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# DEFINITION OF TETHERED BALLOON SYSTEMS

Endip F. Myers Jerome J. Volschek

Coodyear AeroSpace Corporation

Contract No. F 19628-71-0-0091

Project No. 7659 Task No. 765906 Work Sait No. 7659061

Scientific Report No.

31 March 1971

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Each balloon type is sized twice at 10,000 feet; one for a NOLARO tethering, and the other for the Amgal-Monitor wire rope.				
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# DEFINITION OF TETHERED BALLOON SYSTEMS

Philip F. Myers Jerome J. Vorachek

Goodyear Aerospace Corporation Akron, Ohio 44315

Contract No. F 19628-71-C-0091

Project No. 7659 Task No. 765906 Work Unit No. 76590601

Scientific Report No. 1

31 March 1971

Contract Monitors: Edward F. Young, Major, USAF and Don E. Jackson, Captain, USAF Aerospace Instrumentation Laboratory

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## ABSTRACT

An analytical investigation of the behavior of tethered balloons is in progress. This report, the first of three scientific reports, covers balloon system definition for three design altitudes, 5,000, 10,000, and 20,000 feet above sea level.

Three balloon shapes being considered are the Vee-Balloon\*, the Bateman and Jones (BJ) barrage balloon, and Goodyear Aerospace Corporation (GAC) Model No. 1649 single-hull balloon. Tether constructions are Columbian Rope Company's NOLARO utilizing prestretched polyester filaments, and US Steel Corporation's Amgal-Monitor AA wire ropes.

Eight specific balloon/cable combinations are defined, covering the three design altitudes. Total cable curve, downwind displacement, etc., have been calculated by computer program and results are tabulated.

Each balloon type is sized twice at 10,000 feet, one for a NOLARO tethering, and the other for the Amgal-Monitor wire rope.

The BJ shape only is sized for the 5,000 and 20,000 foot design altitudes, and with NOLARO tether.

Aerodynamic characteristics, weight, inertias, and dynamic characteristics are developed and tabulated for use in the following phases of this program. The Characteristic Equation Stability Analyses and Dynamic Simulation Analyses will be based on the information and data of this report. The contract of the state of th

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\*T.M., Goodyear Aerospace Corporation, Akron Ohio 44315

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The project is being carried out under the direction of Major Edward Young and Captain Don Jackson as Contract Monitors for the Air Force Cambridge Research Laboratories. Mr. Jerome Vorachek is the Goodyear Aerospace Corporation Project Engineer. Technical assistance was provided by Mr. Philip Myers, Mr. Walt Stricker, Mr. Nicholas Costakos, Mr. William Ebert, Mr. George Doyle and Mr. Louis Handler.

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F.	Expenses spec
F	Difference in weight densities of air and inflation gas ( = 0.862 P g) lb/ft <sup>3</sup> alt
<b>B.</b> 5.	Sresking strength, 15
(A	Center of additional mass
33	Center of pravity
c <sub>p</sub>	Aerodypasic drag coefficient
۲	Aerodynamic lift coefficient
¢,	Aerodynamic pitching moment coefficient
с <sub>в</sub>	Aerodynamic yawing moment coefficient
c <sub>y</sub>	Aerodynamic side force coefficient
D	Aerodynamic drag, 15
D	Diameter, ft or in.
DC	Dyuamic center
и 4	Aerodynamic dræg of balloon, 15
ď <sub>r</sub>	Net drag, horicontal component of tension at the top end of the cable, 1b
đ	Downwind displacement or horizontal distance from the top end of cable to botcom end measured parallel to earth plane, ft.
Fx	Horizontal force, lb
₽ y	Side force, lb
Fz	Vertical force, lb
f	Fineness ratio or ratio of length to max. diameter
fps	Feet/second
G	Specific gravity
g	Acceleration of gravity (32.2 ft/sec. <sup>2</sup> )
'n	Float Altitude above mean sea level, ft.
	xii

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LIST OF SYMEOLS (Continued)

IAS Indicated air speed, knots Mass moment of inertia in roll, slug ft<sup>2</sup> ľ Mass moment of inertia in pitch, slug ft<sup>2</sup> ī, Mass moment of inertia in yaw, slug ft I<sub>z</sub> ¥ Various coefficients **Hull length** L L' Vee balloon hull length along & of symmetry Aerodynamic lift, lb L L<sub>r</sub> Set lift of balloon or vertical component of tension at the top end of the cable, 1b LS Net static lift (gross static lift -  $W_{g}$  - P), lb Pitching moment, ft 1b Н Rolling moment a' but the X axis at zero angle of attack Жx ЖC Mass center HEL Mean sea level N Yawing moment, ft 1b P Payload weight, 1b Rolling velocity Ρ Dynamic Pressure ( = 1/2  $\rho_{alt} y^2$ )  $lb/ft^2$ ę Yawing velocity r Empennage area, ft<sup>2</sup> S Sea level SL Ţ Tether tension, lb Time at float altitude, hr t Horizontal velocity increment, fps u Balloon hull volume, ft<sup>3</sup> ¥ xiii

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# LIST OF SYMBOLS (Continued)

¥	Wind velocity, fps
V <sub>k</sub>	Wind velocity, knots
v	Sideslip velocity
¥ <sub>B</sub>	Total balloon and suspension weight, 1b
¥ <sub>C</sub>	Total weight of cable segment, 1b
5	Unit weight of balleon fabric, lb/fr <sup>2</sup>
3	Vertical velocity of balloon during transient motion
x	Downwind displacement, ft (on computer printout)
Y	Side force
٤	Distance vertically down from design altitude, ft.

α Angle of attack, degrees

- $\beta$  Angle of sideslip, degrees
- $\theta$  Angle between the cable and the vertical, degrees (PHI in computer printout)
- ρ Density of air, slugs/ft<sup>3</sup>

Note: A variety of symbols are defined and used in Setion IV and Appendices I and II which are not necessarily listed in the tabulation above.

----

## SECTION I

## INTRODUCTION

The objective of this program is to investigate the dynamic behavior of tethered balloons and in so doing to establish design criteria for tethered balloons, tethers and payloads. The program is organized into three steps.

- (1) Definition of balloon systems for dynamic analysis
- (2) A study of stability characteristics of tethered balloon systems
- (3) A study of dynamic response of tethered balloon systems to wind gusts.

This first scientific report presents a definition of tethered balloon systems to be investigated in subsequent dynamic studies.

For design purposes in the subject investigation the following design parameters were specified in Reference 1:

# Payload and Design Altitude

<u>Payload (lb)</u>	<u>Float Altitude (ft above MSL)</u>
P	h
1500	5,000
1000	10,000
600	20,000

# Tethers

Two specific tether constructions are to be considered, NOLARO by Columbian Rope Company, and Amgal-Monitor AA wire rope by United States Steel. A safety factor of 2.0 will be used with NOLARO; 1.5 for Amgal-Monitor. Tether design load will be based on a survival wind of 1.3 times the operational wind at balloon altitude.

# Wind Profile

The wind profile as specified by Reference 1 is shown in Figure 1 and tabulated below:

<u>Altitude</u> (ft above MSL)	Operational <u>Wind Speed</u> (knots)	Survival <u>Wind Speed</u> (knots)
Sea Level	10	13.
5,000	31	40.3
10,000	40	52.
20,000	54	70.2

# and a construction of the second seco

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Survey 25'

This profile of operational wind is closely approximated by the relation:

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$$v_{\text{knots}} = 0.8794 \text{ (altitude + 350)}^{0.415}$$

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The 1962 U. S. Standard Atmosphere is used as the source for atmospheric data (see Table I).



Figure 1. Wind Profile

		Density Batio Buoyency Given Fo Different Puritie of Helium		Siven For Purities Lium	
Alțitude (Ft)	Density (Slug/ft <sup>3</sup> )	(Alt./Zero Alt.)	Pressure (Lb/ft <sup>2</sup> )	100% (Lb/ft <sup>3</sup> )	97 <b>%</b> (Lb/ft <sup>3</sup> )
0.	0.0023769	1.0000000	2116.2170410	0.0659	0.0639
1000.	0.0023081	0.9710660	2040.8571777	0.0640	0.0621
2000.	0.0022409	0.9427790	1967,6914062	0.0621	0.0603
3000.	0.0021751	0.9151295	1896.6716309	0.0603	0.0585
4000.	0.0021109	0.8881069	1827.7478027	0.0585	0.0568
5000.	0.0020482	0.8617023	1760.8730469	0.0568	0,0551
6000.	0.0019868	0.8359040	1695,9997559	0.0551	0.0534
7000.	0.0019269	0.8107038	1633.0812988	0.0534	0,0518
8000.	0.0018684	0.7860914	1572,0712891	0.0518	0.0503
9000.	0.0018113	0.7620566	1512.9265137	0.0502	0.0487
10000.	0.0017555	0.7385901	1455,6020508	0.0487	0.0472
11000.	0.0017011	0.7156832	1400.0544434	0.0472	0.0458
12000.	0.0016479	0.6933257	1346.2407227	0.0457	0,0443
13000.	0.0015961	0.6715091	1294.1193848	0.0443	0.0429
14000.	0.0015455	0.6502230	1243.6489258	0.0429	0.0416
15000.	0.0014961	0.6294589	1194.7880859	0.0415	0.0402
16000.	0.0014480	0.6092079	1147.4982910	0.0402	0.0389
17000.	0.0014011	0.5894610	1101.7407227	0.0388	0.0377
18000.	0.0013553	0.5702096	1057.4758301	0.0376	0.0365
19000.	0.0013107	0.5514442	1014.6652832	0.0363	0.0353
20000.	0.0012672	0.5331573	973.2741699	0.0351	0.0341

# Table I. Standard Altitude and Unit Helium Lift

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# SECTION II

#### BALLOON TYPES AND CHARACTERISTICS

#### 1. BALLOONS SELECTED FOR STUDY

For this study of dynamic behavior of tethered balloon, four aerodynamically shaped balloons were investigated. The balloons investigated were Vee-Balloon, a GAC model single hull (No. 1649) with "thin" or "thick" fins, and the BJ British barrage balloon. These shapes were selected for investigation because a wide range of physical and functional characteristics such as aerodynamic lift, drag, fineness ratio, volume per surface area, fin size, etc., is encompassed. In addition, wind tunnel test data is available for all of the balloons and full-scale vehicles of each except the GAC No. 1649 balloon have been flown. Realistic size and weight scale factors can therefore be obtained for analyzing balloons designed for many wind velocities and altitudes.

# 2. BALLOON DESCRIPTION

#### a. General

A ballonet system for accommodating volume change and maintaining pressure for all aerodynamically-shaped balloons was assumed. A blower and battery type were assumed for all ballonet systems except the BJ. For this type, it was assumed that dynamic pressure alone, such as in the barrage balloons, was sufficient to retain pressurization.

In order to give relative size of each balloon with respect to a different shape of comparable volume, Table II lists the basic dimensions and areas for the various shapes, each with a hull volume of 100,000 cubic feet.

# b. Vee-Balloon Configuration

The Vee-Balloon (Figure 2) was chosen because it represents the high aerodynamic lift-type tethered balloon. The configuration consists of two streamlined hulls joined at the nose to form a "V". A horizontal tail is connected between the hulls with the two vertical fins mounted on the aft end of each hull. The balloon exhibits one of the highest aerodynamic lift coefficients and the highest drag coefficient of any of the aerodynamicallyshaped balloons selected for the evaluation. The empennage is heliuminflated.

# c. BJ (Beteman and Jones)

The BJ configuration (Figure 3) was chosen because it represents a typical single-hull, streamlined shape, tethered balloon. The basic shape

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; ;=; ;;; Table II. Physical Dimensions of Various Balloon Configurations for Hull Volumes of 12. Table II.

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	Reference	Hull			SE	ไลวเ	Each Ro	rizontal	Fin	Įŧ	Each V	ertical	Fin	Total	Total
uoo	Hull Volume	Length	Max. Dia.	Wetted Area	oija Oija	to su	Pro- jected	Wetted	Vo 1 ume	su siji siji si	Pro- jected	Wetted	Volume	Wetted Area	Volume
2	(ft <sup>3</sup> )	(ft)	(ft)	(ft <sup>2</sup> )	N N TJ	Ч он оN	Arga (ft <sup>2</sup> )	$(ft^2)$	(ft <sup>3</sup> )	FT Ve No	Area (ft <sup>2</sup> )	Area (ft <sup>2</sup> )	(ft <sup>3</sup> )	(ft <sup>2</sup> )	(ft <sup>3</sup> )
noo	100,000	118.8 (113.30	29.7	15,016	4 <b>.</b> 0	H	1523	3366	6242	2	169	392	231	19,166	106,704
	100,000	109.1	43.8	11,660	2.5	7	496	1155	4125	r-4	776	1807	8078	15,777	116,329
1649 Thin	100,000	123.9	41.3	12,485	3.0	5	797	1722	3669	Fi	797	1722	3669	17,651	111,006
1649 Thick	100,000	123.9	41.3	12,485	3.0	2	267	1945	9723	1	797	1945	9723	18,320	129,168

L (cos  $17-1/2^{\circ}$ ) where hull included angle of intersection is  $35^{\circ}$ ŧ Ļ ļ (113.30)

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Figure 2 . Vee-Balloon Configuration

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consists of a streamlined hull with a Y-type tail. The balloon exhibits the lowest aerodynamic lift coefficient and almost the lowest drag coefficient of any of the aerodynamically-shaped balloons selected for evaluation. and the second and the second second second and the second se

d. GAC No. 1649 Balloon With Thin Fins

This body (Figure 4) represents an appreciable aerodynamic improvement over the BJ or the frequently used Class "C" shape. Its <u>serodynamic L/D</u> ratio is best of those considered.

e. GAC No. 1649 Balloon With Thick Fins

This is the same body-of-revolution as in (d) above, but fitted with much thicker expensage and has aerodynamic performance comparable to the BJ balloon. This body will not be carried on in the dynamic study.

3. AERODYNAMIC CHARACTERISTICS

Aerodynamic lift coefficients, drag coefficients, and lift-to-drag ratio versus angle of attack for the aerodynamically-shaped balloons are given in Figures 5 through 7. The hull volume to the two-thirds power is used as a reference area. Aerodynamic side force, yawing moment and pitching moment coefficients are given in Figures 8 through 18.

Aerodynamic data was taken from References 2 through 9.

The aerodynamic coefficients are defined as follows:

Lift Coefficient, 
$$C_{L} = \frac{L_{a}}{q \psi^{2/3}}$$
  
Drag Coefficient,  $C_{D} = \frac{D_{a}}{q \psi^{2/3}}$ 

Side Force Coefficient,  $C_{Y} = \frac{F_{Y}}{q \psi^{2/3}}$ 

Pitching Moment Coefficient,  $C_m = \frac{M}{a^{u}}$ 

Yawing Moment Coefficient,  $C_n = \frac{N}{q v}$ 

where  $\forall$  is the hull volume for the single hull balloons and the volume of the two hulls for the Vee-Balloon.

The axis for measurement of moments is located along the longitudina. axis measured from the nose of the balloon. For the Vee-balloon the fractional



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Figure 5. Aerodynamic Lift Coefficient for Various Balloon Configurations



Figure 6. Aerodynamic Drag Coefficient for Various Balloon Configurations

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Figure 7. Aerodynamic Lift-Drag Ratio for Various Balloon Configurations

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Figure 15. Aerodynamic Pitching Moment Coefficient, GAC No. 1649 Balloon



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length from the nose is based on the projected length of the hulls on the longitudinal centerline and is measured from the nose intersection of the two hull centerlines.

The forces and moments measured in the wind tunnel are measured about a fixed axis. During dynamic maneuvers, these moments will act about the dynamic center, so that the test results must be transposed to the new center of moments. Since the dynamic center includes the added mass effects, its location will be slightly different for motions about each axis. The following pages show the method used to transpose these moments.

Figures 19 and 20 present the transfer of pitching moment or yawing moment to the dynamic center.

# 4. WEIGHT ANALYSIS OF AERODYNAMICALLY SHAPED BALLOONS

# a. Stress Considerations

Internal pressure in the balloon at float altitude was based on the following requirements:

- The nose of the balloon shall not cup or dimple in the wind at altitude, as this will create a large increase in drag, and cause the balloon to lose its aerodynamic characteristics.
- (2) The minimum operating pressure for a reliable pressure relief valve shall have a minimum opening pressure of approximately 1/4 in.  $H_00$ .

Therefore, the required balloon internal pressure was selected to be 1.15 times the stagnation pressure at altitude or 1/4 in.  $H_20$ , whichever is greater. The critical pressure required to prevent buckling of the hull was assumed to be less than that required to prevent dimpling of the nose of the balloon. In most cases, the critical pressure to prevent buckling is less than that required to prevent dimpling. However, in any further detailed design study or prototype development, the validity of this assumption must be verified. The actual stress used in the weight analysis was the sum of the stresses caused by the internal pressure, buoyant lift, aerodynamic load, and hull bending moment.

#### b. Balloon Material

At the present time, material for fabrication of the balloon was investigated only on a strength-to-unit-weight basis. Figure 21 is a plot of breaking strength versus unit weight for various existing materials that are used for fabrication of balloons. The curve of Figure 21 was used in the weight analysis to determine the hull material weight after the stress (allowing a factor of safety of 4) has been determined. See Table III for fabric code numbering system.

c. Balloon Weight

Once the stress is determined for a particular balloon shape, the weight can be estimated. The product of wetted area and unit weight, where



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Figure 19. Transfer of Pitching Moment From Point of Measurement "A" to Dynamic Center





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Figure 21. Quick Break Strength vs Unit Weight for Various Balloon Materials

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Table III. Goodyear Aerospace Corporation Fabric Code Numbering System

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[.		]
Last Number	Type Pigment Outer Coating	0-None 1-Aluminum 2-TiO <sub>2</sub>
Numbers	Fabric oz/yd <sup>2</sup> to tenths	
Letter	Elastomer Type	B-Butyl H-Hypalon N-Neoprene P-Polyurethane S-Silicone U-Uncoated
Numbers	Cloth Type No. of Film Plies No. of Cloth Plies	100-Cotton 200-Nylon 300-Dacron 400-Fiberglass 500-Stainless 600-NOMEX 700-Rene' 41 2nd Digit = No. Film Plies 3rd Digit = No. Cloth Plies
Letters	GX- Goodyear Aerospace Corporation	



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wetted area depends on shape and unit weight depends on stress, determines the major part of balloon weight. An allowance of 10 percent was made for seam weight; i.e., hull weight, fin weight, etc., were increased by 10 percent. Wetted areas were scaled up from existing sizes, or in the case of the Nc. 1649 balloon, from model dimensions. Where a blower is provided for pressurization, blower and battery weight depend on design altitude, balloon volume, differential pressure, and power density of the battery. Other weight contributions and the detailed method of calculating stress and weight of aerodynamically-shaped balloons are given in Appendix II. Computer printout data for a 100,000 cu. ft. Vee-balloon configuration is given in Tables IV and V.

The balloon weights as generated by the Appendix II computer program for the payload/altitude/wind criteria of Section II are plotted in Figures 22 and 23. The four configurations are plotted in Figure 22 for the 10,000-foot design altitude, with specific sizes to be used later indicated. Figure 23 presents the BJ balloon weights for design altitudes of 5,000, 10,000 and 20,000 feet and the appropriate payloads.

# 5. TRIM ATTITUDE

The computer program weight analysis of Appendix II includes a stress consideration of balloon angle of attack. Table VI presents the operational and survival winds at the various design altitudes corrected to a sea-level indicated air speed. The trim attitudes are tabulated in Table VI for the BJ and the Vee-balloon, as taken from Figure 24. These curves are from Reference 7, Figure 8, and Reference 10, Figure B-3.

These angles of attack are used in the determination of balloon aerodynamic lifts and drags and thus (for survival winds) affect balloon weight and tether breaking strength and weight. The lift and drag loads for the operational wind are used in the solution of selected tethers in the operational wind profile.

The Vee-balloon angle of attack profile with wind is due to its unique suspension system, incorporating stretchable, bungee links in the aft suspension. At nine or ten knots, suspenion loads become large enough to start elongating the aft suspension, changing the suspension geometry and literally effecting a reduction in angle of attack. It is not expected that the equations of motion will be made to handle other than a rigid body balloon/suspension arrangement. Airloads used will be based on the Figure 24 angles of attack, as the Vee-balloon and tether weights quoted in this report are not achievable in the desired winds without this unique suspension.
TABLE IV.

IDENTIFICATION OF CONPUTER PRINTOUT

MAXIMUM ALTITUDE .. FT

CABLE SAFETY FACTOR - DIMENSIONLEUS

INPUTS: PAYLOAD - WEIGHT (LD) ANGLE OF ATTACK - DEGNERS FOR TYPE - DALLOON TYPE

Velocity - FT/Bec Optime - Openating Time (Hours) Material Facton of Savety - Dimenbionlebs

ALTITUDE - Pro VOLUME - Pro (1 - VEE, 3 - BINOLE HULL)

UNIT FADRIC WEIGHT - LD/FT3

WH - WEIGHT HULL (LB) WINTA - WEIGHT HULL (LB) WINTA - WEIGHT HULL INTERSECT ATTACH.(LU) WYTA - WEIGHT HULL INTL ATTACH.(LD) WYTA - WEIGHT RIGMERS (LD) WAVAL - WEIGHT AIR VALVE (LD) WENTS - WEIGHT BUNGEE (LD) WENTS - WEIGHT BUNGEE (LD) WENTS - WEIGHT BULONET SEAMS (LD) WENTS - WEIGHT BULONET SEAMS (LD) Q - EXTERNAL DYNAMIC PRESSURE (LU/FT<sup>2</sup>) L - HIAL LENGTH (FT) APHT - PROJECTED AREA HONIZ, TAIL (FT<sup>2</sup>) AWHT - LETTED AREA OF HONIZ, TAIL (FT) HVTA - TUICKNESS OF VERT, TAIL (FT) VTOT - TOTAL VOLUME (FT<sup>3</sup>) ABNT - AREA OF DALLONET (FT<sup>2</sup>) ABNT - AREA OF DALLONET (FT<sup>2</sup>) VLEAK - HULLUM LEAK RATE (FT<sup>2</sup>/24 HKB) QT - TOT, VOLAIR PUMPED ADIA - AREAOPYNAMIC STRESS (LD/YT)

VOL

NDEE - DEBIGN STREGE (LN/YT) AIL - INUL AREA (YT) LUAXD - LENGTI FROM NOSE WIERE MAX, DIAMETEN COCURE (FT) VYT - THICKVERGH HOMLZ, TAIL (FT) VYT - VOLUME VERT, EMILONET (YT) SOLY - DIAMETER EMILONET (YT) SOLO - ULONER FLOW TO DE NEED - VOLUME OF KELKUW TO DE REPLACED DUE TO LEEMAGE (TY) MI - INTERNAL PUER, GTNY (MYT) PSF - INTREMAL FIREBURE (LEVF1<sup>2</sup>) D - MAXIMUN DIANETER (FT) ARVT - PROJECT AREA VERT\_TAIL (FT<sup>2</sup>) ANVT - WEITED AREA VERT\_TAIL (FT<sup>2</sup>) ANVT - VOLIME HORIZ, TAIL (FT<sup>2</sup>) VONT - VOL DALLONET (FT<sup>3</sup>) AINT - ANEA HULL INTERBECT (FT<sup>3</sup>) AINT - ANEA HULL INTERBECT (FT<sup>3</sup>) AINT - ANEA HULL INTERBECT (FT<sup>3</sup>) AINT - VOLUME CIANGE DUE TO VATEM - VOLUME CIANGE DUE TO TOWER - DEBUCENT BLOAKH OPER.TIME (HNG) HU - DUOYANT STREAG (LAVFT)

WIS - WEIGHT HULL, DEAUS (Ln)WINT - WEIGHT HULL, DEAUS (Ln)WITT - WEIGHT HORIZ, TAIL DEAUS (LD)WINT - WEIGHT HORIZ, TAIL DEAUS (LD)WITT - WEIGHT HORIZ, TAIL DEAUS (LD)WITT - WEIGHT VERT, TAIL ATKACH, (LD)WYTT - WEIGHT YERT, TAIL DEAUS (LD)WITT - WEIGHT VERT, TAIL (LD)WYTT - WEIGHT VERT, TAIL DEAUS (LD)WYTT - WEIGHT VERT, TAIL (LD)WYTT - WEIGHT VERT, TAIL (LD)WYTT - WEIGHT VERT, TAIL (LD)WYTT - WEIGHT BIOE (LD)WYTE - WEIGHT VERT, TAIL (LD)WYTE - WEIGHT BIOE (LD)WYEE - WEIGHT VERT, TAIL (LD)WEIGE - WEIGHT BIOE (LD)WYEE - WEIGHT WIGC, YAUNE (LD)WIL - WEIGHT MICC, YAUNE (LD)WINT - WEIGHT ALLONET (LD)WIL - WEIGHT MICC, YAUNE (LD)WINT - WEIGHT ALLONET (LD)WIL - WEIGHT MICC, YAUNE (LD)WINT - WEIGHT ALLONET (LD)

BUOYANT LIFT - (LB)

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DUOY, LIFT+L-HALL AKNONYMANIC LIFT #T-FAYLOAD (LD) (LN)

AKROITYMAM LC DHAO (LD)

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PAYLOAD WEIGHT (LD)

UNIT LIFT OF HELLINA AT ALTITUDE (LLVFT)

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DRAG CORFFICIENT (DIMENSIONLESS)

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Table V. Vew-Balloon Computer Printont

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MAXTAUM ALTITUDE 1.000E 04

CABLE SAFETY FACTOR 2.0

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1 1100	ABRIC WEIGHT -	0.04346					
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+ 101 +	140055.6250		- 1841 -	+18+1.5234		THAN	
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	197.4520		- 1112	0 L . U			
* * * *	4°3010		+ 415%	21.0225			
Kero -	16.7975		4841 -	16-0107			
- TVACH	6.7321		NSVAL .	0.0			
40309N	0.0		N 5-104 -	0-0			8825°2
N7NT 54	19.0790		Y JILIN	55.5265			5971 · 713
• 5/11	931.9700		• "DIM	176.7253			
ANAYOUS	· LIFT • 7555.]	14 77					
	אטר	ĉ	CL CL	BALLOON NT	UNIT LIFT		PAYLOAD
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	1 > 304 - 18	11.5046	0.0	3682.11	\$ 35U4.10	9771.28	

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Table VI. Trim Attitudes for Operational and Survival Wind

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ત	TAS	(Knots)	/ 0	10	IAS	(Knota)		
Altitude (Ft)	v Surv	v Oper	7/po	°4/2 √2	v Surv	v Oper	a Surv	a Oper
Sea-Level	13.000	10.000	1.000	1.0000	13.000	10.000	3.4°	2.8°
5,000	40.3091	31.007	0.86170	0.92828	37.418	28.783	8.7	7.0
10,000	53.0062	40.776	0.73859	0.85941	45.554	35.042	10.2	8.2
15,000	62.4260	48.020	0.62946	0.79338	49.528	38.098	10.8	8.8
20,000	70.1753	53.981	0.53316	0.73018	51.241	39.416	11.0	0.6

Vee-Balloon

a Oper	و <b>.</b> 9°
α Surv	5.7°
	35.042
	45.554
	0.85941
	0.73859
	40.774
	53.0062
h Altitude (Ft)	10,000

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Figure 22. Balloon and Suspension Weights, All Configurations for 10,000 Feet Design Altitude



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Figure 23. BJ Ballcon and Suspension Weights, Design Altitudes of 5,000, 10,000 and 20,000 Feet



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Figure 24. Equilibrium Pitch Angles for Balloons

#### SECTION III

#### BALLOON MASS CHARACTERISTICS

#### 1. GENERAL

The balloons' physical and apparent mass characteristics, consistent with the geometries of Table II and the total weights of Figures 22 and 23 (tabulated in Tables VII and XII) are presented in this section. Figure 25, 26 and 29 present the balloons' actual physical mass characteristics (including internal gases) and Figures 25, 27, and 30 present the additional mass characteristics at the design altitudes. If a specific balloon is later studied at a lower altitude, the physical mass characteristics will have to be adjusted to represent the changed masses of either internal helium and/or air. The apparent masses will change as the air density changes. Figure 28 represents the dynamic center location.

The physical mass characteristics do not include payloads. Payloads will be added during the later work and physical mass characteristics appropriately adjusted.

Table VII lists the mass characteristics for some of the arbitrary balloon sizes run out by the computer program. The actual selected balloon sizes of Table XIV are bracketed by the sizes of Table VII.

## 2. ADDITIONAL MASS

The acceleration of the balloon in any of the six degrees of freedom causes aerodynamic forces in addition to the velocity and attitude changes. It has been shown by Lamb (Reference 11) that the derivatives of these acceleration forces have the dimension of mass. For all practical purposes, this additional mass term may be added to the actual mass of the balloon for purposes of calculating forces and responses of the system. References 12 and 13 were also useful in the development of this section.

The additional mass and additional moments of inertia for acceleration in a fluid have been worked out theoretically for a number of ellipsoids of revolution. Figures 31 and 32 show these coefficients plotted against fineness ratio. The added mass is obtained by multiplying these coefficients by the mass of the displaced air. It has been proposed and has become the custom to use (for airships and balloons) values based on the ellipsoid having the same volume and the same length as the hull. In addition, the theoretical longitudinal coefficient of additional mass shown on the curves will be increased 50% to allow for the boundary layer which is dragged along with the ballcon. Table VII. Balloon Mass Characteristics

Type         Alttitude         Lampte         Values         Value	Balloon	Destan	Hull			Cente	r of	Balloon	Hese C	enter	IPPY	tional M.	808	Center o	E Adds ti	otal Mass			Dynamic	conter	
	Type	Altitude	Length	Volume	2	ž	vity			-				In P.	tch	In Y	2	In PL	tch	In Ye	
(ft)         (ft) <t< th=""><th></th><th></th><th></th><th></th><th>G</th><th></th><th>į</th><th>į</th><th></th><th>i. K</th><th>Long.</th><th>Vert.</th><th>Lateral</th><th>Hora -</th><th></th><th>intra.</th><th>i je</th><th>Hortz</th><th>÷ Š</th><th>Nete.</th><th>·***</th></t<>					G		į	į		i. K	Long.	Vert.	Lateral	Hora -		intra.	i je	Hortz	÷ Š	Nete.	·***
5,000         86.57         50,000         687         49.37         4.39         53.04         2.99         15.35         107.57         111.64         45.65         0         47.07         3.07         4.07           84.57         50,000         868         48.39         4.82         55.76         32.00         3.41         13.18         92.22         95.70         45.65         0         47.07         3.07         4.6           86.57         50,000         868         48.39         4.82         55.76         32.01         19.74         138.11         143.44         52.25         0         47.07         3.07         4.6           117.50         125,000         2,993         100.44         11.64         485.61         100.52         8.59         95.05         65.36         0         4.16         7.77         3.45         139.70         6.53         0         71.48         4.67         7           20.000         186.52         500.000         8.933         100.42         112.05         68.19         77.77         5.42         46.09         74.76         119.77         119.77         7148         4.67         7         7         76.78         7.65         10		(it)	(žt)	(tr <sup>3</sup> )	ા	Ê	E		E	Ē	(slugs)	(slugs)	(slugs)	ĴÊ.	Ĵ	Ê	Ĵ	Æ	Æ	Ê	Æ
B6.57         S0,000         B68         48.39         5.6.70         3.5.76         52.00         3.4.8         55.76         55.70         4.7.07         3.07         4.7           B1         10,000         99.10         75,000         1,276         54.07         55.76         82.83         59.31         3.97         19.74         138.31         143.44         52.26         0         47.18         5.467         3.55         5         5         5         5         5         7         3.55         5         5         5         5         7         136.5         5         6         4.18         3.55         5		5,000	86.57	50,000	687	49.37	4.39	54.95	53.04	2.99	15.35	107.57	111.64	45.65	0	47.07	3.07	48.15	1.01	49.04	3.05
xJ         10,000         99.10         75,000         1,276         54.62         5.67         82.83         59.31         3.97         19.74         138.31         143.44         52.26         0         53.87         3.55         55         54.07         5.06         2.99         4.18         5.23         52.26         0         53.87         3.55         54.07         7.35         3.46         7.77         5.42         46.09         32.91         230.56         69.35         0         71.48         4.67         7.7           20.000         186.52         5000         2.933         10.46         485.61         108.52         8.59         95.05         665.66         69.35         0         71.48         4.67         7.7           20.000         186.52         500         1,50         6.4.07         11.64         485.61         108.52         66.5.66         69.33         0         71.46         4.67         7.7           20.000         186.52         500         1,50         60.40         7.45         112.05         68.28         4.91         77.71         75.23         0         52.67         0.74         6.65         10         113.57         12.5         0			86.57	50,000	868	48.39	4.82	55.76	52.00	3.4.1	13.18	92.22	92.20	45.65	0	47.07	3.07	48.05	1.29	48.89	3.20
117.50       125,000       2,095       64.07       6.96       137.07       54.20       46.09       322.96       539.08       61.96       0       63.88       4.18       6.67       77         20.000       131.45       175,000       2,939       70.78       7.88       192.08       77.77       5.42       46.09       322.96       69.35       0       71.48       4.67       77         20.000       186.52       5000       1,939       10.64       485.61       108.52       8.59       95.07       665.66       69.35       0       71.48       4.67       77         107       107.96       75.000       1,450       60.40       5.95       68.19       37.77       3.95       46.04       177.04       119.07       67.46       0       22.67       0.74       6       65.65       0.74       65       67       0.74       65       77       76       77       76       77       77       76       10       77       76       77       76       77       76       77       76       77       76       77       76       77       76       77       76       77       76       77       76       77 <td< td=""><td>2</td><td>10,000</td><td>99.10</td><td>75,000</td><td>1,276</td><td>54.82</td><td>5.67</td><td>82.83</td><td>59.31</td><td>3.97</td><td>19.74</td><td>138.31</td><td>143.44</td><td>52.26</td><td>0</td><td>53.87</td><td>3.55</td><td>54.90</td><td>1.49</td><td>55.86</td><td>3.70</td></td<>	2	10,000	99.10	75,000	1,276	54.82	5.67	82.83	59.31	3.97	19.74	138.31	143.44	52.26	0	53.87	3.55	54.90	1.49	55.86	3.70
111.45         175,000         2,939         70.78         7.88         192.08         77.77         5.42         46.09         322.95         334.9C         69.35         0         71.48         4.67         73           20.000         186.52         500.000         8.933         100.44         11.64         485.61         108.52         8.59         95.05         665.66         690.37         98.26         0         71.48         4.65         10           VEE         107.96         75.000         1,450         60.40         5.95         68.19         37.77         3.95         46.04         177.04         119.07         63.46         0         22.67         0.74         61         66         66         66         67.66         69.35         0         714         65.14         65.51         67.74         61         65         66         714         65         714         65         714         717.04         119.07         63.26         0         64.65         66         712         65         714         717.04         119.07         63.26         0         63.3         71           VEE         10.000         128.00         27.40         112.05         46.04 </td <td></td> <td></td> <td>117.50</td> <td>125,000</td> <td>2,095</td> <td>64.07</td> <td>6.96</td> <td>137.07</td> <td>06.63</td> <td>4.78</td> <td>32.91</td> <td>230.50</td> <td>239.08</td> <td>61.96</td> <td>•</td> <td>63.88</td> <td>4.18</td> <td>64.92</td> <td>1.78</td> <td>66.07</td> <td>4.40</td>			117.50	125,000	2,095	64.07	6.96	137.07	06.63	4.78	32.91	230.50	239.08	61.96	•	63.88	4.18	64.92	1.78	66.07	4.40
20.000       186.52       500.000       8.933       100.46       11.64       485.61       108.52       8.59       95.05       665.66       690.37       98.36       0       101.39       6.65       103         VEE       107.96       75.000       1,450       60.40       5.95       68.19       37.77       3.95       46.04       177.04       119.07       63.46       0       22.67       0.74       61         VEE       10,000       128.00       124.50       60.40       5.95       68.18       37.77       3.95       44.04       177.04       119.07       63.46       0       22.67       0.74       61       5       55       107.75       52.35       0       62.28       0.83       77       5       55       107.77       75.23       0       62.28       0.93       37       5       55       55       102.75       412.94       56       0.95.65       0.95.65       0.95.65       0.74       55       244       6       0       53.67       0.74       65       74       65       24       6       0       53.51       6       54.46       6       6       5.44       6       5       24.45       6       74.4			131.45	175,000	2,939	70.78	7.88	192.08	77.77	5.42	46.09	322.96	334.90	69.35	•	71.48	4.67	72.49	2.02	73.77	4.94
VEE         107.06         75.000         1,450         60.40         5.95         68.19         37.77         3.95         46.04         117.04         119.07         63.46         0         22.67         0.74         61           VEE         10,000         128.00         175,000         2,364         71.34         7.45         112.05         68.28         4.91         73.41         295.11         197.71         75.23         0         62.28         0.83         73           VEE         163.00         128.00         3.287         79.61         8.60         156.15         76.55         102.75         423.94         276.90         84.23         0         69.69         0.93         81           #1549         112.60         75.000         3.287         79.46         81.43         56.55         102.75         41.33.46         64.96         0         69.46         0         69.69         0.93         81         64.93         2.75         14.77         165.36         16.95         0         67.46         64.96         0         73.41         54.46         64.96         0         73.31         2.92         74         65         74         65         74         65         <		20,000	186.52	500,000	8,933	100.44	11.64	485.61	108.52	8.59	<b>30°56</b>	665.66	690.37	98.36	•	101.39	6.65	102.65	3.62	104.34	7.45
VEE 10,000 128.00 129.00 2,364 71.34 7.45 112.05 68.28 4.91 73.41 295.11 197.71 75.23 0 62.28 0.83 7; 1(3.19 175,000 3.287 79.61 8.60 156.15 76.24 5.65 102.75 423.94 276.90 84.23 0 69.69 0.93 8; 12.60 75,000 1,457 63.36 4.94 81.43 64.93 2.75 14.73 169.36 154.44 64.96 0 61.85 2.44 64 Vith 10,000 133.50 125,000 2,365 73.98 6.10 133.77 76.39 3.35 24.59 282.06 257.29 76,99 0 73.31 2.92 71 Thin Fine 10,000 133.50 15,000 3.292 82.13 6.98 186.70 85.11 3.83 34.41 395.16 360.23 86.16 0 82.02 3.25 8			107.96	75,000	1,450	60.40	5.95	68.19	57.77	3.95	44.04	177.04	119.07	63.46	•	52.67	0.74	61.88	1.10	54.52	1.91
143.19         175,000         3,287         79.61         8.60         156.15         76.24         5.65         102.75         4.73.40         276.90         84.23         0         69.69         0.93         87           \$1549         112.60         75,000         1,457         63.36         4.94         81.43         64.93         2.75         14.73         169.36         16.4,96         0         61.85         2.44         64           vith         10,000         133.50         125,000         2,356         4.94         81.43         76.39         3.52         24.59         76.99         0         73.31         2.92         74         64           vith         10,000         133.50         125,000         2.358         6.10         133.77         76.39         3.4.41         360.23         86.16         0         73.31         2.92         74           Thin Fins         14.9.34         175,000         3.292         82.11         3.83         34.41         395.16         360.23         86.16         0         73.23         8         16.32         2.25         8	VEE	10,000	128.00	125,000	2,364	71.34	7.45	112.05	68.28	4.01	13.41	295.11	197.71	75.25	•	62.28	0.83	73.33	1.35	24.45	2.30
#1549         112.60         75.000         1.457         63.36         4.94         81.43         64.93         2.75         14.73         169.36         154.44         64.96         0         61.85         2.44         64           with         10,000         133.50         123.60         2,365         73.98         6.10         133.77         76.39         3.35         24.59         282.06         257.29         76.99         0         73.31         2.92         7         7         7         76.39         3.33         34.41         360.23         86.16         0         73.31         2.92         87         7         7         7         7         76.39         34.41         350.23         86.16         0         82.02         3.235         8         7         7         8         8         3         34.41         355.16         360.23         86.16         0         82.02         3.255         8			143.19	175,000	3,287	79.61	8.60	156.15	76.24	5.65	102.75	413.94	276.90	84.23	•	69.69	0.93	82.04	1.55	72.05	2.63
With       10,000       1133.50       125,000       2,365       73.98       6.10       133.77       76.39       3.35       24.59       282.06       257.29       76.99       0       73.31       2.92       76         Thin Fine       149.34       175,000       3.292       82.13       6.98       186.70       85.11       3.83       34.41       355.16       360.23       86.16       0       82.02       3.25       8	<b>1</b> 549		112.60	75,000	1.457	63.36	4.94	81.43	64.93	2.75	14.73	169.36	154.44	64,96	0	61.65	2.44	64.95	0.89	62.52	×.~
Thin Fine [149.34 [175,000] 3,292 [ 82,13] 6,98 [ 186,70 [ 85,11 ] 3,83 ] 34,41 ] 355,16 ] 360.23 ] 86,16 ] 0   82,02 ] 3,25 ] 8	with	10,000	133.50	125,000	2,365	73.98	6.10	133.77	76.39	3.35	24.59	282.06	257.29	76.99	•	73.31	2.92	76.80	1.08	76.37	3.02
	Thin Fins		149.34	175,000	3,292	82.13	6.98	186.70	85.11	3.83	34.41	395.16	360.23	86.16	•	82.02	3.25	85.83	1.23	83.08	3.44

3al loon	Design			Balloon	Additional
lype	Altitude	Volume	Axis	Mass Moment	Mass Moment
		~		of Inertia	of Inertia
	(ft)	(ft')		(slug ft <sup>2</sup> )	(slug ft <sup>2</sup> )
			Roll	8,874	14,377
	5,000	50,000	Pitch	40,318	49,540
			Yeu	38,881	55,693
			Roll	429,311	413,194
2	20,000	500,000	Pitch	1,731,251	1,423,965
			Yaw	1,639,971	1,597,608

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Balloon and suspension weight, no gas, payload or tether
 Total balloon mass including internal gas and air
 Feet aft of theoretical bow
 Feet below horizontal £

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Figure 29. Mass Moment of Inertia (Pitch and Yaw)

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Figure 30. Additional Mass Moment of Inertia (Pitch and Yaw)





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The fineness ratio of the equivalent ellipsoid to the hull must be computed based on equal volumes and equal lengths.

$$V = \frac{\pi}{6} d^2 L$$
$$d = \sqrt{\frac{6 V}{\pi L}}$$
$$= \frac{L}{1\sqrt{6 V}} = \sqrt{\frac{\pi L^3}{6 V}}$$

Π.

Fineness ratio =

The flat tail surfaces also exhibit an added mass effect when accelerated normal to their chords For large aspect ratios, the added mass is equivalent to the mass of air contained in a cylinder whose diameter is equal to the chord of the tail. Tests have provided corrections for smaller aspect ratios and for taper. The tail added mass terms can be obtained from Figure 33 and added to the hull added mass for the total added mass and moment of inertia effects of each balloon, and for determining the dynamic center.

The added mass of the tail is obtained by multiplying these coefficients of the mass of air contained in a cylinder having the length equal to the span and a diameter equivalent to the chord of a rectangular tail having the same area.

#### 3. DYNAMIC CENTER LOCATION

Under dynamic loads the ballcon will have a mass and moment of inertia which includes the additional mass and additional moment of inertia of the affected surrounding air.

It has been assumed that the axes chosen are the principal axes so that the products of inertia drop out.

The additional mass along each major axis is added directly to the mass of the balloon. The center of the additional mass, however, joes not coincide with the center of gravity. The combination of these two masses will determine the dynamic center about which the complete balloon will act in air. Since the value and location of the additional mass is different for accelerations along each axis, the dynamic center will be located at different places for the lateral and vertical accelerations.

Figure 34 shows how the dynamic center is located and the combined moment of inertia is calculated.



Figure 33. Veriation of the Coefficients of Additional Mass and Moment of Inertia with Aspect Ratio of Rectangular Plates

Location of CA and DC will be different about all three area



Figure 34. Location of Dynamic Center from Mass Center and Center of Additional Mass 33

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#### SECTION IV

#### STATIC AND DYNAMIC AERODYNAMIC DERIVATIVES

## 1. GENERAL

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The fundamental equations of motion state that the sum of the forces equals the mass times an acceleration in the fashion of Newton's Second Law of motion.

$$F = \frac{H}{g} a$$
 and  $H = I 0$ 

where F and H are the unbalanced force and moment on the balloon of mass  $\frac{W}{8}$  and moment of inertia I undergoing accelerations a and 0.

The Force F is the unbalanced force resulting from the vector sum of all applied forces to the balloon. The applied forces include buoyancy, gravity, cable forces and aerodynamic forces. The moment H is likewise the unbalanced moment.

The aerodynamic forces are fundamentally caused by the wind and its relation to the position and attitude of the balloon. At equilibrium, all the forces are balanced and the acceleration is zero. There are secondary forces applied due to changes in attitude, velocity and acceleration when the balloon is disturbed or returning to equilibrium.

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The forces and moments are resolved into components along the major axes and it is assumed that these components can be introduced into the equation as acting about or along that axis.

In order to keep the mathematics to a reasonable effort, it is assumed that the dynamics of the situation having 6 degrees of freedom can be handled as two separate problems without cross coupling of one to the other. The first occurs in the pitch plane and includes lift, drag and pitching moment. The other 3 degrees of freedom are handled as a single problem in roll, yaw and side force.

The force components are assumed to be added arithmetically and are caused by very small deviations from the equilibrium attitude. The deviations are assumed to be linear and can be expressed by the form

$$\frac{\partial y}{\partial x} \cdot \Delta x.$$

The aerodynamic partial derivatives will be evaluated for insertion into the six equations of motion representative of the six degrees of freedom of the balloon. When tests of a complete balloon are not available, it will be assumed that the effect of components, i.e., hull, tail, etc., are additive with a minimum of interference effects. The following discussions eliminate, when they are zero, or determine coefficient forms of the aerodynamic parameters.

The space position of the balloon, i.e., displacement along any axis, has no effect on the aerodynamic parameters. There is a very small effect with vertical position because both wind velocity and air density change with altitude. In the linearized equations, however, it is assumed the displacement is so small that its effect can be neglected.

Velocity along the space axis also has no effect except where it changes the relative wind, which is assumed constant and horizontal. Since model tests and the evaluation formulas are referenced to the relative wind, the space velocity derivatives are dropped in favor of aerodynamic derivatives.

Likewise rotational attitude and velocity are referenced to the relative wind instead of the space reference coordinates.

Acceleration along an axis produces a change in the flow with resulting aerodynamic forces. Sir Horace Lamb showed that the acceleration derivatives have the dimension of mass and could be considered as an additional mass added to the mass terms on the right hand side of the equation. The additional mass terms will be handled later. The added moments of inertia are handled the same way.

#### 2. LIFT

The uncoupled derivatives that must be evaluated for lift are related to angles of attack, and to velocities along the X and Z axis and rotation velocity about the Y axis.

 $\frac{\partial L}{\partial \alpha}$ ,  $\frac{\partial L}{\partial u}$ ,  $\frac{\partial L}{\partial w}$ ,  $\frac{\partial L}{\partial \dot{\alpha}}$ 

The effect of angle of attack change on lift,  $\frac{\partial L}{\partial \alpha}$ , can be determined from the lift curve. This is usually determined in wind tunnel tests and plotted as lift coefficient vs angle of attack. These curves are presented in Figure 5.

$$\frac{\partial L}{\partial \alpha} = \left(\frac{1}{2} \cdot \rho \, v^2 \, v^{2/3}\right) \, c_{L\alpha} \tag{1}$$

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where  $c_{L\,\alpha}$  is the slope of the lift coefficient curve measured at the equilibrium angle of attack.

The effect of small change in velocity,  $\frac{\partial L}{\partial u}$ , can be evaluated

$$L = \frac{1}{2} \cdot \rho v^2 v^{2/3} c_L$$

Since u is a small change in V, differentiating,

$$\frac{\partial L}{\partial u} = \rho_V v^{2/3} C_L$$

Multiply by  $\frac{2V}{2V}$ ,

$$\frac{\partial L}{\partial u} = \left(\frac{1}{2} \cdot \rho \, v^2 \, v^{2/3}\right) \quad \frac{2C_L}{v}$$

$$\frac{\partial L}{\partial u} = (Lift) \frac{2}{v}$$

The effect of vertical velocity on lift,  $\frac{\partial L}{\partial w}$ , can be resolved as an induced angle of attack change.

$$\frac{\partial L}{\partial w} = \frac{\partial L}{\partial \alpha} \cdot \frac{\partial \alpha}{\partial w}$$
(2)

For small angles,

$$\alpha = \alpha_0 + \frac{w}{v}$$
.

differentiating;

$$\frac{\partial \alpha}{\partial w} = \frac{1}{v}$$

From equations (1) and (2) above,

$$\frac{\partial L}{\partial w} = \left(\frac{1}{2} \cdot \rho v^2 v^{2/3}\right) \quad \frac{\partial L}{v}$$

This can also be expressed

$$\frac{\partial L}{\partial w} = \frac{\partial L_a}{\partial \alpha} \times \frac{1}{V}$$

The lift due to pitch rotation,  $\frac{\partial L}{\partial \dot{\alpha}}$ , can be measured on models in a whirling arm test facility or by oscillating curved models in a conventional wind tunnel. Curved models have also been used in a wind tunnel. These data have not been measured on models of the configuration of these balloons.

To evaluate this derivative, standard airship design practices based on model airship tests will be used. This assumes that the hull derivative can be added to the tail contribution to make up the whole. The effect of the shape of the Vee-Balloon hull is unknown.

## 3. DRAG

In a parallel and similar manner, the derivatives of drag are obtained.

$$\frac{\partial D}{\partial \alpha} = \left(\frac{1}{2} \rho v^2 v^{2/3}\right) C_{D_{\alpha}}$$

$$\frac{\partial D}{\partial u} = \left(\frac{1}{2} \rho v^2 v^{2/3}\right) \frac{2C_D}{V} \quad \text{Also } \frac{\partial D}{\partial u} = (\text{drag}) \frac{2}{V}$$

$$\frac{\partial D}{\partial w} = \left(\frac{1}{2} \rho v^2 v^{2/3}\right) \frac{C_D_{\alpha}}{V} = \frac{\partial D}{\partial \alpha} \times \frac{1}{V}$$

The derivative  $\frac{\partial D}{\partial \dot{\alpha}}$  has not been evaluated experimentally or theoretically and is neglected in airship dynamic analyses. If it is neglected this means the value zero is assigned to it. Rather, it is thought better to try to assign some value to it, possibly related to the lift through the induced lift-drag ratio,

$$\frac{\partial \mathbf{D}}{\partial \dot{\alpha}} = \frac{\partial \mathbf{L}}{\partial \dot{\alpha}} \times \frac{\mathbf{D}}{\mathbf{L}}$$

where,  $\frac{D}{L} = \frac{C_{D_{i}}}{C_{T}} = \frac{KC_{L}^{2}}{C_{T}}$  where K =

where K = .9 for general airship shapes

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 $\frac{\partial \mathbf{D}}{\partial \dot{\alpha}} = \frac{\partial \mathbf{L}}{\partial \dot{\alpha}} \times .9 C_{\mathbf{L}}$ 

#### 4. PITCHING MOMENT

Also, it is obvious that the following relationships concerning pitching moment are,

 $\frac{\partial M}{\partial \alpha} = \left(\frac{1}{2} \cdot \rho V^2 \psi\right) C_{m_{\alpha}}$   $\frac{\partial M}{\partial u} = \left(\frac{1}{2} \cdot \rho V^2 \psi\right) \frac{2C_{m}}{V} = (Moment) \frac{2}{V}$   $\frac{\partial M}{\partial w} = \left(\frac{1}{2} \cdot \rho V^2 \psi\right) \frac{C_{m_{\alpha}}}{V} = \frac{\partial M}{\partial \alpha} \times \frac{1}{V}$ 

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The rotary derivative  $\frac{\partial M}{\partial \dot{\alpha}}$  can be evaluated from airship data using airship design methods for the circular balloons. The value for the Vee-balloon hull is not known due to the shape of its hull.

## 5. ROLLING MOMENT

Rolling moment, as with yawing moment and side force, is studied uncoupled from the pitch plane. All model tests are made at zero angle of attack. Accordingly, the derivatives will be evaluated at zero angle of attack and assumed to be independent of it. The following derivatives are assumed to have a non-zero value which can be estimated.

$$\frac{\partial M}{\partial R}, \quad \frac{\partial M}{\partial p}, \quad \frac{\partial M}{\partial r}, \quad \frac{\partial M}{\partial v}, \quad \frac{\partial$$

Rolling moment due to yaw,  $\frac{\partial R}{\partial \beta}$ , for symmetrical balloons would be zero about the longitudinal axis. If the center of gravity is not on the axis, then there is a rolling moment due to side force multiplied by a suitable moment arm. This term will be handled when the center of moments is shifted to the center of gravity and is not included in the aerodynamic efforts. For the unsymmetrical tail of the Vee-balloon, there is an additional moment due to the side force of the vertical tail.

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$$M_{x} = \frac{1}{2} \rho v^{2} A_{v} \cdot C_{L_{t}} \cdot z$$

Where z is the vertical distance between the longitudinal axis and the center of pressure of the vertical tail area,

$$\frac{\partial M_{x}}{\partial \beta} = \left(\frac{1}{2} \rho v^{2} A_{v} z\right) C_{L_{z}}$$

moment due to the tail will be estimated in the following way.

Rolling moment due to rolling velocity,  $\frac{\partial M_x}{\partial p}$ , is caused by the damping effect of the apparent angle of attack of the tail. This is composed of the sum of the effect of all the tail surfaces, plus, in the case of the Vee-balloon, an effect of the hull. The latter effect has not been measured experimentally; however, some value should be estimated for it. The rolling



where c is the local tail chord

 $C_{L_{t}} = C_{L_{t}\alpha} \frac{p\ell}{V}$   $M_{x} = \int_{\ell_{1}} \frac{1}{2} \rho v p C_{L_{t}\alpha} c\ell^{2} d\ell$   $\frac{\partial M_{x}}{\partial p} = \frac{1}{2} \rho v C_{L_{t}\alpha} \int_{\ell_{1}}^{\ell_{2}} c\ell^{2} d\ell$ 

Rolling moment due to yawing velocity,  $\frac{\partial M}{\partial r}$ , is zero for a balloon symmetrical about the X-Y plane. In the Vee-balloon the tail side force is produced by an apparent angle of attack change which is,  $\frac{Xr}{V}$ , where X is the longitudinal distance between the center of rotation and the center of pressure of the tail. The moment of the force about the roll axis of symmetry becomes,

$$M_{x} = \frac{1}{2} \rho_{V}^{2} A_{V} z C_{L_{t_{\alpha}}} \frac{Xr}{V}$$

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When z is the distance between the axis and the center of pressure of the tail,

$$\frac{\partial M_{x}}{\partial r} = \frac{1}{2} \rho V A_{y} X z C_{L_{t_{\alpha}}}$$

Rolling moment due to sideslip velocity,  $\frac{\partial M_x}{\partial v}$ , only has a value for the unsymmetrical tail. Here the side slip velocity introduces an apparent angle of attack change  $\frac{v}{v}$ . The moment then becomes

$$M_{x} = \frac{1}{2} \rho v^{2} A_{v} z C_{L_{t_{\alpha}}} \frac{v}{v}$$

$$\frac{\partial^{H} x}{\partial v} = \frac{1}{2} \rho_{V} A_{v} z C_{L_{t\alpha}} = \frac{\partial M}{\partial r} x \frac{1}{x}$$

6. YAWING MOMENT

The yawing moment due to yaw,  $\frac{\partial N}{\partial \beta}$ , is the slope of the yawing moment curve at zero yaw obtained from wind tunnel data. This can be expressed 
$$\frac{\partial N}{\partial \beta} = \left(\frac{1}{2} \rho v^2 v\right) c_{n\beta}$$

The yawing moment due to rolling velocity,  $\frac{\partial N}{\partial p}$ , is zero for a balloon with a symmetrical tail. For the Vee-balloon with an unsymmetrical tail, a net force is caused by the apparent angle of attack change of the tail caused by the following velocity which produces a moment in yaw,

$$N = XF = X \int_{l_1}^{l_2} \frac{1}{2} \rho V^2 c C_{L_{t_{\alpha}}} \frac{\ell_p}{V} d$$
$$\frac{\partial N}{\partial P} = \frac{1}{2} \rho V X C_{L_{t_{\alpha}}} \int_{\ell_1}^{\ell_2} c\ell d\ell$$

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Due to symmetry, there will be no yawing moment due to rolling velocity of the hull.

The yawing moment due to yawing velocity,  $\frac{\partial N}{\partial r}$ , has not been measured on the balloon shapes. This rotary derivative can be estimated from airship data using standard airship design methods. When symmetry exists, it is related to the pitching moment due to pitching velocity.

The yawing moment due to side slip velocity,  $\frac{\partial N}{\partial v}$ , is caused by an apparent angle of yaw due to the relative wind.

$$N = \frac{1}{2} \rho_{V}^{2} v_{n} c_{n} \frac{v}{v}$$
$$\frac{\partial N}{\partial v} = (\frac{1}{2} \rho_{V}^{2} v) \frac{\frac{c_{n}}{\beta}}{v} = \frac{\partial N}{\partial \beta} \times \frac{1}{v}$$

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7. SIDE FORCE

The side force due to yaw,  $\frac{\partial Y}{\partial \beta}$ , is available from wind tunnel tests.

$$y = \frac{1}{2} \rho_{v}^{2} v^{2/3} c_{y}$$

$$\frac{\partial Y}{\partial \beta} = \left(\frac{1}{2} \rho_{V}^{2} V^{2/3}\right) c_{Y_{\beta}}$$

A side force due to rolling velocity,  $\frac{\partial Y}{\partial p}$ , will occur when the balloon is not symmetrical about the longitudinal axis. The rolling velocity produces a local angle of attack of the tail with a resulting side force,

$$dY = -\frac{1}{2} \rho v^{2} C_{L_{t_{\alpha}}} \frac{\ell_{p}}{v} c d\ell$$

$$Y = -\frac{1}{2} \rho v p C_{L_{t_{\alpha}}} \int_{\ell_{1}}^{\ell_{2}} c\ell d\ell$$

$$\frac{\partial Y}{\partial p} = \frac{1}{2} \rho V C_{L_{t_{\alpha}}} \int_{l_{1}}^{l_{2}} c \ell d\ell = \frac{\partial N}{\partial p} \times \frac{1}{X}$$

The side force due to yawing velocity,  $\frac{\partial Y}{\partial r}$ , for symmetrical balloons is related to the rotary derivatives of lift due to pitching velocity. There are very little wind tunnel data available on this derivative; however it will be combined with airship data and a value will be estimated by established techniques.

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The side force due to the side slip velocity,  $\frac{\partial Y}{\partial v}$ , can be evaluated as an apparent angle of attack change,

$$\mathbf{y} = \frac{1}{2} \quad \rho \, \mathbf{v}^2 \, \mathbf{v}^{2/3} \, \mathbf{c}_{\mathbf{y}_{\beta}} \, \frac{\mathbf{v}}{\mathbf{v}}$$

and the second 
$$\frac{\partial Y}{\partial v} = \left(\frac{1}{2} \rho V^2 V^{2/3} C_{Y\beta}\right) \frac{1}{V} = \frac{\partial Y}{\partial \beta} \times \frac{1}{V}$$

## SECTION V

## TETHER CABLES

## 1. PHYSICAL PROPERTIES

Appropriate tethers for the systems under study are restricted to NOLARO and Amgal-Monitor AA wire ropes.

The NOLARO is an unbraided (NO-LAy-ROpe) construction of the Columbian Rope Company. Yarns may be nylon, polyester (Dacron), or polypropelene. Jackets can be of polyethylene, polyvinyl chloride, polyurethane, etc. Table VIII presents some typical polyester NOLARO line. To maximize strength/weight ratio this tabulation was refigured for a polyester jacket of 0.040 in. wall and is presented in Table IX. These values are used throughout this report in describing a system using NOLARO tether. BS/N was determined as implied by Table VIII values.

## Table VIII

## Columbian Rope Company "NOLARO"

Nominal Size (InStrand)	Approx. B.S.*(Lb)	Polyester Diameter (In.)	Nominal Jacket Thickness (In.)	Weight Lbs/M Ft	Unit Weight Ft/Lb
3/16 -4	1,400	0.142	0.025	13.2	75.8
1/4 -6	2,100	0.174	0.038	20.5	48.8
5/16 -10	3,400	0.225	0.044	31.6	31.6
3/8 -16	5,300	0.284	0.045	45.7	21.9
7/16 -22	7,300	0.334	0.052	57.4	17.4
1/2 -30	10,000	0.390	0.055	81.7	12.2
5/8 -50	16,500	0.502	0.060	128.0	7.81
3/4 -80	25,000	0.635	0.060	187.0	5.35
1 -155	46,000	0.887	0.060	332.0	3.01
1-1/4 -340	60,000	1.100	0.075	527.0	1.90
1-5/8 -400	100,000	1.420	0.102	868.0	1.15

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## Prestretched Polyester Jacketed with Polyethylene

\* Breaking Strength

B.S. (1b)	<u>B.S</u> N (1b)	N	d (in.)	D (in.)	Yarn wt/1000 ft (1b)	Jacket wt/1000 ft (1b)	Total wt/1000 ft (1b)
2,000	337.8	5.93	0.173	0.253	10.0	10.7	20.7
5,000	334.5	14.5	0.27	0.35	24.4	15.5	39.9
10,000	329.0	30.4	0.39	0.47	51.1	21.5	72.6
20,000	318.0	62.8	0.56	0.64	105.5	29.3	134.8
30,000	307.0	97.7	0.70	0.78	164.0	36.9	200.9
40,000	296.0	135.0	0.82	0.90	227.0	41.1	268.0
50,000	285.0	175.3	0.94	1.02	295.0	48.6	344.0
60,000	274.0	219.0	1.05	1.13	368.0	56.1	424.0
70,000	263.0	266.5	1.16	1.24	448.0	59.2	507.0
80,000	252.0	317.5	1.26	1.34	534.0	62.4	596.0
90,000	241.0	374.0	1.37	1.45	629.0	68.6	698.0
100,000	230.0	435.0	1.48	1.56	731.0	78.0	809.0

# Prestretched Polyester Jacketed With 0.040 Polyethylene

Table IX

where B.S. = breaking strength, 1b number of prestretched yarns N **1**2  $\begin{bmatrix} d = 0.071 & \sqrt{N} \end{bmatrix}$ diameter of yarn bundle (in) d == 0.D. (in) [D = d + 2t, where t = 0.040]D = Wt 1.68 (N) yarn  $(D^2 - d^2) G$ Wtjacket = specific gravity of jacket [0.92 for PE; 1.25 for PVC] = G Polyethylene PE = Polyvinyl Chloride PVC =

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Approximate elongation for prestretched polyester NOLARO rope is given below in Table X:

## Table X

## Approximate NOLARO Elongation

Load as Percent of Breaking Strength	Approximate Elongation(%)
10	1.0
20	1.8
30	2.8
50	4.3
70	5.6

Table XI presents U. S. Steel's Amgal-Monitor AA wire rope. Figures 35 and 36 present the cable weight vs breaking strength and cable weight vs diameter for the two constructions.

In combined balloon-tether solutions later the specific Amgal wire rope sizes as given in Table XI will be used, as these are the available sizes. Any desired size of NOLARO, along the curves of Figures 35 and 36 can be manufactured. Thus an infinite range of sizes is available in the NOLARO construction.

The computer solution, as presented in Appendix I, incorporates a  $C_D$  for the cable of 1.1 which is consistent with Reference 14. Both constructions are solved with this same drag factor, although NOLARO is smooth and Amgal-Monitor is a lay-up of three main elements of rough surface. However, Reference 14 indicates that a surface roughness in the appropriate Reynold's number regime provides a reduction in  $C_D$ . The reference diameter for the Amgal-Monitor is that of a circumscribing circle, which is 115% of the sum of the diameters of any two main rope elements

 $(\frac{1}{\sin 60^{\circ}} = 1.15).$ 

Comparative solutions of cables for the 10,000 foot altitude balloons resulted in 1-2% more tether out and 5-8% more downwind displacement for  $C_{\rm D}$  = 1.5 as against  $C_{\rm D}$  = 1.1.

Results for both constructions in this report are based on  $C_D = 1.1$ .

#### 2. AERODYNAMIC FORCES ON THE CABLE

The drag coefficient on cylinders and cables which represent the tether cable may be found in Reference 14. This cable will be operating at a Reynold's number of  $10^4$  which is well below the critical number for cylinders and is in an area where the C<sub>D</sub> value is essentially constant at 1.1.

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# Table XI

# UNITED STATES STEEL TETHERS Amgal-Monitor AA Wire Rope

Minimum Breaking Strength (1b)	Di <b>a</b> meter (in.)	Design Construction	Weight per 1000 Feet (1b)
2,800	0.156 (5/32)	3 x 7	40.2
3,500	0.172 (11/64)	3 x 19	50.7
4,000	0.187 (3/16)	3 x 19	58.6
5,400	0.218 (7/32)	3 x 19	79.5
6,750	0.250 (1/4)	3 x 19	99.7
10,300	0.312 (5/16)	3 x 19	153.0
14,800	0.375 (3/8)	3 x 19	220.0
20,000	0.437 (7/16)	3 x 19	304.0
25,700	0,500 (1/2)	3 x 19	392.0
32,500	0.562 (9/16)	3 x 19	492.0
40,300	0.625 (5/8)	3 x 19	602.0
57,800	0.750 (3/4)	3 x 19	879.0
78,000	0.875 (7/8)	3 x 19	1210.0
100,690	1.000 (1)	3 x 19	1560.0

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In a cable such as this where the pressure drag is very large compared to the friction drag, the latter may be ignored in the calculations. Also it is assumed that the cable force per unit of length always acts normal to it and has a value varying as the  $\cos^2 \theta$ . こうちょうとうというないでいいろうないできょう



Since the equations are written as moments about the base

$$M = Fs = \int_{O}^{O} \frac{1}{2} \rho V^{2} \times 1.1 \cos^{2} \theta t s ds$$
$$M = 0.55 t \cos^{2} \theta \int_{O}^{O} \rho V^{2} s ds$$

where  $\rho$  and V are functions of altitude and thus s.

The cable also has a damping moment due to rotation and translation velocities, the latter caused by movement of the upper end of the link below. The moment equation thus becomes

$$M = 0.55 \text{ t} \cos^2 \theta \int \rho (V + u + s \theta \cos \theta)^2 \text{ s} ds$$

The vertical component of the velocity is small and has a secondary effect only changing  $\theta$  a small amount. Accordingly, it was not included in the damping equation.

For convenience in handling this mathematically and to arrive at a damping number, it is assumed temporarily that V and  $\cdot \rho$  are not significant functions of s.

$$M = 0.55 \ \rho \ t \ \cos^2 \theta \qquad \left| \begin{array}{c} {}^{8} \circ \\ \circ \end{array} \frac{(V + u + s \ \dot{\theta} \ \cos \theta)^4}{4 \ \dot{\theta}^2 \ \cos^2 \theta} \right|^4}{4 \ \dot{\theta}^2 \ \cos^2 \theta} \\ - \frac{(V + u) \ (V + u + s \ \dot{\theta} \ \cos \theta)^3}{3 \ \dot{\theta}^2 \ \cos^2 \theta} \\ M = \frac{0.55 \ \rho \ t \ s^2 \ \cos^2 \theta}{12} \left( 8 \ Vs \ \dot{\theta} \ \cos \theta + 6 \ V^2 + 12 \ Vu + 8 \ u \ s \ \dot{\theta} \ \cos \theta + 6 \ V^2 + 3 \ s^2 \ \theta^2 \ \cos^2 \theta \right)$$

Differentiating,

Allow

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$$\frac{\partial M}{\partial \phi} = \frac{0.55 \rho t s^2 \cos^2 \phi}{12} (8 \text{ Vs } \cos \phi + 8 \text{ u s } \cos \phi + 6 s^2 \phi \cos^2 \phi)$$
  
u and  $\phi = 0$ 

$$\frac{\partial M}{\partial \dot{g}} = 0.366 \ \rho V t s^3 \cos^3 \theta$$

Motions of the link below this one also introduces a damping force on this link. This can be resolved by differentiating the moment with respect , to this velocity u.

$$\frac{\partial M}{\partial u} = \frac{0.55 \rho_t s^2 \cos^2 \theta}{12} \quad (12 v + 8 s \theta \cos \theta + 12 u)$$

Section 20

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Allow u and  $\emptyset \longrightarrow 0$ .

$$\frac{\partial M}{\partial u} = 0.55 \ \rho \, V \, t \, s^2 \, \cos^2 \theta$$

## SECTION VI

#### BALLOON/CABLE SYSTEMS

#### 1. STATIC SOLUTIONS

The balloon aerostatic lift capability in no wind, and tether weight for the proper strength tether as determined by survival wind, are plotted in Figures 37 through 41 for the several balloon configurations and payload/ altitude criteria. Net static lift, L<sub>S</sub>, is gross aerostatic lift less balloon weight and payload weight. Tether weight for lengths from sea-level vertically to design altitude (of breaking strength appropriate to the survival loads x factor of safety) is plotted as a function of balloon volume. The intersection of the two curves indicates the minimum balloon size which is aerostatically adequate. A given balloon/cable combination which is statically adequate may not be operationally adequate; the balloon total lift and drag under the operational wind profile may be inadequate to support the greater length (and weight) of tether which must be paid out under the wind condition, and the system may not be able to maintain design altitude.

The cable solutions for the various balloon/cable systems shown in this section have been solved by the Appendix I program for the operational wind profile, and provide satisfactory solutions both in operational as well as no wind. Results are tabulated in the following section.

Initially, it was intended to size balloons with approximately a 10 percent excess of buoyant lift for static conditions. One of the parameters to be varied during the study of dynamic behavior is "free" lift. However a number of practical problems interfere with this goal.

Since the wire rope must be used in specific sizes available, the weight curves for this tether have a typical stair-step shape. Balloon sizes usable are not smoothly variable but must be selected in jumps. A considerable increase in balloon size may be involved in moving from one rope size to the next. For the wire rope, the largest balloon with the smallest cable which provided a positive static solution was always chosen. For instance a BJ balloon at 10,000 feet was sized at 75,000 cubic feet with a 1/4-inch wire rope. The minimum size possible with a 1/4-inch rope would be 65,000 cubic feet with no "free" lift. A larger size than 75,000 cubic feet necessitates a 5/16-inch wire rope, and sizes of 85,000 to 117,000 cubic feet. To keep balloon sizes minimal within these constraints, it was not always possible to achieve 10 percent excess buoyancy. At 20,000 feet, static solutions are not possible with the wire rope (see Figure 41). For the BJ balloon the minimum static solution is with a 320,000 cubic feet volume for NOLARO tether. A 500,000 cubic foot size has been selected and this size provides approximately a 6 percent excess static buoyancy. Ten percent excess buoyancy requires a 700,000 cubic foot size.



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Figure 39. GAC No. 1649 Balloon System, Static Solution for 10,000 Feet Altitude



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Figure 40. BJ Balloon System, Static Solution for 5,000 Feet Altitude





Table XII summarizes the balloon/cable systems of the several balloon configurations. The BJ shape has been selected and sized for the 5,000 and 20,000 foot altitudes as representing the lightest and thus the smallest possible system of those investigated.

For all single hull ballcons (BJ and No. 1649) only the hull was assumed helium inflated; i.e., hull volume is total helium volume at design altitude, and with helium purity of 97 percent.

With the Vee-balloon, the empennage is helium inflated and adds 6.7 percent volume to the reference hull volume (see Table II, Section II). Unless otherwise stipulated, the Vee-balloon volumes quoted in this report are hull volume only.

Table XII includes balloon weight, net static lift, and operational and survival aerodynamic loads developed by the balloon. Tethers are sized with a factor of safety of 1.50 for Amgal-Monitor and 2.00 for NOLARO. Despite these factors the NOLARO permits smaller total systems throughout the design range.

## 2. DESIGN LOADINGS

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Tether loading is the vector sum of  $L_s$ , net static lift;  $L_a$ , aerodynamic lift; and, D, aerodynamic drag.  $L_s + L_a = L_N$ , or total lift. Tether angle from the vertical is the angle defined by  $L_N/D$ .

Table XII loadings for operational wind are applied to the selected cables with results presented in Section VII.

Table XII. Summary of Balloon/Cable Systems

			Gross					Survi	Iav			Operation	1	-		Tether	
Balloon	£	Hull	Static	;	,	 ,		-	-		-	a	-	*	Type	0.D.	B.S.
Type		Volume (ft <sup>3</sup> )	(91)	8 (qL)	(q1)	," (q	," (q)	(9I)	<u>م</u>	(91)	(q1)	(11)	41)	(91)		(in)	(41)
											01		1 058	\$11.1	NOT ARD	121.0	1.813
24	\$,000	46,000	2,534	635	1,500	399	1.391	929	06/1	1,300	600	15	aro. 1				
	10,000	80,000	4,029	1,541	1,000	1,488	6,427	2.422	7,916	8,279	764.4	1,514	5,925	6,116	NOLARO	0.585	16,600
Vee- Balloon		(85,363) <sup>1</sup> 144.000	7.253	2.712	1.769	1,541	605.6	3,583	13,050	13,533	6,564	2,239	10,105	10,350	ACAL	7/16	20,000
		(153,654) <sup>1</sup>															}
		60° 000	2,832	1:031	1,000	108	2,706	1,219	3,507	3,713	1,391	651	2,192	2,287	NOLABU	0.410	7,540
2		75,000	3,540	1,276	1,000	1,264	3,140	1,414	4,405	4,626	1,614	755	2,878	2,975	ANGAL	1/4	6,750
/n 67914		80,000	3,776	1,548	1,000	1,228	4,963	1,346	6, 191	6,336	2,508	757	3,736	3,812	ONALON	0.320	12,700
Thin Fins		133,000	6,278	2,511	1,000	2,767	6,965	1,887	9,732	6,913	3,519	1,061	6,286	6,376	ANGAL	3/8	14,800
2	20,000	500,000	700,71	8,933	600	7,504	15,420	6,785	22,924	23,907	1.571	3,577	15,075	15,494	NOLARO	0,993	47.314

<sup>1</sup> Total Kelium Volume
 D Reference Table X1 and Figures 35 and 36

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#### SECTION VII

## TETHER CABLE PROFILE PARAMETERS

The profile parameters chosen for representation are the angle between the cable and the vertical at the bottom end of the cable  $(\theta_B)$ , the top end excursion or downwind displacement relative to the bottom end (d), and the total weight of the cable segment  $(W_c)$ . A supplemental factor is presented in conjunction with  $\theta_B$  to define the altitude  $(h_1)$  at which  $\theta_B$  occurs. These parameters are illustrated in Figure 42.

Occasions arise where the cable segment becomes horizontal at a point above mean sea level, in which case the factor h1 is used to define altitude at which a second balloon must be added.

Float altitudes were selected as 5,000, 10,000 and 20,000 feet above MSL. Wind profile is presented in Section I. Cable types are based on the information presented in Sections V and VI.

Flexibility of the cable design solution is made possible by use of the equations given in Reference 15. GAC's IBM S/360, Model 40, digital computer was used for solutions of these equations. The computer program is flexible in that specific values of cable weight and diameter can be assumed, or cable weight, diameter, and breaking strength can be assumed to be a function of cable tension. Any float altitude, wind profile, and cable strength/weight/ diameter relation may be specified. Design curves are then obtained by specifying particular values of  $L_N$  and  $L_N/D$ .

Results of these profile calculations show comparative performance. Derivation of the difference equations and equations defining cable properties are given in Appendix I.

Table XIII presents a typical computer printout, the NOLARO cable for the 46,000 cubic foot BJ balloon, h = 5,000 feet.  $F_Z$  and  $F_X$  are  $L_N$  and D from Table XII, Section VI, for the operational wind.

In the printout: x is downwind displacement (ft) z is distance down from design altitude (ft) PHI is tether angle to the vertical (deg) T is tether tension (lb) Length is running summation of tether length (ft) Velocity is windspeed at that altitude (fps) Diameter is tether diameter (ft) Weight is tether weight (lb/ft)

Table XIV is a summary of the cable solutions for the eight specific balloon/cable systems.



Figure 42. Tether Cable Profile Parameters
Table XIII. Cable Solution for NOLARO Cable For 46,000 Ft<sup>3</sup> BJ Balloon in Operational Wind

× × • • • • • • • • • • • • • • • • • •	2								
		14614	рні	-	<b>LENGTH</b>	ALPHA	A11CTBA	DIAMETER	NEICH
- 65 - 129 - 129 - 1299 - 2699 - 2699 - 2699 - 2699 - 4920 - 4920 - 4920 - 4920 - 600 - 700 - 600 - 700 - 600 - 700 - 70	•0	0,01	161.6	1115.	•	0*0	52.37	0.02679	0+0321
- 129 - 198 - 198 - 269 - 269 - 484 - 480 - 00 - 499 - 499	-190.	180.0	160.8	1109.	200-	-0-0	51.55	0.02679	0.0321
- 198. - 269. - 269. - 4343. - 4343. - 499. 0.	-379.	180.0	159.9	1103.	•00+	0.0-	42.02	0.02679	0-0321
- 269. - 343. - 4420. - 4499. 0.	-567.	182.0	159.1	1097.	.003	0-0-	49.93	0.02679	0.0321
-343. -420. -499. 0.	-153.	182.0	158.3	1091.	800.	0.0-	<b>49.12</b>	0.02679	0.0321
- 420.00.00.00.00.00.00.00.00.00.00.00.00.0	-934.	187.0	157.4	1005.	1000.	0.0-	48.32	0.02679	0.0321
-499.	-1124.	180.0	156.7	1079.	1200.	0*0-	47.45	0.02679	3-0321
	-1307.	180.0	155.9	1074.	1400.	0*0-	46.54	0.02679	0.0321
-581 0.	-1493.	183.0	155.1	1069.	1600.	0.0-	45.64	0.02679	0.0321
-665-	-1671.	182.0	154.4	1062.	1800.	0*0-	44.74	0.02679	0.0321
-751.	-1852.	182.0	153.7	1056.	2000.	0.0-	43.85	0.02879	0.0321
-940	-2031.	183.0	153.0	1051.	2200+	0.0-	45.94	0.02679	0.0321
- 630-	-2209.	0.01	152.3	1045.	2400.	-0-0	41.89	0.02679	0.0321
-1021. 0.	-2386.	10.01	151.7	1039.	2600.	0.0-	49.04	0.02679	1260-0
-1118- C	-2563.	180.0	151.0	1034.	2800.	-0-0	39.60	0.02679	0.0321
-1215. 0.	-2738.	180.0	150.4	1028.	3000.	C*0-	38.77	0.02679	0-0321
-1314. 0.	-2912.	162.0	149.8	1023.	3230.	0.0-	37.74	0.02679	0.0321
-1414- C	-3084.	180.0	149.3	1017.	3400.	-0-0	36.58	0.32679	0.0321
-1516- 3-	-3255.	180.0	148.7	1012.	3600.	0-0-	35.26	0.02679	0.0521
-1620- 0.	-3427.	183.0	148.2	1026.	3820.	-0-0	33.95	0.02679	0.0321
-1726. 0.	-3597.	180.0	147.7	1001.	+000+	0*0-	32.65	0.02679	0-0321
-1833. 0.	-3766.	187.0	147.2	995.	4200.	0,0-	31.36	0.02679	0.0321
-1941. 0.	-3934.	160.0	146.7	990.	4400*	0.0-	30.08	0.02679	1260-0
-2051。 0.	-4101.	180.0	146.2	985.	4600.	0.0-	28.29	0,02679	0.0321
-2162. 0.	-4268.	183.0	145.0	.619.	4800-	C*0-	26.18	0.02679	0-0321
-2275. 0.	-4433.	183.0	145.4	974.	5000.	0*0-	24.03	0.32679	0.0321
-2389. 0.	-4598.	183.0	145.0	969.	5200.	-0.0	21.39	0.02670	0.0321
-2503. 0.	-4762.	183.0	144.7	964.	5400.	-0-0	19.01	0.02679	0.0321
-2618. 2672 0.	-4925. 2000.	180.0	144.3 14.4 9	• 958. 05	64 5600.	5692'-0.0	17.84	0.02679	0.0321
-2735. 0.	-5081. JUUU	180.0	144.0	953.	5800-	0.0-	15.78	0.02679	0.0321
TIMII GUNI MINA I AMMIN						1026			

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TOTAL CABLE WEIGHT

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Balloon Type	Alsitude	Rull Volume	Tether Type	8.5.	0.D.	₩t/¥t	x	ş	T	Length	Total Tether
	(ft)	(ft <sup>3</sup> )		(15)	(ft)	(15/ft)	(ft)	(deg)	(15)	(ft)	(16)
ស	5,000	46 000		3 413	0.02639	0 01211	0	151.6	1,115	0	
h = 5,000 ft P = 1,500 lb	S.L.	40,000		3,015	0.02079	0,05111	2 ,672	144.2	956	5,692	183
	10,000						0	165.7	6,115	0	
Vee-Balloon	s,000	80,000	NOLARO	16,600	0.04875	0.11400	1,775	154.7	5,552	5,324	606
h = 10.000 ft	s.t.			ļ			4,594	145.6	4,991	11,050	1,260
P = 1,000 lb	10,000						0	167.5	10,350	0	
	5,000	244,000	ANGAL	20,000	0.03642	0.30400	1,389	160.8	8,836	5,193	1,580
	S.L.		1	l	ł		3,452	153.9	7,300	10,605	3,230
BJ h • 10,000 fe P • 1,000 lb	10,000						0	163.4	2,287	0	
	5,000	60,000	NOLARO	7,540	0.03420	0.05600	2,456	143.6	2,036	5,600	314
	S.L.						7,377	127.7	1,761	12,639	708
	10,000			1			0	165.3	2,975	0	••
	5,000	75,000	ANGAL	6,750	0.02083	0.09970	1,643	153.2	2,482	5,340	532
	S.L.						5,072	140.3	1,989	11,305	1,128
	10,000		1	]		]	0	168.5	3,812	0	
#1649 w/Thin Fins	5,000	80,000	NOLARO	12,700	0.04330	0.0930	1,702	153.0	3,374	5,298	476
5 - 10 000 ft	S.L.						4,950	141.1	2,930	11,274	1,015
P = 1,000 15	10,000						0	170.4	6,375	0	
	5,000	133,000	AHGAL	14,800	0.03125	0.22000	1,193	161.8	5,281	5,145	1,132
	S.L.		[				3,253	152.7	4,187	10,559	2,325
	20,000	[			1	[	0	166.7	15,494	0	
ស	15,000	1			1	1	1,646	155.9	13,897	5,272	1,710
h = 20,000  fc	10,090 5,000	500,000	HOLARO	47.814	0.08281	9.32427	4,495 9,106	143.7 130.2	12,171 10,702	11,039 17,856	3,580 5,790
P = 600 15	S.L.	<u> </u>	<u> </u>	1	<u> </u>	[	17,231	112.0	9,107	27,436	8,900

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### Table XIV. Summary of Cable Solutions

#### APPENDIX I

### CABLE PROFILE ANALYSIS

#### 1. MATHEMATICAL ANALYSIS

The mathematical analysis of a cable-balloon system subjected to a wind-vector profile involves techniques similar to those used in the solution of related cable studies arising in a variety of engineering disciplines. These studies include problems on towing cables, mooring lines, supporting cables in bridges, cable-car lines, electric power lines, submarine cables, etc. Problems of this type in their greatest generality involve determination of cable tension as well as three-dimensional cable shape for a transient condition, i.e., time-dependent cable configuration; while reduced problems involve determination of above parameters in two dimensions for transient as well as steady-state condition and also three-dimensional steady-state configuration.

Many problems have been worked out in two dimensions for a flexible cable for a steady as well as transient motion of a cable. The shape and tension of a cable subjected to a fluid flow have been studied by H. Glauert (Reference 16) for a steady condition on the assumption that the cable is uniform and the speed of the fluid is the same at every point of the cable. In this study, only the normal component of cable drag was considered, neglecting tangential or a frictional component; while a study which incorporates both the normal and the tangential components was performed by L. Landweber and M. H. Protter (Reference 17). A transient. cable motion has been studied by F.O. Ringleb (Reference 18) and by T.S. Walton with H. Polacheck (Reference 19). In the former work, the change in cable cension was investigated due to a sudden impulse, while in the latter, an extensive analysis has been performed on cable tension due to a periodic motion of one end of the cable with the other end fixed.

The techniques developed for the above two-dimensional problems are useful for the threedimensional problem at hand. The prime objective of these studies is to select appropriate balloon-cable designs such that they will be operable at a desired altitude under a variety of wind vector profiles, as well as to determine the "operative envelope", i.e., to indicate the optimum configuration of different parameters for various operative conditions.

#### 2. STEADY CONDITION

The problem for a steady-state condition is to determine the tension in a cable as well as the shape, with one end of the cable attached to a free balloon at a given altitude and the other end fixed at the ground. From this then, it is possible to determine the elevation required at tether site. In the solution of the problem, the variation of the following parameters is considered:

- (1) Wind-vector profile in the operating range
- (2) Wind-vector at float altitude
- (3) Float altitude
- (4) Terrain height at tether side (determined parameter)
- (5) Cable geometry diameter as function of cable length
- (6) Cable weight/length as function of cable length
- (7) Cable weight
- (8) Balloon buoyancy and drag at float altitude.

To evaluate the effect of these parameters on cable form and tension, a mathematical model is developed incorporating these quantities.

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<sup>&</sup>lt;sup>1</sup> Subsections 1 through 4 of this appendix are excerpts from Reference 15, pages 3-93 through 3-99.

#### 3. MATHEMATICAL MODEL

In developing a mathematical model for the steady-state condition, a set of assumptions are imposed so as to make the problem tractable. It is assumed that the only forces acting on a cable element are the gravity force, pressure drag force, and tension. The gravity is assumed to be uniform in the operating range in the light of the fact that the change is approximately 1.0 percent. The skin-friction drag is neglected due to the fact that the skin-fraction drag coefficient is smaller by two orders of magnitude as compared to basic drag coefficient (see Reference 14) and the fact that the cable is nearly vertical. The buoyancy on the cable is negligible compared to other forces and also is not taken into account. It is assumed that the moments are not transmitted in the cable, thus implying that the cable is perfectly flexible. A physical assumption made is that the drag force on the cable element normal to the element can be determined using the wind vector component normal to the element. This is so-called cosine or sine principle, depending on the definition of angle of attack.

Selecting the origin of the coordinate system at the balloon (see Figure 43) and equating the sum of the forces on an infinitesimal cable element to zero, three equations are obtained.

(ds) 
$$F'_{unx} - (T \sin \phi \cos \theta)_{s} + (T \sin \phi \cos \theta)_{s+ds} = 0$$
  
(ds)  $F'_{uny} - (T \sin \phi \sin \theta)_{s} + (T \sin \phi \sin \theta)_{s+ds} = 0$   
(ds)  $F'_{unz} - (T \cos \phi)_{s+ds} - \omega(ds) = 0$ 

(1)

(2)

where

T is cable tension

s is length of cable from the origin to the element

ds is infinitesimal cable length

 $\phi$  and  $\theta$  are spherical coordinates that determine the direction of tangent vector to the cable at position s

 $\omega$  is weight of cable/length as function of s

u is magnitude of wind-vector as function of z

 $\alpha$  is direction of wind-vector horizontally as function of z (the vertical is neglected)

 $F'_{unx}$  is drag force on cable element/length in x direction

F'uny is drag force in y direction

 $F'_{unz}$  is drag force in z direction.

To evaluate the drag forces, a normal component of the wind-vector has to be computed (as mentioned above) from which the drag force normal to the element can be evaluated, leading thus to the desired results, which become:

$$F'_{unx} = D \left[ \cos \alpha - \sin^2 \phi \cos \theta \cos (\theta - \alpha) \right]$$
  

$$F'_{uny} = D \left[ \sin \alpha - \sin^2 \phi \sin \theta \cos (\theta - \alpha) \right]$$
  

$$F'_{unz} = -D \left[ \sin \phi \cos \phi \cos (\theta - \alpha) \right]$$

with

 $D = 1/2 \rho C_{Dd} \left[ \left[ 1 - \sin^2 \phi \cos^2 (\theta - \alpha) \right]^{1/2} \right] u^2,$ 

where

u is wind speed

 $\rho$  is air density as function of z



Figure 43. Coordinate System

C<sub>D</sub> is cable drag coefficient

d is diameter of cable as function of s.

Dividing each of the equations in set 1 by (ds) and in the limit as  $ds \rightarrow 0$ , the following differential equations are obtained:

<u>d</u> s	$(T \sin \phi \cos \theta) + F'_{unx} = 0$
<u>d</u> ds	$(T \sin \phi \sin \theta) + F'_{uny} = 0$
<u>d</u> ds	$(T \cos \phi) + F'_{unz} - \omega = 0$

(3)

A A

with the boundary conditions  $T = T_0$ ,  $\theta = \theta_0$ , and  $\phi = \phi_0$  at  $s = s_0$ . It is of interest to note at this point that for u = o everywhere (except at float altitude) and  $\omega$  independent of s, the above three differential equations simplify to a simple equation, which is the equation of a catenary:

A 
$$\frac{d^2y}{dx^2} = \omega \sqrt{1 + \left(-\frac{dy}{dx}\right)^2}$$

where A is arbitrary.

To find an analytical solution to the three differential equations is an extremely difficult, if not impossible, task since the diameter of a cable and the linear density are arbitrary functions of s as well as wind-vector profile and air density are both functions of z. In the light of these facts, an approximate technique has to be developed. This is accomplished by representing the differential equations by 2 set of difference equations which can easily be evaluated by means of a digital computer. Denoting the position s on a cable by i and the position s + ds by i + 1, the following set of equations result from set 3:

 $\theta_{i+1} = \theta_i + \arctan\left[\frac{(ds) F'_{unxi} \sin \theta_i - (ds) F'_{unyi} \cos \theta_i}{T_i \sin \phi_i - (ds) F'_{unxi} \cos \theta_i - (ds) F_{unyi} \sin \theta_i}\right]$ 

 $\phi_{i+1} = \phi_i + \arctan$ 

$$\begin{cases} \frac{\left[T_{i} \sin \phi_{i} \sin \theta_{i} - (ds)F'_{unyi}\right] - \sin \theta_{i+1} \tan \phi_{i} \left[T_{i} \cos \phi_{i} + \omega_{i}(ds) - (ds)F_{unzi}\right]}{\sin \theta_{i+1} \left[T_{i} \cos \phi_{i} + \omega_{i}(ds) - (ds)F'_{unzi}\right] + \tan \phi_{i} \left[T_{i} \sin \phi_{i} \sin \theta_{i} - (ds)F_{unyi}\right]} \right] \\ T_{i+1} = \frac{\omega_{i}(ds) + T_{i} \cos \phi_{i} - (ds)F'_{unzi}}{\cos \phi_{i+1}} \\ z_{i+1} = (ds) \sum_{k=0}^{i} \cos \phi_{k} \\ x_{i+1} = (ds) \sum_{k=0}^{i} \sin \phi_{k} \cos \theta_{k} \\ y_{i+1} = (ds) \sum_{k=0}^{i} \sin \phi_{k} \sin \theta_{k} \end{cases}$$

This set of six equations together with boundary conditions are used to compute cable form as well as the tension for a given wind-vector profile and a given cable hence known d = d(s) and  $\omega = \omega(s)$ . It is of importance to get an approximate error resulting from the difference equations. An estimate of this is presented below.

#### 4. ERROR ANALYSIS

The errors in the cable form and tension resulting from approximate computing technique depends, of course, on the magnitude of cable increment chosen for the computation - the smaller the increment the greater the accuracy in the two quantities. However, with decreasing increment the computation time increases, thus leading to a trade-off between accuracy and cost. Preliminary analysis indicates that the ratio (ds) (cable length) in the range 1/200to 1/240 is quite satisfactory to satisfy the two requirements.

The comparison of the approximate solutions is possible with an exact one in special cases, i.e., when the differential equations can be solved analytically. Such a comparison has been made with the result that the errors in cable position and tension increase with cable length, as would be expected, with maximum errors of 0.75 and 0.45 percent, respectively, at approximately half of the required length. The maximum error for the entire cable would be nearly double these numbers.

#### 5. SOLUTIONS OF DIFFERENCE EQUATIONS

The differential equations in subsection C lead to difference equations in unknowns  $\theta$ ,  $\circ$ , and T. The difference equations were derived as follows:

 $T_{i+1} \sin \phi_{i+1} \cos \theta_{i+1} - T_i \sin c_i \cos \theta_i + F'_{unx} \Delta S = 0$  $T_{i+1} \sin \phi_{i+1} \sin \theta_{i+1} - T_i \sin c_i \sin \theta_i + F'_{uny} \Delta S = 0$  $T_{i+1} \cos \phi_{i+1} - T_i \cos \phi_i + F'_{unz} \Delta S - \omega \Delta S = 0.$ 

Solutions for unknowns  $\theta$ ,  $\phi$ , and T are found sequentially.

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$$\tan \theta_{i+1} = \frac{T_i \sin \phi_i \sin \theta_i - F'_{uny} \Delta S}{T_i \sin \phi_i \cos \theta_i - F'_{unx} \Delta S}$$
$$\tan \phi_{i+1} = \frac{T_i \sin \phi_i \sin \theta_i - F'_{uny} \Delta S}{(T_i \cos \phi_i - F'_{unz} \Delta S + \omega \Delta S) \sin \theta_{i+1}}$$

For small values of  $\theta_{i+1}$  where sin  $\theta_{i+1} \rightarrow 0$ , an alternate equation is used.

$$\tan \phi_{i+1} = \frac{T_i \sin \phi_i \cos \theta_i - F'_{unx} \Delta S}{(T_i \cos \phi_i - F'_{unz} \Delta S + \omega \Delta S) \cos \theta_{i+1}}$$

Then to avoid angle adjustment due to quadrant variations, the solutions for  $\theta$  and  $\phi$  are changed to difference equations by the identity

$$\tan (a - b) = \frac{\tan a - \tan b}{1 + \tan a \tan b}$$

Tan  $(\theta_{i+1} - \theta_i)$  and tan  $(\phi_{i+1} - \phi_i)$  are therefore computed before solving for  $\theta_{i+1}$  and  $\phi_{i+1}$ . Then

$$T_{i+1} = \frac{T_i \cos \phi_i - F'_{unz} \Delta S + \omega \Delta S}{\cos \phi_{i+1}}$$

unless  $o_{i+1} \rightarrow 90$  degrees where  $\cos o_{i+1} \rightarrow 0$ . But if  $o_{i+1} \rightarrow 90$  degrees, the computation is terminated, since at  $o_{i+1} = 90$  degrees, the cable is parallel to the ground plane.



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#### APPENDIX II

#### DETAILED ANALYSIS OF TETHERED AERODYNAMICALLY SHAPED BALLCONS

#### 1. GENERAL

This appendix contains additional information on the physical dimensions, stress analysis, and weight analysis of the aerodynamically shaped balloons.

#### 2. PHYSICAL SHAPE

For geometrically similar balloons, the linear dimensions are proportional to the onethird power of balloon volume, and the surface area is proportional to the two-thirds power of balloon volume. Therefore, the various lengths and surface areas for various balloon shapes can be obtained by determining the appropriate proportionality constants. These scaling factors (proportionality constants) were based on wind tunnel models or actual balloon designs.

Table XV, which contains scaling factors, and the relationships listed below were used in the computer program to determine the physical size for each balloon shape.

Hull Length (ft)	
$L = K_1 \Psi^{1/3}$	(4)
Maximum Hull Diameter (ft)	
$D = \frac{1}{f} L$	(5)
Wetted Hull(s) Area (It <sup>2</sup> )	
$A_h = K_3 \Psi^{2/3}$	(6)
Projected Area of One Horizontal Tail (ft <sup>2</sup> )	
$A_{pht} = K_4  \Psi^{2/3}$ .	(7)
Projected Area of One Vertical Tail (ft <sup>2</sup> )	
$A_{pvt} = K_5 \Psi^{2/3}$	(8)
Location of Maximum Diameter (ft)	
$L_{max d} = K_L L$	(9)
Wetted Area of One Horizontal Tail (ft <sup>2</sup> )	
$A_{wht} = K_h A_{pht}$	(10)
Wetted Area of One Vertical Tail (ft <sup>2</sup> )	
$A_{wyyt} = K_{y} A_{pyt}$	(11)

			Ba	lloon Typ	be	
The section of the	Ormahal	Used	Vee-		GAC Sing	gle Hull
Constant	Symbol	in Eq	Balloon	BJ	Thin Fin	Thick Fin
Hull Length	К <sub>1</sub>	4	2.56	2.35	2.67	2.67
Fineness Ratio	f	5	4.00	2.49	3.00	3.00
Wetted Hull(s) Area	K3	6	6.97	5.412	5.795	5.795
Projected Area of One Hori- zontal Tail	К4	7	0.707	0.23	0.37	0.37
Projected Area of One Verti- cal Tail	К <sub>5</sub>	8	0.0785	0.36	0.37	0.37
Location of Maximum Diameter	КL	9	0.45	0.287	0.300	0.300
Wetted Area of One Horizontal Tail	К <sub>h</sub>	10	2.21	2.33	2.16	2.44
Wetted Area of One Verticai Tail	К <sub>v</sub>	11	2.32	2.33	2.16	2,44
Tail Thickness	к <sub>t</sub>	12	0.191	0.374	0.163	0.432
Number of Horizontal Tails	n <sub>ht</sub>	16	1	2	2	2
Number of Vertical Tails	n <sub>vt</sub>	16	2	1	1	1
Hull Intersect Area	K <sub>int</sub>	20	0.336	0	0	0
Gas Leakage Rate Constant	К <sub>le</sub>	21	←0.00	. <sup>6</sup> 19 639 6	t <sup>2</sup> 'day	) 
Ratio of Temp Difference over Avg Temp at Altitude	K <sub>temp</sub>	22	0.1	0.1	0.1	0.1

## Table XV. Proportionality Constants for the Physical Dimensions of Various Aerodynamically Shaped Balloons

Average Thickness of Horizontal Tail (ft)

$h_{hta} = K_t \sqrt{A_{pht}}$	(12)
Average Thickness of Vertical Tail (ft)	
$h_{vta} = K_t \sqrt{A_{pvt}}$	(13)
Volume of One Horizontal Tail (ft <sup>3</sup> )	
∀ht = <sup>h</sup> hta <sup>A</sup> pht	(14)
Volume of One Vertical Tail (ft <sup>3</sup> )	
₩vt <sup>= h</sup> vta <sup>A</sup> pvt	(15)
Volume of Total Balloon (ft <sup>3</sup> )	
$\forall_{tot} = \forall + n_{ht} \forall_{ht} + n_{vt} \forall_{vt}$	(16)

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Diameter of Spherical Ballonet (ft)

$$D_{bnt} = 1.24 (\Psi_{bnt})^{1/3}$$
 (18)

Wetted Area of Spherical Ballonet (ft<sup>2</sup>)

$$A_{\rm bnt} = 4.84 \left( V_{\rm bnt} \right)^{2/3}$$
 (19)

Hull Intersect Area (ft<sup>2</sup>)

$$A_{int} = K_{int} \frac{\psi^2/3}{\sqrt{2}}$$
(20)

Volume of Gas Lost by Leakage (ft<sup>3</sup>/day)

$$\vec{v}_{leak} = K_{le} \left( A_h + n_{ht} A_{v,ht} + n_{vt} A_{wvt} \right)$$
(21)

(22)

Volume due to Temperature Change at Float Altitude per Day (ft<sup>3</sup>/day)

¥<sub>temp</sub> = K<sub>temp</sub> ¥<sub>tot</sub>

3. STRESS ANALYSIS

a. General

As noted in the text of the report, the design stress used in the balloon analysis was the sum of the stresses caused by the internal pressure, buoyant lift, hull bending moment and aerodynamic load with the appropriate factor of safety.

$$N_{des} = F.S. (N_i + N_b + N_{bm} + N_a)$$

where

N<sub>des</sub> is design stress for selection of balloon material (lb/ft)
F.S. is factor of safety
N<sub>i</sub> is stress due to internal pressure (lb/ft)
N<sub>b</sub> is stress due to buoyant lift (lb/ft)
N<sub>b</sub> is stress due to hull bending moment

 $N_a$  is stress due to aerodynamic loads (lb/ft).

Maximum stresses on the balloon due to internal pressure and buoyant lift occur at the maximum diameter of the balloon. Maximum \_ esses due to aerodynamic loads occur somewhat forward of the maximum diameter, but for this analysis, were conservatively assumed to act at the maximum diameter. Therefore, the location of maximum stress occurs at the maximum diameter just above the attachment points of the balloon suspension (bridle) system, which were assumed to be attached near the equator of the balloon. The calculations given in the following paragraphs determine the stresses in the balloon skin at the equator.

#### b. Stress due to Internal Pressure

The required balloon internal pressure at altitude, as explained in Section V, was selected to be 15 percent greater than the dynamic pressure at altitude, or 1/4 in. H<sub>2</sub>O = 1.3 lb/ft<sup>2</sup>, whichever is greater. Therefore, P<sub>1</sub> = 1.15q or 1.30 lb/ft<sup>2</sup>, whichever is greater. This pressure was assumed to be at the bottom of the balloon.



Figure 44. Internal Pressure Occurring in the Balloon at the Maximum Diameter

Referring to Figure 44, the pressure at the balloon equator is

$$P_{eq} = P_i + 0.862 \rho_{alt} g \frac{D}{2}$$
.

The second term represents the helium pressure head at altitude between the bottom of the balloon and the equator.

The maximum internal pressure stress is

$$N_{i} = P_{eq} \frac{D}{2}$$
$$= \left(P_{i} + 0.862 \rho_{alt} g \frac{D}{2}\right) \frac{D}{2} lb/ft.$$

c. Stress due to Buoyant Lift

From Figure 45, the maximum stress due to buoyant load at altitude acting on a onefoot section of the hull is

$$N_b = \frac{1}{2} \left[ L_b(\text{one-foot section}) \right]$$

where

 $L_b$  = buoyant lift of helium at altitude

= b x volume of the section.

Therefore,

$$N_{b} = \frac{1}{2} \left[ \left( 0.862 \ \rho_{alt} \ g \right) \left( \pi \ \frac{D^{2}}{4} \right) \right] lb/ft.$$

Stress due to due to Hull Bending Moment d.

The stress due to aerodynamic bending moment for design q at altitude for the typical hull/suspension arrangements is: 1/3

$$N_{bm} = 0.123q \quad \forall \quad (1b/ft) \text{ for all single hulls}$$
 (25a)

$$N_{bm} = 0.185q \quad \psi \quad (1b/ft) \text{ for Vee Balloon}$$
 (25b)

e. Stress due to Aerodynamic Loads

From wind tunnel tests on the General Mills Aerocap Model Balloon (Reference 20), the maximum local pressure was determined to be approximately

$$x = 0.1 \alpha$$





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Figure 45. Buoyant Force on Balloon at the Maximum Diameter

(25)

(24)

where

- x is maximum local pressure  $(lb/ft^2)$
- 4 is dynamic pressure (b/ft<sup>2</sup>)
- a is angle of attack (degrees).

This occurs at approximately 30 percent aft of the balloon nose However, for this analysis, it was assumed to act at the maximum diameter (see Figure 46).

Therefore, the total aerodynamic force acting on the one-foot section (assuming a linear load distribution) is

$$F = (x)\left(\frac{D}{2}\right) = 0. lq \ \alpha \frac{D}{2} lb.$$

This load is reacted by the suspension lines of the balloon. Therefore, the stress in the fabric directly above the suspension lines is

$$N_a = \frac{1}{2} F = 0.05q \ a\left(\frac{D}{2}\right) lb ft.$$

#### 4. BALLOON WEIGHT

or

#### a. Balloon Material

Once the design stress has been determined, the unit fabric weight can be determined to be

$$w = 0.0111 + 0.344 \times 10^{-4} N_{des} lb/ft^{2} N_{des} = \langle 2,000$$
(27)  
$$w = 0.0327 + 0.236 \times 10^{-4} N_{des} lb/ft^{2} N_{des} = \rangle 2,000$$

This is the equation of the curve of Figure 21. Due to groundhandling problems, a minimum weight material of 4.7  $oz/yd^2$  (.0327 lb/ft<sup>2</sup>) was assumed to be the lightest material from which an aerodynamically shaped balloon would be fabricated.

b. Hull, Tail, and Ballonet Weights

Based on the necessary unit material weight and the various physical dimensions that were calculated in the previous sections of this appendix, the hull and tail weights can be determined. However, since little differential pressure acts across the ballonet, a 4.7  $oz/yd^2$  (0.0327 lb/ft<sup>2</sup>) ballonet material was assumed for all sizes of all balloon types.

Proportionality constants for the weights of components of various aerodynamically shaped balloons are given in Table XVI. The equations used in the computer solution are as follows:

$$\frac{\text{Weight of Hull Fabric (1b)}}{\text{W}_{hf}} = \text{wA}_{h}$$
(28)



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Figure 46. Assumed Aerodynamic Loading on the Maximum Diameter of the Balloon

(26)

		Nood.	Balloon Type					
Proportionality Constant	Symbol	in	lla a		GAC Sing	le Hull		
		Eq	Balloon	BJ	Thin Fin	Thick Fin		
Factor of Safety on Fabric Stress	F.S.	23	4 —			>		
Seam Weight	K	29	0.10 -			>		
Unit Weight of Tail Fabric-Horizontal	wth	32	v	. 5w	. 5w	. 5w		
Unit Weight Tail Fabric- Vertical	w tv	35	w	.75w	.75w	.75w		
Unit Weight of Partition Material	ພ	34	2w					
Unit Weight of Ballonet Material	w <sub>b</sub>	38	.0327	1b/ft <sup>2</sup> -				
Power Density of Battery	Kbat	45-47	3600 wat	t minute	s/1b			
Miscellaneous Equipment Weight	K me	48	0.5					
Total Balloon Weight	к <sub>tb</sub>	54	1.193 —					
Suspension Line Weight	K	55	0.0007 -					
Handling Line and Catenary	K <sub>h1</sub>	56	0.336 -					
Tail Attachment Weight	Ka	33&36	0.330	0.330	0.330	0.330		
Misc. Fabric Parts Weight	K <sub>mf</sub>	39a	0.050	0.050	0.050	0.050		
Air Valve Weight	Kav	53	0.01445	0,01445	0.01445	0.01445		

# Table XVI. Proportionality Constants for the Weights of the Components of Various Aerodynamically Shaped Balloons

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Weight of Hull Seams (lb)	
$W_{hs} = K_s W_{hf}$	(29)
Intersect Weight (lb)	
$W_{int} = W A_{int}$	(30)
Weight of Intersect Attachments (lb)	
$W_{int a} = W_{int}$	(31)
Weight of One Horizontal Tail (lb)	
$W_{ht} = w_{th}A_{wht}$	(32)
Weight of Attachments of One Horizontal Tail (lb)	
$W_{hta} = K_a W_{ht}$	(33)
Weight of Interior Partitions of One Horizontal Tail (1b)	
$W_{iha} = w_p A_{pht}$	(34)
Weight of One Vertical Tail (lb)	
$W_{vt} = W_{tv}A_{wvt}$	(35)
Weight of Attachments of One Vertical Tail (lb)	
$W_{vta} = K_a W_{vt}$	(36)

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Weight of Interior Partitions of One Vertical Tail (lb)

$$W_{iva} = w_p A_{pvt}$$
(37)

Weight of Ballonet (lb)

 $W_{bnt} = W_b A_{bnt}$ (38)

Weight of Ballonet Seams and Attachment (lb)

$$W_{bnt,s} = K_s W_{bnt}$$
 (39)

Weight of Miscellaneous Fabric Parts

$$W_{mf} = K_{mf} \left( W_{hf} + W_{hs} \right)$$
(39a)

c. Blower, Battery, and Exit Valve Analysis

(1) <u>Volume and Volume Flow Rate of Air through an Exit Valve or Blower</u>. The volume of air to be expelled through an exit valve of a bailoon during ascent or to be filled by a blower during descent may be determined by the expressions given below. It is assumed that the total volume of the balloon remains constant and that the weight of a given mass of air is constant throughout the elevations considered.

The weight of a certain volume (V) of air at an altitude (h) is given by

 $W_h = \gamma_h V_h lb$ 

where  $\gamma_h$  is the weight density (lb 'ft<sup>3</sup>) of air at float altitude h. Also, at altitude h - dh,

 $W_{h-dh} = (\gamma_h + d\gamma) V_{h-dh},$ 

but

$$W_h = W_{h-dh}$$
.

Therefore,

$$\gamma_h V_h = (\gamma_h + d\gamma) V_{h-dh}$$

or

$$v_{h-dh} = \left(\frac{\gamma_h}{\gamma_h + d\gamma}\right) v_h$$

Let Qt be the volume filled during the change in altitude from h to h-dh. Therefore,

$$d(Qt) = V_{h} - V_{h} - dh$$
$$= V_{h} \left( 1 - \frac{\gamma_{h}}{\gamma_{h} + d\gamma} \right)$$
$$= V_{h} \frac{d\gamma}{\gamma_{h} + d\gamma}$$

Neglecting second-order effects,

$$d(Qt) = V_h \frac{d\gamma}{\gamma_h}$$
.

However,  $V_h = \text{constant} = \Psi_{\text{tot}}$ .

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Therefore,

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$$Qt = \frac{\Psi}{tot} \int_{h}^{0} \frac{d\gamma}{\gamma_{h}}$$

$$Qt = \Psi_{tot} \ln \frac{\gamma_{0}}{\gamma_{h}} ft^{3}$$
(4)

where

Qt is volume filled by blower  $(ft^3)$ 

 $V_{tot}$  is total volume of balloon (ft<sup>3</sup>)

 $\gamma_0$  is weight density of air at sea level launch altitude (lb/ft<sup>3</sup>)

 $\gamma_{\rm b}$  is weight density of air at float altitude (lb/ft<sup>3</sup>).

To determine the volume flow rate (Q) through the exit valve or blower, an ascent and descent rate of 400 ft/min was assumed.

$$Q = Qt \left(\frac{400}{h}\right) ft^3/min$$
(41)

or

2000 ft<sup>3</sup>/min, whichever is greater. (h is again the float altitude of the balloon.)

(2) Blower and Check Valve Weight. An empirical relation based on information listed in a blower catalog (Reference 21) is given in Figure 47. The plot contains blower weight versus differential pressure for blowers rated at 4000 ft<sup>3</sup>/min. Blowers used in this plot include rated flow rates from 500 to 4000 ft<sup>3</sup>/min, which were modified to an equivalent rate of 4000  $ft^{3}$ /min by use of the following relation:

$$W_{blo} = W_{actual} \left(\frac{4000}{Q_{rated}}\right)$$

where

W<sub>blo</sub> is plower weight equivalent (lb)

Wactual is blower weight listed in catalog (lb)

 $Q_{rated}$  is flow rate of blower, as listed in catalog (ft<sup>3</sup>/min).

Ratings for these blowers are for standard atmospheric conditions. The resulting expression based on Figure 47 is

$$W_{\rm blo} = \frac{Q}{4000}$$
 (7.5 P<sub>io</sub> + 17.8) lb

where

١

 $P_{i0}$  is the differential pressure at sea level in in. H<sub>2</sub>O.

Use of this blower at higher altitudes will result in differential pressures that vary with the density of the air being blown. That is,

$$P_{i} = \frac{P_{alt}}{\rho_{0}} P_{i0} \frac{1}{0.1922} lb / ft^{2}$$
(42)

0)





where

P<sub>i</sub> is differential pressure at altitude

 $\frac{\rho_{\text{alt}}}{\rho_0}$  is ratio of air density at altitude to sea level.

Thus,

$$W_{blo} = \frac{Q}{4000} \left( 1.442 - \frac{\rho_0}{\rho_{alt}} P_i + 17.8 \right) lb$$
 (43)

where Q is the desired flow rate of the blower ( $ft^3$  min).

The check value is mounted on the blower, and therefore its weight was assumed to be proportional to the blower weight. Previous experience has shown that this constant of proportionality is approximately 1/2. Therefore, the weight of the check value is

$$W_{chk} = \frac{1}{2} W_{blo} lb.$$
 (44)

(3) <u>Battery Weight</u>. Battery power is required to operate the blower at altitude to account for daily temperature changes and leakage losses and to operate the blower during descent to maintain a full ballonet. The typical equation for battery weight is

$$W_{\text{bat}} = \frac{Pt_{\text{oper}}}{K_{\text{bat}}}$$

where

W<sub>bat</sub> is the battery weight (lb)

P is the power required (watts)

toper is the operating time of the blower (minutes)

K<sub>bat</sub> is the power density of the battery (watt min/lb).

By plotting battery power versus sea level differential pressure for equivalent 4000  $ft^3$  min blower capacity, an empirical relation for power required to operate the blowers can be determined to be

 $P = 1000 P_{io}$  watts

where  $P_{i_0}$ , as previously defined, is the differential pressure at sea level in in. H<sub>2</sub>O (see Figure 48).

Battery weight required at altitude is that required to operate the blower at an equivalent sea level pressure of

$$P_{i} = \frac{\rho_{alt}}{\rho_{0}} P_{i0} \frac{1}{0.1922}$$
,

as defined in Equation 42. Thus, the power required is

$$P' = 1000 (0.1922) \frac{\rho_0}{\rho_{alt}} P_i lb ft^2.$$

However, this power would operate the blower at sea level, whereas the power required at altitude varies directly with the density of the air being blown. Thus, the actual power required for the battery is

P = 
$$\frac{\rho_{alt}}{\rho_0}$$
 P'  
P =  $\frac{\rho_{alt}}{\rho_0}$  (1000) (0. 1922)  $\frac{\rho_0}{\rho_{alt}}$  P<sub>i</sub>  
= 192.2 P<sub>i</sub> watts.

The battery weight was analyzed as that required while at float altitude and that required during descent. Therefore,

$$W_{bat} = W_{bat,a} + W_{bat,d}$$
 (lb)

where

W<sub>bat, a</sub> is amount of batteries required at altitude (lb)

W<sub>bat, d</sub> is amount of batteries required during descent (lb).





The equivalent time of operation of the blower at altitude is equal to the volume of air to be replaced each day ( $V_{repl}$ ) divided by the 4000 ft<sup>3</sup>/min blower rate and multiplied by the number of days at float altitude (t/24). Thus, the battery weight required at altitude is

$$W_{bat,a} = \frac{192.2P_i \ (\Psi_{repl}) \ (t'24)}{K_{bat} \ (4000)} \text{ pounds.}$$
(45)

Note that  $V_{repl}$  is modified in the computer program to provide a factor of safety of 2.

The work done on the gas during descent is equivalent to the work done on the gas if entirely filled at sea level. It will be assumed that the differential pressure to be maintained in the balloon at all times is  $P_i$ , the pressure that was required at altitude. This assumption neglects the fact that dynamic pressure at lower altitudes will probably be greater than that designed at altitude.

However, the fabric in the balloon is also designed for conditions at altitude while neglecting conditions below so that the assumptions are consistent. Thus,

 $P_{i0} = P_i (0.1922) lb/ft^2$ ,

which is identical with Equation 40 when

 $\rho_{alt} = \rho_0$ .

The operating time of the blower during descent is that time required for a 4000 ft<sup>3</sup>/min blower to fill the ballonet, or ( $\Psi_{bnt}/4000$ ).

Therefore, with a safety factor of 2,

$$W_{\text{bat, d}} = (2) \frac{\frac{192.2P_{\text{i}} \frac{\Psi_{\text{bnt}}}{4000}}{K_{\text{bat}}}}{K_{\text{bat}}}$$
  
= (2)  $\frac{192.2P_{\text{i}} \Psi_{\text{bnt}}}{K_{\text{bat}} (4000)}$  lb. (46)

The total battery weight is

 $W_{bat} = W_{bat,a} + W_{bat,d}$ 

$$\mathbf{w}_{\text{bat}} = \frac{192.2P_{\text{i}}}{K_{\text{bat}} (4000)} \left[ \mathbf{v}_{\text{repl}} \left( \frac{t}{24} \right) + 2 \mathbf{v}_{\text{bnt}} \right] \text{lb}$$
(47)

where

 $P_i$  is differential pressure at altitude (lb/ft<sup>2</sup>)

 $v_{repl}$  is volume of air that blower has to replace at altitude (ft<sup>3</sup>/day)

t is float time at altitude (hr)

 $\Psi_{\text{bnt}}$  is balloon ballonet volume (ft<sup>3</sup>).

The weight of the miscellaneous equipment for the blower and battery is

$$W_{\rm me} = K_{\rm me} W_{\rm bat}, \tag{48}$$

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which was included to cover the weight of the battery heater, wiring, etc. See Table XVI for the values of  $K_{\rm bat}$  and  $K_{\rm me}.$ 

(4) <u>Weight of Exit Valve</u>. The volume rate of flow through an orifice is given in any fluid mechanics book (e.g., Reference 22) is

 $Q = CA \sqrt{2gZ}$ 

where

Q is volume rate of flow through orifice (ft<sup>3</sup>/min)

C is discharge coefficient

A is exit area of orifice  $(ft^2)$ 

Z is pressure head on the fluid at the orifice (ft).

The pressure head (Z) may be written as

 $Z = \frac{p}{\gamma}$ 

where

p is pressure head  $(lb/ft^2)$ 

 $\gamma$  is weight density of the fluid (lb/ft<sup>3</sup>).

Therefore,

$$Q = CA \sqrt{2g \frac{p}{\gamma}}$$

$$Q = CA \sqrt{2 \frac{p}{\rho}}.$$
(49)

For purposes of scaling the weight of the valve, assume that the weight is proportional to its exit area. That is,

$$\frac{W_1}{W_2} = \frac{A_1}{A_2} \quad . \tag{50}$$

Solving Equation 49 for  $A_1$ , and adding the subscripts 1, we have

$$A_{1} = \frac{1}{C} \frac{Q_{1}}{\sqrt{2 \frac{P_{1}}{\rho_{1}}}}$$
(51)

However, the value of the discharge coefficient may be obtained using data from an existing valve, since C is a constant for a particular orifice type. Thus,

$$C = \frac{Q_2}{A_2 \sqrt{\frac{2p_2}{\rho_2}}}$$
(52)

Substituting Equations 51 and 52 into Equation 50,

$$\frac{W_1}{W_2} = \frac{A_2 \sqrt{\frac{2p_2}{\rho_2}}}{Q_2} \frac{Q_1}{A_2 \sqrt{\frac{2p_1}{\rho_1}}}$$

 $\mathbf{or}$ 

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$$W_1 = W_2 \sqrt{\frac{p_2}{\rho_2}} \sqrt{\frac{\rho_1}{p_1}} \frac{Q_1}{Q_2}$$

Values for a typical exit valve are as follows:

Size = 
$$28$$
 inch in diameter

$$A_2 = 4.24 \text{ ft}^2$$

$$Q_2 = 8500 \, \text{ft}^3/\text{min}$$

$$p_2 = 3 \text{ in. } H_2O = 15.62 \text{ lb/ft}^2$$

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SAL GOUDING CONTRACTOR STATISTICS

 $W_2 = 31.0$  lb (aluminum)

$$\rho_2 = \rho_0$$
 at sea level

$$W_{1} = (31.0) \sqrt{\frac{15.62}{\rho_{0}}} \sqrt{\frac{\rho_{1}}{p_{1}}} \frac{Q_{1}}{8500}$$
$$W_{1} = 0.01445 \sqrt{\frac{\rho_{1}}{\rho_{0}}} \frac{Q_{1}}{\sqrt{p_{1}}} .$$

To compute the weight of a valve required at float althude, note the following changes in notation:

$$\rho_1 = \rho_{alt}$$

$$p_1 = p_i$$
.

Therefore,

$$W_{aval} = W_{l} = K_{av} \sqrt{\frac{\rho_{alt}}{\rho_{0}}} \frac{Q_{l}}{\sqrt{p_{i}}} .$$
 (53)

(5) <u>Suspension (bridle) System Weight</u>. The weight of the suspension system is proportional to the length of the balloon and the tether tension in the bridle.

 $W_{SUS} \propto LT$ ,

or from Equation 4,

 $W_{sus} \propto V^{1/3} T.$ 

However, to obtain the tether tension, the weight of the balloon (which we are trying to estimate) has to be known. Therefore, an initial estimate of the total weight is made by summing the already estimated parts of the balloon, which include everything except the suspension system, handling line, and catenary weights, and multiplying by an appropriate factor.

The initial estimate of the tether tension is

$$T_{lb} = \left\{ \left[ L_{a} + L_{b} - P - (K_{tb}) W_{i(tot)} \right]^{2} + D_{b}^{2} \right\}^{1/2}$$
(54)

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where

 $L_a$ , aerodynamic lift, =  $C_L q \Psi^{2/3}$  (lb)

 $L_b$ , buoyant lift, = 0.862gV<sub>tot</sub>  $\rho_{alt}$  (lb) (helium 97% purity)(lb)

P is payload package weight (lb)

K<sub>tb</sub> is the factor to obtain total balloon weight

 $W_{\rm i(tot)}$  is the initial estimate of weight, which includes all weight except the suspension, handling line, and catenary weight (lb)

 $D_b$ , aerodynamic drag on balloon, =  $C_D q \Psi^{2/3}$  (lb).

Therefore, the weight of the suspension system is

$$W_{sus} = K_{sus} T_{lb} (\Psi_{tot})^{1/3} lb.$$
 (55)

The weight of the handling line and catenary is

$$W_{hl} = K_{hl} W_{sus} lb.$$
 (56)

See Table XVI for the values of  $K_{tb}$ ,  $K_{sus}$  and  $K_{hl}$ .

(6) <u>Total Balloon Weight</u>. The total balloon weight can be obtained for a particular balloon type (Vee-Balloon, BJ, #1649) from the previous equations by inputing the following information:

Payload weight, P (lb) Float altitude, h (ft) Wind velocity, v (knots) Angle of attack,  $\alpha$  (degrees) Hull volume,  $\forall$  (ft<sup>3</sup>) Operating Time at altitude, t (hr)

The total balloon weight is equal to the following:

$$W_{tot} = W_{hf} + W_{hs} + W_{int} + W_{int} a$$

$${}^{n}_{ht}(W_{ht} + W_{hta} + W_{iha}) + {}^{n}_{vt} (W_{vt}$$

$$+ W_{vta} + W_{iva}) + W_{blo} + W_{bat}$$

$$+ W_{aval} + W_{chk} + W_{bnt} + W_{bnt,s}$$

$$+ W_{me} + W_{sus} + W_{hl} (pounds) + W_{mf}$$
(57)

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