments on the horizon.

Weight.- The next point was to examine the feasibility of the balloon-alone recovery system from the standpoint of weight. As already indicated, the assumed reentry configuration weights used were intended to include the weight of the booster, the recovery system, and any residual fuel necessary as fuel for the burners of the hot-air balloon. In figure 10, an example of the most obvious way in which the results can be interpreted is shown using the total assumed system weight of 400,000 pounds. As listed on the figure, the normal weight of the booster at cut-off is about 338,600 pounds. This weight includes about 50,600 pounds of residual and trapped fuel, oxidizer, and gas for pressurizing the oxidizer. If it is assumed that none of this fuel or oxidizer is jettisoned, 61,400 pounds of weight are available for the weight of the recovery system within the 400,000-pound reentry weight for which this trajectory was calculated. The weight of the burners, suspension lines, and controls was estimated as 14,000 pounds on the basis of inputs from manufacturers of balloons, burners, and controls, and the weight of the balloon sealant coating was estimated as 5 ounces per yard, or 13,400 pounds. This left a remainder of 34,000 pounds for the bare balloon of René 41 metal cloth. The maximum fabric stress for a balloon of this weight made of a uniform gage of material would be 275,000 psi. This maximum fabric stress was estimated on the basis of simple hoop stress inside a hollow sphere, using maximum differential pressure across the fabric. The stress indicated is much larger than can be tolerated by the René 41 metal fabric, which as noted in figure 9, has been measured at 147,000 to 172,000 psi. Consequently, much larger allowances must be made for the recovery system weight.

Figure 11 shows the highest recovery system weight that can be assumed within the total recovery configuration weight used in the calculations. This breakdown is based on the assumption that all of the residual oxidizer, the oxidizer pressurizing gas, and all of the fuel except 8,000 pounds are jettisoned. This 8,000 pounds of remaining fuel is sufficient for final deceleration and 1 hour of buoyancy at low altitude for final recovery. The allowances for burners, etc., and sealant coating are the same as before. This leaves an allowance of 96,600 pounds for the bare balloon. In this case the stress in the balloon would be 103,000 psi which is considerably less than the 147,000 to 172,000 psi ultimate strength of René 41 fabric, but the factor of safety would be undesirably low.

The results from these two weight-breakdown analyses can be extrapolated to indicate that a more reasonable factor of safety of 2.0 could be obtained with a total recovery system weight of 132,000 pounds. This is about 45 percent of the weight of the booster recovered, which at first seems high, but it is only 2 percent of the 6,000,000-pound launch weight. Perhaps the best measure of the cost of the recovery system in terms of performance is what it costs in terms of reduction in payload.

Figure 12 shows curves of payload degradation as a function of recovery system weight. The curves are each based on three points from unpublished data calculated in the range of recovery system weights up to 50,000 pounds. In this range the curves seem to be exactly straight lines and are consequently extrapolated as straight lines. Using these curves, which are certainly questionable because of the large extrapolation, we see that the application of the balloon-alone recovery system at a weight of 132,000 pounds would cause payload degradations of about 10,000 pounds for the primary mission or 25,000 pounds for the secondary missions. The payloads for the secondary missions are about 2.5 times that for the primary mission; so these values correspond to a reduction of payload of slightly less than 10 percent for either mission.

Summation, balloon-alone system.- Taken together, the analyses of the balloon-alone recovery system indicate that the decelerations encountered on the booster are within reasonable levels, that the aerodynamic heating of the decelerator can be handled by René 41 woven wire cloth, and that the recovery system does not seem to be ruled out from the standpoint of weight, or loss of payload. The prohibitive factor is that the woven wire cloth, as presently fabricated, is expensive beyond consideration and that new developments in the materials area are needed to make the system feasible - developments such as much lower costs for the woven wire fabric and the development of suitable fabrication techniques, or the development of a new material such as high-temperature glass cloth to work in the 1,000° F temperature range, or the development of low-temperature ablative coatings for high-temperature textile fabrics such as Nomex.

Decelerator Plus Balloon System

Procedures and assumptions.- The analytical procedures in investigating the decelerator plus balloon system were much the same as they were for the balloon-alone system except that a range of decelerator sizes was investigated and the range of total reentry weights covered in the calculations was larger than for the balloon-alone system.

The balloon for the decelerator plus balloon system was not subjected to aerodynamic heating and the high stresses of reentry, and was consequently assumed to be made of a light-weight plastic. A balloon diameter of 350 feet was selected, as was the case for the balloon-alone system, as being that necessary to provide buoyancy in the lower atmosphere with a reasonable level of air heating. The weight of this balloon was estimated as 10,000 pounds, on the basis of information in reference 2.

The decelerators were assumed to be inflatable aerodynamic decelerators of conical shape with an 80° apex angle. This shape has been indicated (refs. 1 and 4) to be the most promising of many types of drag devices from the standpoints of stability and of providing the highest drag coefficients per unit of frontal area in the supersonic Mach number range of interest.

Figure 13 shows the variation of drag coefficient with Mach number used in the calculations for the fully inflated decelerators. The coefficients indicated were based on decelerator cross-sectional area, and the various data points shown were obtained in several test facilities at Langley over the Mach number range of interest.

The weight of the decelerators was determined from a chart of reference 3 which is reproduced herein as figure 14. This chart shows the weight of such decelerators as a function of their diameter for various values of maximum free-stream dynamic pressure q. The weights are based on the decelerators being made of René 41 metal cloth coated with a heat-resistant sealant to make them gas tight. The chart shows a shaded band indicating the range within which such decelerators could be fabricated from single-ply René 41 cloth within the range of cloth weights which it has been possible to fabricate to date - that is, effectively within the state of the art.

Results.- The results of the study for the decelerator plus balloon system are summarized in figure 15. In all of the examples shown the weights of the dry booster, balloon canopy, burners, etc., are constant as shown at the top of the figure. And in all cases the decelerations were found to be within the 10g to 12g tolerance of the booster. Tracing through some of the numbers in figure 15 suggests certain problems, as follows:

In the first line is shown the case of a system with a single large decelerator sized to give a reentry temperature right up to the approximately 1,500° F working limit of the René 41 material. If the decelerator had been smaller, the temperature would have been higher; and if the decelerator had been larger, the system weight would have been higher. A decelerator of this size strong enough to withstand the loads during reentry would weigh 84,000 pounds. But the maximum weight decelerator of this size that can be made from single-ply fabric is only 28,500 pounds. This means that new technology would have to be developed for heavier fabric, or for multi-ply fabric. The total recovery system weight would be 108,000 pounds and this would leave 14,000 pounds for burner fuel within the total reentry weight of 410,000 pounds.

The difficulties with a system such as the one just described are relatively high system weight and the need for advanced materials and fabrication technology for the decelerators. It seemed that if several smaller decelerators were used to achieve the same drag, their total weight would be less and the fabric stress would be reduced to where it might be possible to fabricate them with single-ply fabrics of weights that have already been produced. Consequently the study was extended to consider the use of multiple small decelerators. Nothing is known of the drag or stability of clustered decelerators, but the study was made on the basis of an assumption that there was no interference effect and that the drag of a cluster of decelerators was equal to the sum of the drag of that many isolated decelerators.

The second line in figure 15 shows that if three smaller decelerators having the same total cross-sectional area as the single large decelerator were used, the maximum temperature is the same and that the total reentry weight is less; but that the individual decelerators would still have to be heavier than could be fabricated from single-ply cloth.

The last line in figure 15 shows that if six decelerators having the same total cross-sectional area as the single large decelerator were used, the maximum temperature would still be about the same; also that the decelerators could be fabricated from single-ply fabric of weights that have already been produced, that the recovery system weight would be 53,000 pounds, and that 13,000 pounds would be available for burner fuel within the 354,000 pounds total reentry weight. This much fuel (13,000 pounds) would provide for initial heating and about 2 hours of buoyancy at low altitudes.

A recovery system weight of 53,000 pounds would correspond to a reduction in payload of about 4 percent. Such a recovery system weight for the decelerator plus balloon system is only about 40 percent of that for the balloon-alone system. However, the heating levels are higher, so that such a system would have to have more heat-resistant materials, and it is a more complicated system. Also, some cable and/or tie-line arrangement may have to be used which would add to the weight of the recovery system.

Implications of Analytical Investigation

It should be apparent that these feasibility studies were based on some fairly gross assumptions, particularly with regard to weights, the stability and inflation characteristics of the ram air inflated balloon at hypersonic speeds and extreme altitudes, the drag and stability of clustered decelerators, and the development of fabric materials and fabrication techniques. This is the normal state of affairs in first feasibility studies of new systems - such studies seldom give clear-cut answers of feasible or not feasible. These two studies did, however, indicate that either of the two systems for applying the hot-air balloon as a recovery device for large boosters is sufficiently promising to warrant further investigation of the problems brought out.

EXPERIMENTAL INVESTIGATION

The experimental investigation of the low-speed deployment, inflation, and stability characteristics of a balloon recovery system corresponds to the deployment and inflation of a subsonic balloon such as that incorporated in the decelerator plus balloon system described above. The nominal deployment and inflation sequence used in the tests is illustrated in figure 16.

The first scene in figure 16 shows the payload descending with a drogue parachute for stabilization and speed reduction. The next scene shows the bag in which the balloon is packed being released from the payload. In the third scene, the balloon is shown fully extended but still attached to a break cord which assures full extension of the balloon before the cord breaks. Next, the break cord has broken and the balloon is beginning to inflate by ram air entering its open mouth. The last scene shows the balloon fully inflated. At this point the burner would be lighted to heat the air to provide buoyancy. The tests were actually made without burners, however, to check just the deployment and cold-air inflation of the balloons.

The investigation was made primarily by means of drop tests of 54-foot-diameter balloons with a 1,000-pound payload at the Air Force-Navy Joint Parachute Test Center at El Centro, California; but there were also some supporting tests of a 6-foot-diameter balloon with a scaled-down payload at Langley. This is an example of an approach in which studies of a new system are frequently started with small-scale wind-tunnel tests to try to discover major problems and solve them before starting more expensive tests.

First, free-drop tests of 6-foot-diameter balloons were made in the Langley Spin Tunnel, which is a 20-foot-diameter vertical wind tunnel. In these tests it was found that the balloon inflated very slowly because its mouth tended to open only slightly at first, and that, when the balloon did finally open fully, it began to translate and oscillate in the tunnel and a dimple or impression developed on its lower side. When the simulated altitude was changed from 15,000 feet to 50,000 feet by increasing the relative density of the model-scaled payload, these moderately unstable characteristics worsened. There was a question as to whether these were true stability characteristics of the balloon or whether they were the result of varying tunnel-wall effects as the balloon moved from side to side in the tunnel. Consequently, outdoor drop tests were made in which one of the same 6-foot-diameter balloons was dropped from a helicopter. This balloon exhibited the same type of stability that it had shown in the wind tunnel thereby showing that the instabilities were not due to wind-tunnel wall effects.

In an attempt to decrease or eliminate the oscillations and dimpling of the fully inflated 6-foot-diameter balloon, which were believed to be caused by random shedding of vortices off the top of the balloon, a trip fence was added around the balloon at its maximum diameter to cause the flow to separate at that location. The addition of this fence eliminated the oscillations and dimpling.

When the 54-foot balloon was dropped from an airplane flying at 17,000 feet and 130 knots, it was found that the deployment technique initially used was unsatisfactory and caused the balloon to burst. Figure 17 illustrates what happened. The first scene shows the payload descending with a trailing drogue parachute. The next scene shows the balloon starting to deploy from the bag; note the large bell-mouth shape of the nozzle. The third scene shows the balloon about 50 percent extended and a large bubble of air ingested in it; note that the nozzle opening was then smaller than when the balloon was initially deployed. In the next scene the balloon is only about 70 percent extended, but the uninflated balloon fabric has fallen out of the bag and the break cord has broken prematurely as a result of an up and down pulsing motion of the top of the balloon. The last scene shows the top of the balloon bursting because of the dynamic loads which occurred as the formerly uninflated upper part of the balloon extended and inflated too rapidly.

A modified deployment technique was devised which worked satisfactorily, and this can be illustrated by referring to figure 16 again. A reefing line was used around the bottom of the balloon to keep it completely closed until the entire balloon was out of the bag and the balloon suspension lines were taut. (See scene 3 of fig. 16.) This prevented premature ingestion of a large bubble of air such as had occurred using the original deployment technique. Several seconds later the reefing line was cut by a pyrotechnic device and inflation of the balloon began. It took about 2 minutes for inflation to be completed and the stability and shape of the balloon were, in general, similar to those observed with the 6-foot-diameter balloon in the spin tunnel. At the scale of the 54-foot-diameter balloon, however, the stability characteristics did not seem bad enough to warrant the installation of a trip fence.

CONCLUDING REMARKS

The results of these studies indicate that the hot-air balloon recovery system shows sufficient promise that continued work on the problem areas of the system is justified. This work might possibly include: additional system performance studies; materials development work; deployment, inflation, and aerodynamic-loads tests; and hypersonic stability, drag, and aerodynamic heating evaluations. However, some of the possible problem areas brought out are too big and too important to permit immediate development of the hot-air balloon as an operational system for space-vehicle recovery.

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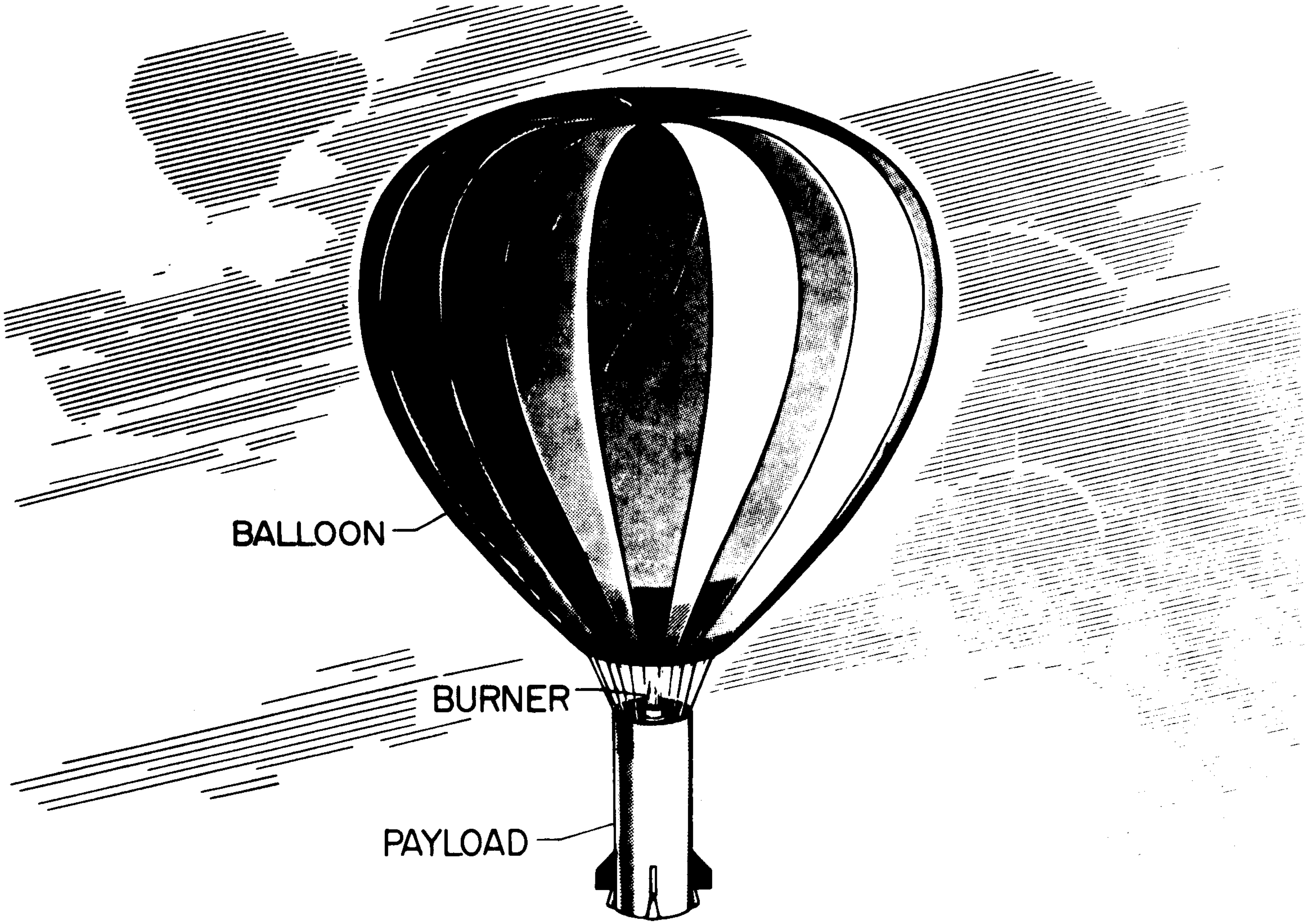

NASA

Figure 1.- Recovery system elements.

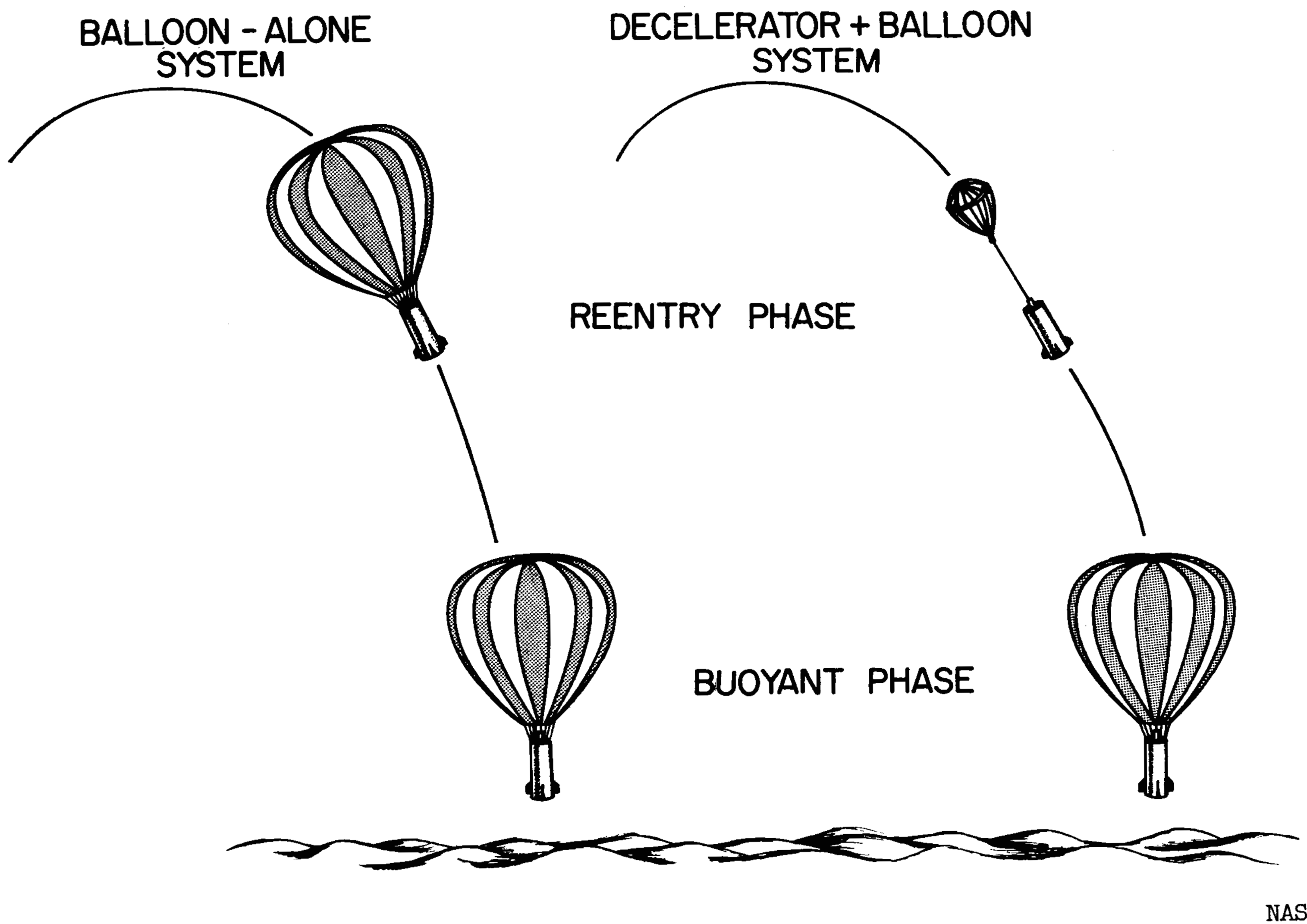

Figure 2.- Two systems studied in analytical investigation.

I. DECELERATION

II. AERODYNAMIC HEATING

III. WEIGHT

NASA

Figure 3.- Factors explored in analytical investigation.

MISSION	ALTITUDE, FT	VELOCITY, FPS	FLIGHT-PATH ANGLE, DEG
PRIMARY	203,000	7700	23.9
SECONDARY 1	208,500	8300	22.5
SECONDARY 2	225,000	8240	26.2

NASA

Figure 4.- Typical flight conditions at stage separation.

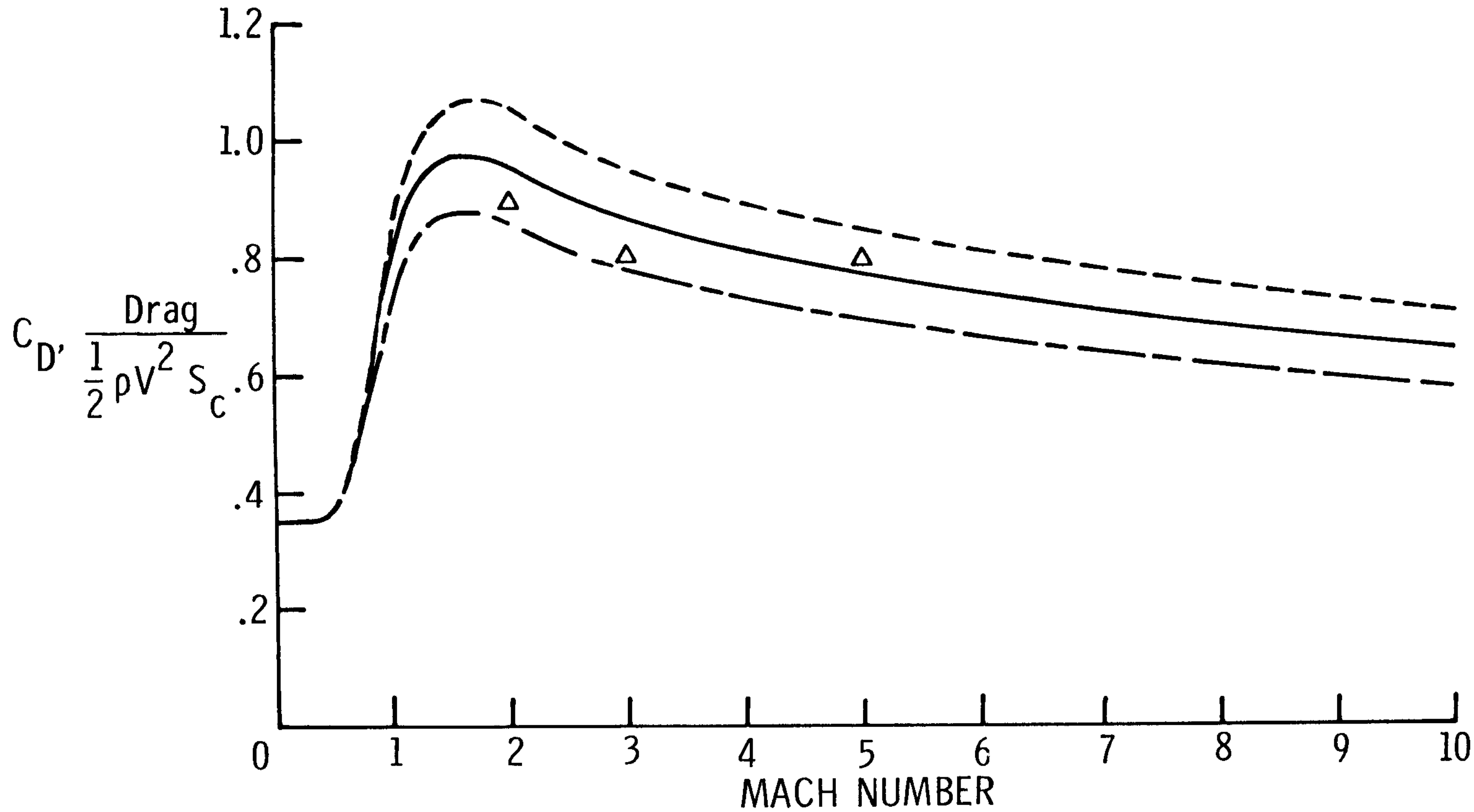

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Figure 5.- Variation of balloon drag coefficient with Mach number.

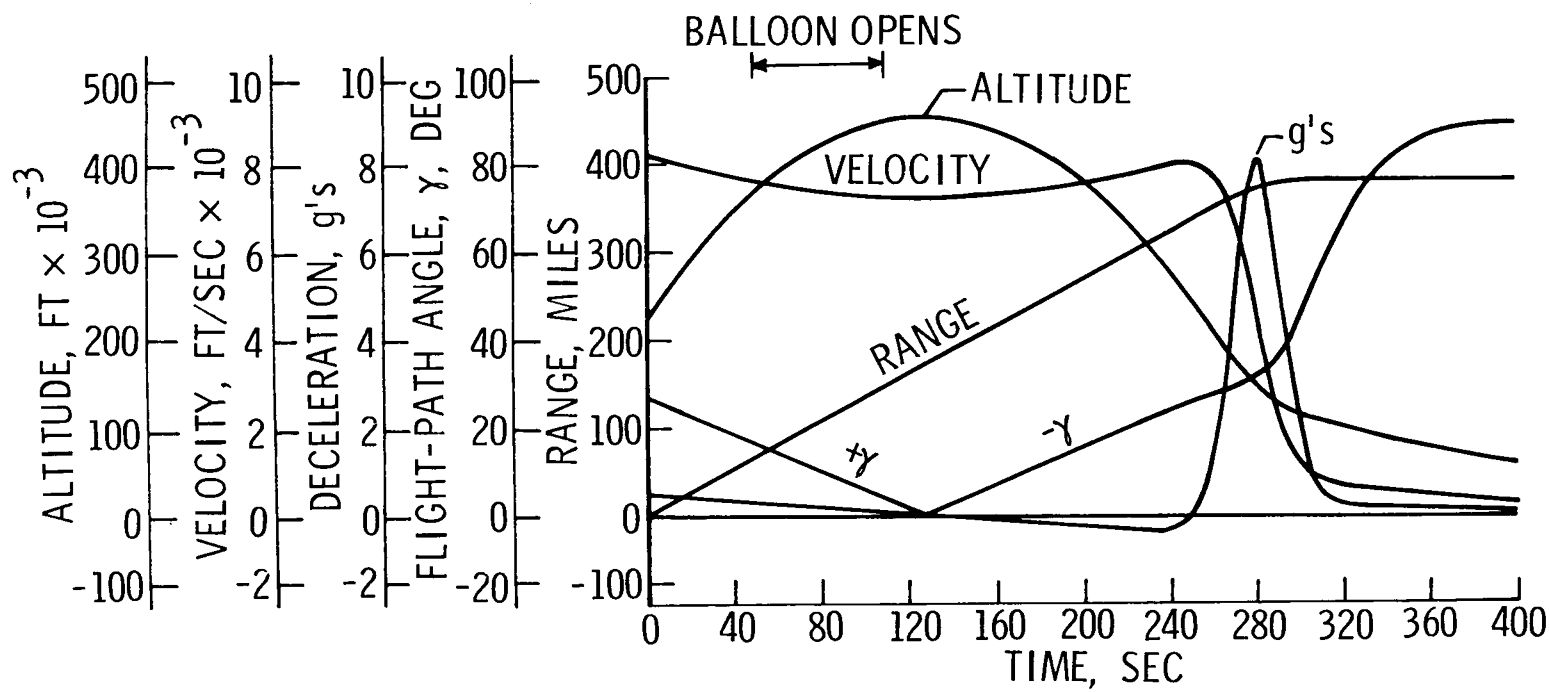

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Figure 6.- Typical time histories of flight variables.

TURBULENT FLOW

EMISSIVITY FACTOR, 0.9

FUNCTION OF:-

- ALTITUDE
- VELOCITY
- NOSE RADIUS
- PRESENCE OF BOOSTER

NASA

Figure 7.- Factors considered with respect to calculation of aerodynamic heating on balloon.

MISSION	CONDITION	TEMP., ^{o}F
PRIMARY	BASIC	810
SECONDARY 1	BASIC	896
SECONDARY 2	BASIC	951
SECONDARY 2	C_D DECREASED 10 PERCENT	979
SECONDARY 2	MASS INCREASED 5 PERCENT	967

NASA

Figure 8.- Summary of aerodynamic heating results on balloon.

BASIC WEIGHT	1.093 LB/YD^2
ULTIMATE STRESS, WARP	147,000 PSI
ULTIMATE STRESS, FILL	172,000 PSI
FULL STRENGTH TO	1100^0 F
HALF STRENGTH AT	1500^0 F
SEALANT COATING WEIGHT	5 OZ/YD^2

NASA

Figure 9.- René 41 metal cloth characteristics.

BOOSTER RECOVERY MASS	338,600 LB	
BURNERS, SUSPENSION LINES, CONTROLS, ETC.	14,000	61,400
SEALANT COATING FOR BALLOON	13,400	
BARE BALLOON	34,000	
TOTAL	400,000	
MAXIMUM FABRIC STRESS	275,000 PSI	

NASA

Figure 10.- An interpretation of the results in terms of weights and fabric stress. Total reentry weight = 400,000 lb.

BURNERS, SUSPENSION LINES, CONTROLS, ETC.	14,000 LB	
SEALANT COATING FOR BALLOON	13,400	124,000
BARE BALLOON	96,600	
DRY BOOSTER	288,000	
RESIDUAL FUEL	8,000	
TOTAL	420,000	
MAXIMUM FABRIC STRESS	103,000 PSI	

NASA

Figure 11.- Weight breakdown for 420,000-lb reentry.

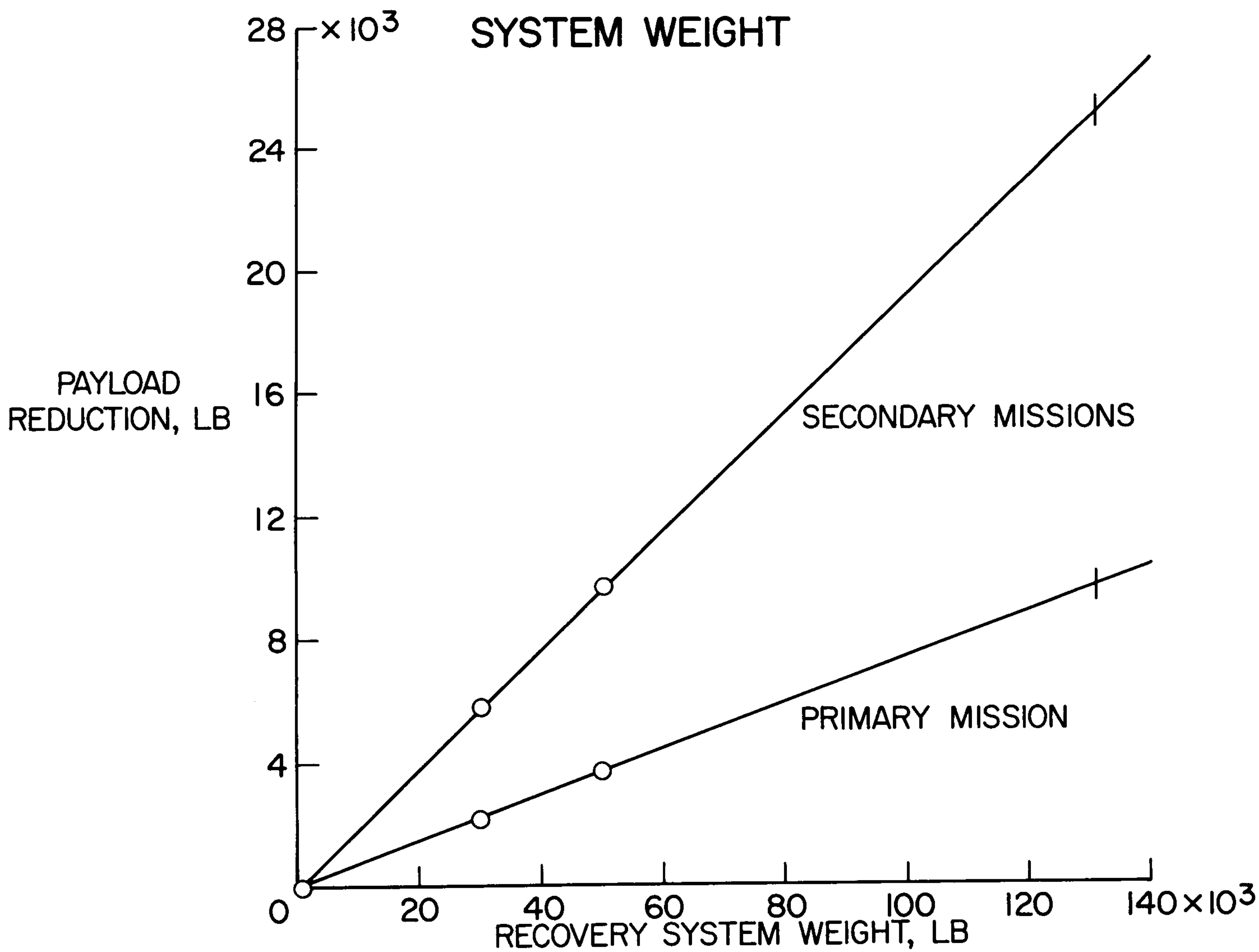

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Figure 12.- Payload reduction weight as a function of recovery system weight.