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RECOVERY OF THE SI-C STAGE OF THE SATURN V - A PRELIMINARY FEASIBILITY STUDY

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BROWN
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SCIENTIFIC RESEARCH LABORATORIES
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ABSTRACT

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This report is a preliminary study to determine the feasibility of recovering the Saturn V booster by parachute. The major problems that can be expected during recovery are outlined and some possible solutions are discussed.

AUTHOR

LIST OF SYMBOLS

A	Parachute projected area
D	Parachute diameter
d	Diameter of peripheral tube
L	Arc length of peripheral tube between radial tubes
P	Total circumferential force in peripheral tube
Q	Total tangential force in parachute radial rib tube
q	Dynamic pressure
R_o	Radial distance from center line of vehicle to center line of peripheral tube
R_1	Meridional radius
R_2	Hoop radius
R_3	Radius of curvature of peripheral tube
S	Computed maximum tensile stress in tie line
T	Total pull in four tie lines at each radial rib tube
t	Parachute material thickness
V	Velocity

Greek Symbols

α_T	Angular of tie lines with respect to axis of vehicle
α_o	Central angle subtended by length, L
α_1, α_2, α_3	Chord angles as shown in Figure A-1
ρ	Atmospheric density
σ_ρ	Maximum tangential stress in peripheral tube
σ_1	Meridional stress
σ_2	Hoop stress

TABLE OF CONTENTS

INTRODUCTION

The cost of the SI-C stage of the Saturn V vehicle is estimated at \$8,000,000.00. This high cost makes the recovery of these boosters very attractive indeed. Several studies have been made (1, 2, 3, 4, 5, 6)* of the recovery of large boosters using paragliders (Rogallo wing), balloons and parachute clusters. It has been shown (3) that winged recoverable booster systems are not economically competitive for programs involving 50 flights or less, due to their very high development and hardware costs. The balloon systems appear quite attractive but would require the on-board storage of more than 75,000 lb of hydrogen or helium which is quite a large weight penalty.

This preliminary study will investigate the feasibility of recovering the Saturn V booster by parachute. This investigation is not intended to be a detailed study nor is it intended to offer concrete solutions to many of the problems involved. This investigation will outline the major problems that can be expected and discuss possible solutions.

*Numbers in parentheses refer to references at end of report.

ANALYSIS

The problems of booster recovery may be broadly classified as follows:

1. Stabilization after burnout
2. Aerodynamic heating
3. Descent
4. Soft landing and floatation.

Stabilization After Burnout

After booster burnout some device must be used for aerodynamic stabilization to prevent the booster from tumbling and to orient it along the flight path. The shape and center-of-gravity location of the booster indicate that an engine-first attitude is probably most desirable. This attitude gives minimum aerodynamic instability and allows impact loads to be applied to the thrust structure. This attitude also allows recovery devices to be deployed from the inter-stage area which is a convenient location.

Two methods which have been considered for achieving stabilization are (a) the deployment of towed bluff bodies, and (b) the positive actuation of metal dive brakes. The dive brakes, although very effective, are expensive and heavy. A very promising technique is the use of towed metal cones; however, additional information of their free flight dynamic behavior is required (3).

Aerodynamic Heating

This report makes no attempt to compute actual temperatures of the booster or the parachute; however, the stagnation air temperature was computed along the trajectory. The maximum stagnation temperature was found to be approximately 1400° F. It is highly unlikely that this temperature would be reached by the booster or the parachute. A rough estimate indicates that the maximum temperature experienced by these components would be about 700° F.

Descent

The problem of descent is of major importance. The velocity of the vehicle must be reduced to a value which will allow the booster to impact into the water without appreciable damage. The determination of this allowable impact velocity is not only a hydrodynamics problem but also a major structural analysis problem. For the purposes of this report, the allowable impact velocity was assumed to be 100 ft/sec.

To determine the required parachute size for an equilibrium velocity of 100 ft/sec, the parachute drag force at terminal velocity is equated to the booster weight:

$$\frac{1}{2}\rho V^2 A = 570,000$$

At an altitude of 5000 ft, $\rho = 2.05 \times 10^{-3}$ and the required parachute area is

$$A = \frac{2(570,000)}{\rho V^2} = \frac{2(570,000)}{(2.05 \times 10^{-3})(100)^2} = 55,000 \text{ ft}^2 .$$

In order to obtain a velocity-time history of the booster with various sizes of parachutes, a plane trajectory digital computer program (8) was used. This program uses numerical techniques to solve the equations of plane motion of a point mass traveling over a flat, non-rotating earth. The density of the atmosphere is assumed to vary as an exponential function of the altitude, and the aerodynamic drag is assumed to be proportional to the product of density and the square of the velocity. The initial conditions used as an input to this program were:

Altitude - 300,000 ft

Velocity - 3000 ft/sec

Booster Weight - 570,000 lb

Path Angle - 60 degrees

Parachute Drag Coefficient - 0.9

The results of computer runs using parachute areas of 50,000 ft^2 and 60,000 ft^2 are shown in Figure 1. The maximum velocity obtained was about 4000 ft/sec and the maximum dynamic pressure experienced by the parachute was about 70 lb/ft^2. This pressure along with the 700°F temperature constitute the design criteria for the parachute.

The pressure of 70 lb/ft^2 is rather high for a standard parachute shape. For this reason the toroidal shape as shown in Figure 2 was chosen. For the same dynamic pressure, the stress in the compound toroidal shape will be considerably smaller than the stress in the standard parachute shape. Some control of the path of descent can be obtained by moving the bottom ends of the tie lines.

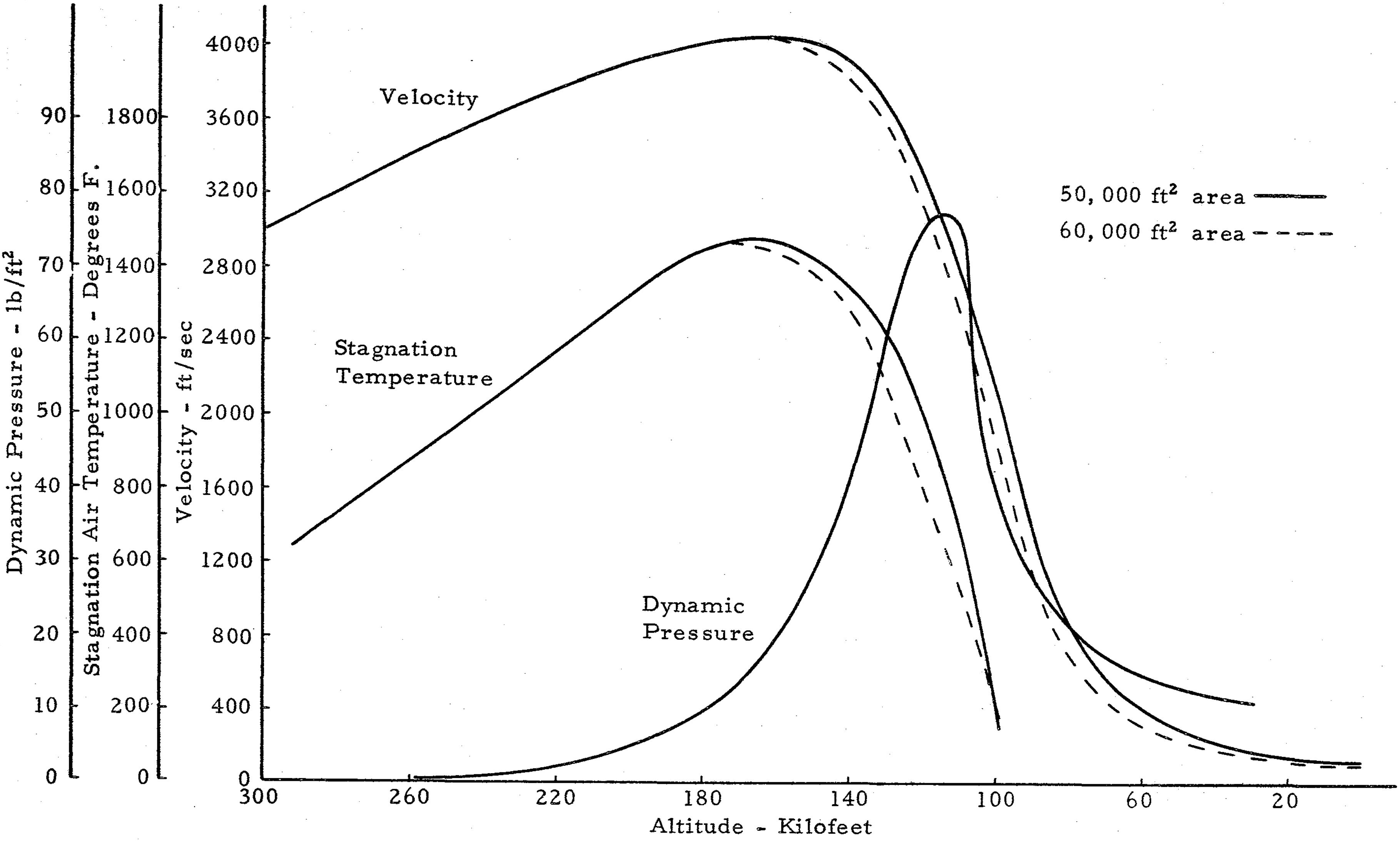

Figure 1

Trajectory Characteristics of Saturn V Booster
with Parachute Deployed

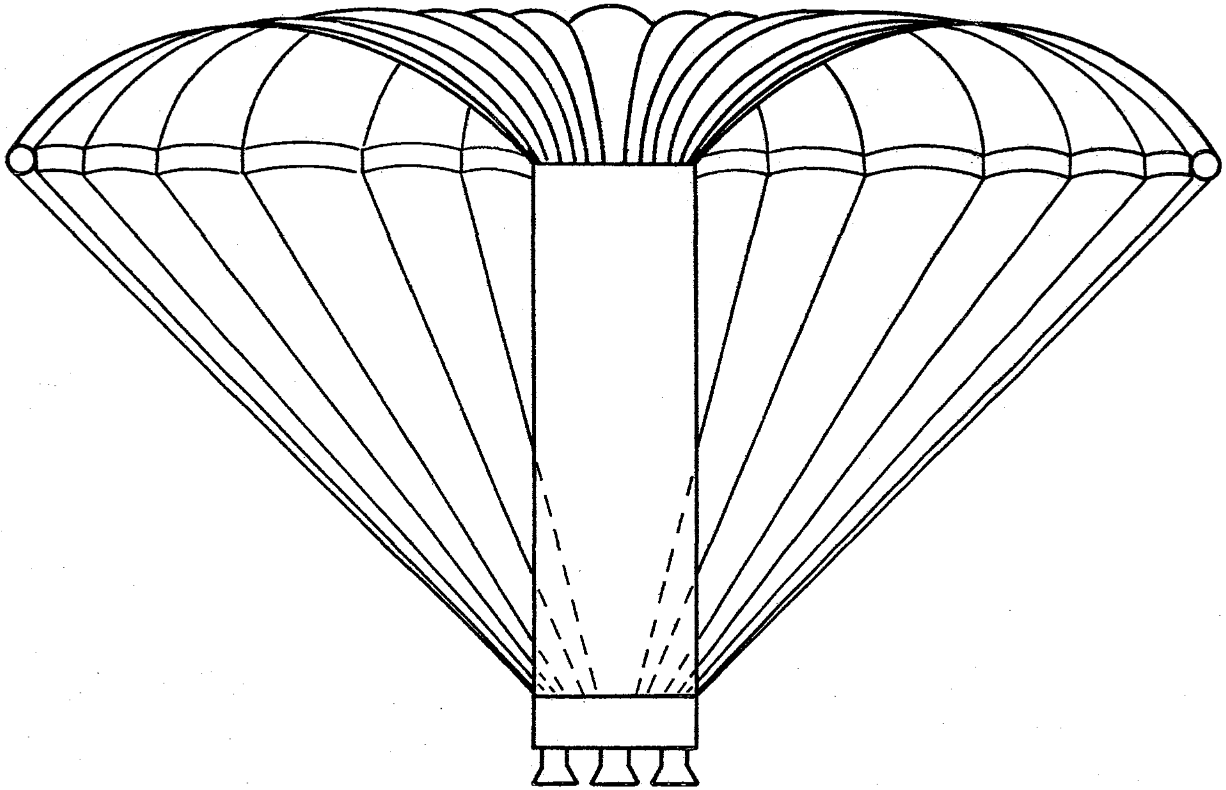

Figure 2

Schematic Arrangement of Toroidal Parachute for Saturn V Booster

The temperatures encountered require that the parachute be made of some heat resistant material such as glass or steel-wire fabric. Glass cloth may be used at 600°F or with reduced strength up to 1000°F. Steel-wire fabric such as Rene 41 wire cloth will withstand extremely high temperatures. Both of these materials have approximately the same strength-to-weight ratios so that choice of materials may depend on other factors such as cost.

Stress analysis of a parachute is very complicated because of the non-uniform aerodynamic pressure distribution, and the fact that the material is not homogeneous. Some estimate of the stresses may be made by considering the parachute to be a smooth torus under internal pressure. The maximum meridional stress is then given by

$$\sigma_1 = \frac{q\,[\,R_2^2 - (R_2 - R_1)^2\,]}{2\rho} = \frac{70(125^2 - 70^2)}{2\,(125)\,t} = \frac{249}{t} \;.$$

The hoop stress is then found by

$$\sigma_2 = R_2 \left(\frac{\rho}{t} - \frac{\sigma_1}{R_1}\right) = 125\,(12) \left(\frac{70}{144t} - \frac{249}{t(12)(55)}\right) = \frac{150}{t}.$$

By properly selecting the parachute canopy type and gore dimensions the stresses can be reduced significantly from that developed in a smooth torus. The approximate stresses in the several parts of the parachute can be held within the allowable limits of glass cloth for thicknesses in the range of 0.01 inches and for steel wire fabric (which is readily available) in the range of 0.0015 to 0.0040 inches.

In order to insure that the parachute remains open at high altitudes, its design could incorporate radial and articulated circumferential elements made from tubing which can be inflated to provide rigidity for the canopy.

The weight of the parachute proper is estimated as 10,000 lb. The weight of the entire recovery assembly, including pressurizing and tie lines, is estimated to be less than 40,000 lb, which is about 7% of the booster burnout weight.

Soft Landing and Floatation

It is possible that space limitations aboard the booster might require the use of a smaller parachute than indicated herein. It is also possible that the assumed impact velocity of 100 ft/sec will be found to be too high. In either event some method of velocity reduction before touchdown must be employed. On the other hand, it is possible that somewhat higher velocities are permissible and a smaller parachute can be used.

The volume of the fuel and lox tanks is large enough to float the entire booster if some method is provided to seal all openings into the tanks.

The salt water immersion tests (4) have substantiated the feasibility of re-using booster engines that have been submerged in salt water.

Another aspect of landing in water is the depth to which the booster can submerge without the hydrostatic pressure becoming great enough to buckle the fuel and lox tanks. Since the vehicle will very likely still have some horizontal component of velocity at impact, it probably will not penetrate the water cleanly. If it did penetrate cleanly, a very large drag force would be created when the parachute encountered the water. For these reasons the engine end of the booster will probably never penetrate more than 130 feet deep. At this depth the fuel tank is subjected to about 45 psi external pressure which is not high enough to cause buckling.

DISCUSSION

This preliminary investigation indicates that the possibilities of recovering the Saturn V booster are good. There is a definite need for further study in the specific areas of

1. Method of stabilization and attitude control after burnout
2. Analysis and control of aerodynamic heating
3. Parachute design
4. Parachute materials
5. Accurate determination of allowable impact velocity.

Such further study would involve the use of special tests and models as well as theoretical analyses. The study of supersonic aerodynamic heating may involve wind tunnel tests and computer analysis.

The design features of the parachute with variable double curvatures will require considerable study. The pressurizing system to inflate the radial ribs and corresponding segments of the larger peripheral tubes will need to be studied and tested.

APPENDIX

PARACHUTE STRESS ANALYSIS

For a parachute 266 ft in diameter,

$$A = \frac{\pi D^2}{4} = 55,000 \text{ sq ft.}$$

In Figure A-1, the following values of dimensions are illustrative of the approximate values which are considered to be within a reasonable range of values which may be determined after study and test.

$$R_0 = 133 \text{ ft} = 1600 \text{ in}$$

R_1 is not constant but for preliminary calculations is assumed such that

$$R_1 = 67 \text{ ft} = 804 \text{ in}$$

If 30 gores are used,

$L = 28$ ft $= 336$ in

$R_2 = 16$ ft $= 192$ in

and $R_3 = 28$ ft $= 336$ in

The dihedral angles may be closely approximated by the following values:

$\alpha_T = 45°$

$\alpha_0 = 12°$

$\alpha_1 = 55°$

$\alpha_2 = 55°$

$\alpha_3 = 24°$

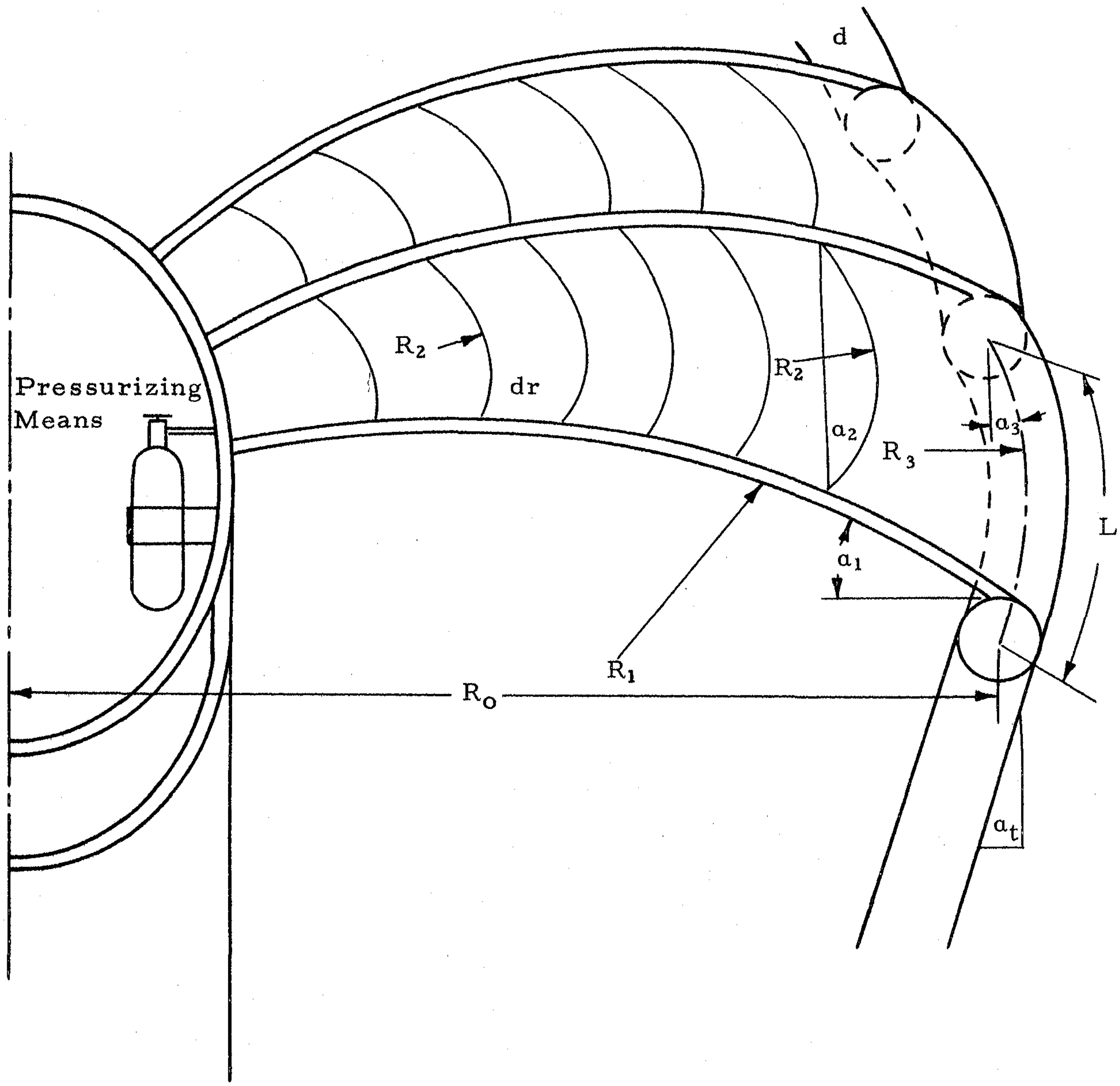

Figure A-1

Schematic Arrangement of Segment of Parachute
Showing Principal Dimensions of Toroidal Parachute for
Saturn V Booster

The maximum aerodynamic pressure in the parachute is calculated to be approximately 72 psf or 0.5 psi. To estimate the stress in the parachute cloth we may use the membrane analysis which gives the relation

$$\frac{\sigma_1}{R_1} + \frac{\sigma_2}{R_2} = \frac{q}{t'}$$

when

$$t' = Kt \text{ for cloth.}$$

A fair approximation can be obtained by assuming $S_1 = S_2$ in which case

$$\sigma_2 = \frac{q}{Kt\left(\frac{1}{R_1} + \frac{1}{R_2}\right)} = \frac{0.5}{t(0.00520 + 0.00124)} = \frac{77.5}{t}$$

With a Rene steel cloth the stress in the individual strands will be approximately 5.0 times the average stress computed for a solid sheet of thickness equal to the total thickness of the cloth. Thus, if we use a wire 0.0020 in diameter, the cloth will be 0.0040 inches thick and weigh approximately 0.080 lb/ft^2.

The corresponding upper limit of the stress is

$$\sigma_2 = \frac{77.5 \times 5}{0.0040} = 96,000 \text{ psi}.$$

This value is high but not dangerously so since the tensile strength of the wire thread is about 200,000 psi (9).

The forces acting on the radial rib tubes will be 77.5 lb times the sine of α_2 acting on each inch of length on each side of the tube.

Thus, the radially outward forces on the radial tube are

$$77.5 \times \sin 55° \times 2 = 125 \text{ lb per inch} \quad .$$

Again an upper limit of force may be found. The total tangential force in the rib tube then is

$$Q = 125 \times R_1 = 125 \times 804 = 100,000 \text{ lb} \quad .$$

To determine the thickness of the metal cloth the cross-sectional area of the resisting member times the tolerable stress must equal 100,000 lb. The cross-sectional area of the resisting member for double woven cloth tube can be estimated as twice the cloth thickness times the circumference of the tube. Assuming a wire cloth made from 0.024" diameter wire twice the cloth thickness will be 0.0480". For a tube 10" in diameter (d_r) the gross cross-sectional area is $10 \pi \times 0.0480 = 1.51$ sq in. The net effective area of the tube, a^1, is $\frac{1.51}{5.0} = 0.302$ sq in.

Two wire cables 3/4 inches in diameter, one on each side of the tube, provide a net area of 0.8 times the gross area or $0.8 \times 0.44 \times 2 = 0.705$ sq in. The total effective area of the radial members is 1.007 sq in and 99,000 psi which is comparable to the corresponding stress in the cloth. Thus, the two parts cloth and rib are compatible.

Before the peripheral tube sections can be determined, the pull in the tie lines must be known. The total force acting on the periphery of the toroidal parachute is nearly two-thirds of the total force or $\frac{2}{3} \times 72 \times 55,000 = 2,640,000 \text{ lb} = P$.

For 30 gores this gives 88,000 lb per gore which should be and is slightly higher than the vertical component of each radial rib at the periphery. This vertical component is equal to the tie line pull in the lines acting at one gore intersection.

The tension in the tie lines T is

$$T = \frac{88,000}{0.707} = 125,000 \text{ lb} \quad .$$

Four 3/4" Q wire ropes deployed as loops, one on each side of the radial rib, will provide 4 x 0.44 x 0.8 = 1.4 sq in of net effective area. The corresponding maximum tensile stress in the tie lines is

$$S_o = \frac{125,000}{1.4} = 89,000 \text{ psi} \quad .$$

Again this value is high but not unsafe.

Figure A-2 shows a free body diagram of the intersection of two segments of the peripheral member, one radial rib and one set of tie lines.

Since $\Sigma F_x = 0$ it follows that

$$125,000 \times \cos 45° + 100,000 \times \cos 55° = 2 \times \frac{\rho \pi D^2}{4} \times \sin 24°$$

$$88,000 + 57,000 = 2 \frac{\rho \pi d^2}{4} = 0.645 \rho d^2$$

$$145,000 = 0.645 \rho D^2 \text{ or } \rho d^2 = 225,000 \quad .$$

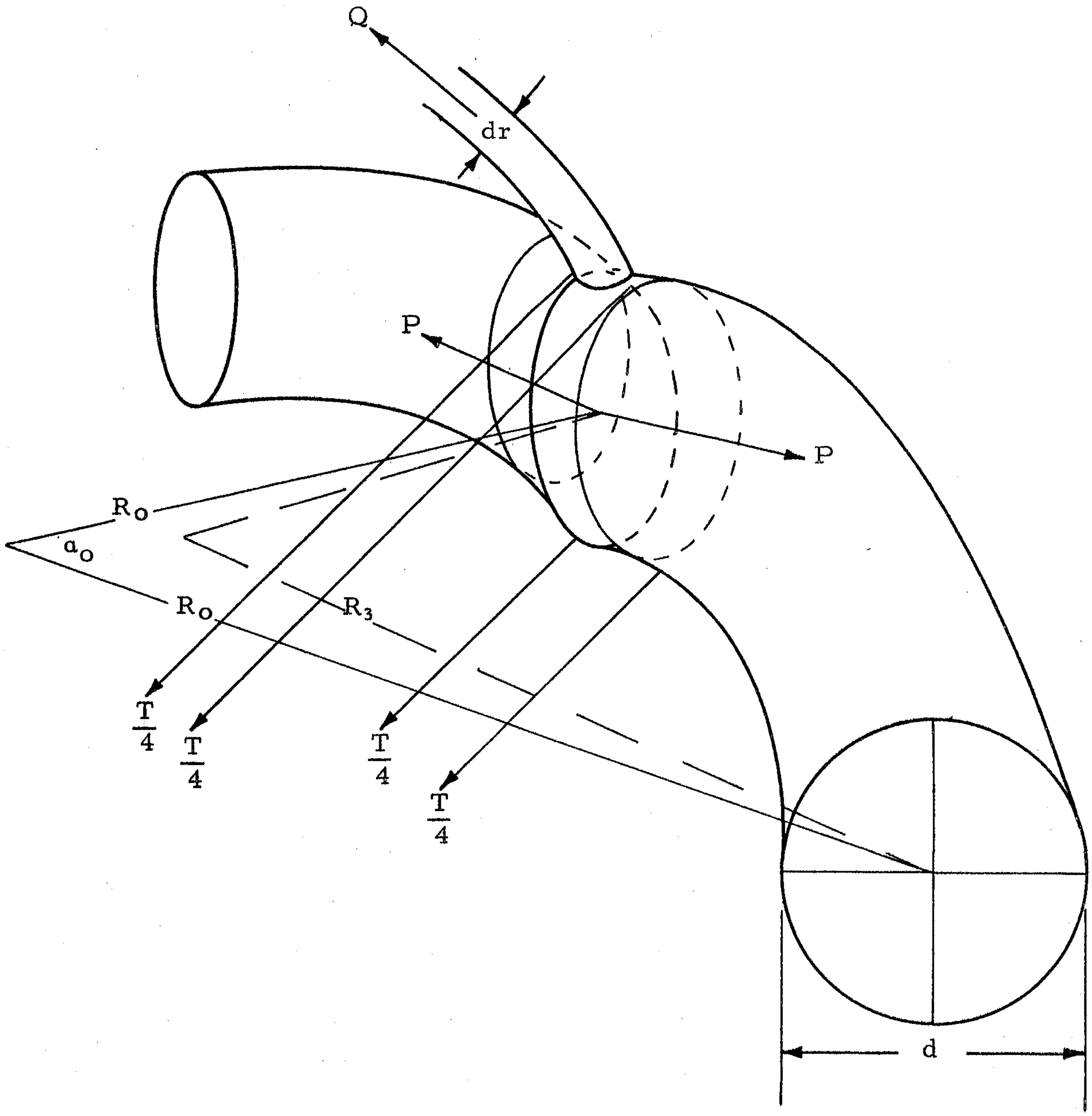

Figure A-2

Free Body Diagram of Intersection of Sections of Peripheral Member of Toroidal Parachute for Saturn V Booster

To select a peripheral segmented tube the cross-section of the tube must be sufficient to safely withstand the force P and safely withstand the internal bursting pressure ρ. By the nature of the loading, the stresses resisting the force P will not be uniform. To account for this, the maximum longitudinal stress is considered to be twice the average.

If the gas pressure in the tube is 50 psi at the instant of maximum dynamic pressure in the parachute, the diameter of the segmented tube may be computed as

$$d = \frac{225,000}{50} = 4500 = 67 \text{ inches} .$$

Assuming a wall thickness of 0.096 inches of 4 ply cloth made from wire thread 0.012 inches in diameter, the effective thickness is 0.0192.

The maximum hoop stress then will be

$$\sigma_{\rho} = \frac{\rho . d}{2t} = \frac{50 \times 67}{2 \times 0.0192} = 87,000 \text{ psi} .$$

The foregoing approximate dimensions and analyses have been predicated on the basis that a vertical landing speed of 100 ft/sec is tolerable. If subsequent studies show that the vertical landing speed is different from 100 ft/sec, the designs and analyses must reflect such conditions.

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