Overview

<table>
<thead>
<tr>
<th>Part I: Introduction</th>
<th>Slide No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecture Objectives</td>
<td>4</td>
</tr>
<tr>
<td>Scope</td>
<td>5</td>
</tr>
<tr>
<td>Further Study</td>
<td>6</td>
</tr>
<tr>
<td>Purposes of Aerodynamic Decelerators</td>
<td>7</td>
</tr>
<tr>
<td>Historical Review</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part II: Parachutes</th>
<th>Slide No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminology</td>
<td>17</td>
</tr>
<tr>
<td>Types and Functions</td>
<td>18</td>
</tr>
<tr>
<td>Stages</td>
<td>24</td>
</tr>
<tr>
<td>Drag</td>
<td>35</td>
</tr>
<tr>
<td>Dynamics</td>
<td>36</td>
</tr>
<tr>
<td>…continued</td>
<td>48</td>
</tr>
</tbody>
</table>
## Overview

<table>
<thead>
<tr>
<th>Part II: Parachutes - <em>continued</em></th>
<th>Slide No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployment</td>
<td>59</td>
</tr>
<tr>
<td>Inflation</td>
<td>71</td>
</tr>
<tr>
<td>Opening Loads</td>
<td>80</td>
</tr>
<tr>
<td>Materials</td>
<td>89</td>
</tr>
<tr>
<td>Mass and Volume</td>
<td>91</td>
</tr>
<tr>
<td>Testing</td>
<td>94</td>
</tr>
<tr>
<td>Fluid-Structures Interaction (FSI) Analyses</td>
<td>103</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part III: Additional Materials</th>
<th>Slide No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbols</td>
<td>105</td>
</tr>
<tr>
<td>Acronyms</td>
<td>108</td>
</tr>
<tr>
<td>Glossary</td>
<td>109</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>116</td>
</tr>
<tr>
<td>Point of Contact</td>
<td>117</td>
</tr>
<tr>
<td>Bibliography</td>
<td>118</td>
</tr>
</tbody>
</table>

## Introduction

<table>
<thead>
<tr>
<th>Part I: Introduction</th>
<th>Slide No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecture Objectives</td>
<td>5</td>
</tr>
<tr>
<td>Scope</td>
<td>6</td>
</tr>
<tr>
<td>Further Study</td>
<td>7</td>
</tr>
<tr>
<td>Purposes of Aerodynamic Decelerators</td>
<td>9</td>
</tr>
<tr>
<td>Historical Review</td>
<td>10</td>
</tr>
</tbody>
</table>
Lecture Objectives

Provide an introduction to the design and analysis of parachutes for planetary entry systems
- Extensive bibliography provided for more detailed study

Target Audience

• Engineers responsible for the development and qualification of such systems
• Program managers and system engineers responsible for setting requirements and supervising development and qualification of such systems

Scope

Lectures emphasize topics most relevant to planetary entry systems, including those for:
- Robotic missions
- Precursor human exploration missions
- Earth sample return missions
- Earth qualification of systems for planetary missions

Topics not emphasized are those only relevant to Earth applications

Topics not discussed:
- Parafoils, inflatable aerodynamic decelerators (IAD)
- Rigid aerodynamic decelerators (e.g., drag rings)
- Systems intended for entry or aerocapture (e.g., inflatable aeroshells)
- Textile impact attenuation devices (e.g., airbags)
Further Study I

- Comprehensive (458 pages)
- Extensive bibliography (> 500) referenced through text
- Published in 1978 - some sections (e.g., materials) are outdated
- As with all documents, watch out for typos and incorrect information
- Required reading for engineers involved in the development and qualification of aerodynamic decelerators for planetary entry systems

- Comprehensive (~250 pages)
- Extensive bibliography referenced through text
- Similar to Recovery Systems Design Guide - not as comprehensive but more up-to-date
- Required reading for engineers involved in the development and qualification of aerodynamic decelerators for planetary entry systems
- Can be ordered at the following web site: www.parapublishing.com/parachute/

Introduction: Further Study

Further Study II

H.G. Heinrich Parachute Systems Short Course
- One-week short course
- Offered on even years (next session in 2006)
- Taught by practitioners in the field with extensive practical experience
- Timed to allow time for questions during and after lectures
- Sponsored by the AIAA Aerodynamic Decelerator Systems Technology Committee
- Comprehensive
- Highly recommended for engineers involved in the development and qualification of aerodynamic decelerators for planetary entry systems
- Contact: Dr. Jean Potvin
  Department of Physics
  Saint Louis University
  3450 Lindell Blvd.
  St. Louis, MO 63103
  314-977-8424 (voice)
  potvinj@slu.edu
  www.engr.uconn.edu/%7Eadstc/shortcourses.html

Introduction: Further Study
Purposes of Aerodynamic Decelerators

Aerodynamic decelerators typically provide one or more of the following functions:

- Deceleration
- Control acceleration
- Minimize descent rate
- Provide specified descent rate
- Provide stability (drogue function)
- System deployment (pilot function)
- Provide difference in ballistic coefficient for separation events
- Provide height
- Provide timeline
- Provide specific state (e.g., altitude, location, speed for precision landing)

Historical Review

Planetary Exploration Missions Using Parachutes

- Venera 5-14, USSR (Venus, 1969-1982)
- Luna 16, 20, and 24, USSR (Earth Sample Return from Moon, 1970-1976)
- Mars 2 & 3, USSR (Mars, 1971)
- Mars 6, USSR (Mars, 1974)
- Viking 1 & 2, US (Mars, 1976)
- Pioneer Venus, US (Venus, 1978)
- Vega 1 & 2, USSR (Venus, 1985)
- Galileo, US (Jupiter, 1995)
- Mars Pathfinder (MPF), US (Mars, 1997)
- Mars Polar Lander (MPL), US (Mars, 1999)
- Beagle 2, UK (Mars, 2003)
- Mars Exploration Rovers (MER), US (Mars, 2004)
- Huygens, Europe (Titan, 2004)
- Genesis, US (Earth Sample Return from Space, 2004)
- Stardust, US (Earth Sample Return from Comet, 2006)
Mars 2 & 3

Entry
- Rocket-Deployed Pilot Parachute
- Pilot-Deployed Main Parachute
- Reefed Main Parachute
- Full-Open Main Parachute
- Heatshield Release
- Terminal Descent
- Retro-Rocket Firing
- Landing


Pioneer Venus

Entry
- Mortar-Deployed Pilot Parachute at M ~ 0.8, H ~ 67 km
- Pilot-Deployed Main Parachute
- Heatshield Release
- Probe Release at H ~ 47 km

Pilot Parachute: Guide Surface, \( D_0 = 0.76 \) m
Main Parachute: 20° Conical Ribbon, \( D_0 = 4.9 \) m

Mars Pathfinder

- Entry
- Mortar-Deployed Parachute at $M = 1.7$, $q = 590$ Pa
- Heatshield Separation
- Disk-Gap-Band (DGB) Parachute
  - $D_0 = 12.7$ m
- Lander Separation
- Airbag Inflation
- Retro-Rocket Firing
- Bridle Cut
- Bouncing
- Rover Deployment

Mars Exploration Rover EDL

MER EDL Animation
Genesis

Mortar-Deployed Drogue/Pilot Parachute at M ~ 1.4, H ~ 33 km

Descent Under Drogue/Pilot Parachute

Drogue/Pilot-Deployed Parafoil

Descent Under Parafoil

Drogue/Pilot Parachute: DGB, Dp = 2.03 m
Parafoil: S0 = 39 m²

Mid-Air Retrieval

Huygens

Entry

Mortar-Deployed Pilot Parachute at M ~ 1.5

Pilot-Deployed Main Parachute

Heatshield Separation

Descent Under Main Parachute

Main Parachute-Deployed Drogue Parachute

Descent Under Drogue Parachute

Touchdown

Parachutes

Pilot: DGB, Dp = 2.59 m
Main: DGB, Dm = 8.30 m
Drogue: DGB, Dd = 3.03 m

~ 2 hr

15 min

30 s

2.5 s


Introduction: Historical Review
Parachutes

Part II: Parachutes
Terminology
18
Types and Functions
24
Stages
35
Drag
36
Dynamics
48
Deployment
59
Inflation
71
Opening Loads
80
Materials
89
Mass and Volume
91
Testing
94
Fluid-Structures Interaction (FSI) Analyses
103

Terminology I

Apex

Crown
Vent

Skirt

Gore

Suspension Lines

Confluence Point

Suspension Lines

Riser

Bridle
Terminology II

**Nominal Area,** $S_0$
- Area based on canopy constructed surface area
- Includes vent area and other open areas (e.g., gap area in a DGB parachute)
- Often (but not always!) used as reference area for aerodynamic coefficients

**Nominal Diameter,** $D_0$
- Fictitious diameter based on $S_0$:
  \[ D_0 = \sqrt{\frac{4S_0}{\pi}} \]
- Often (but not always!) used as reference length for aerodynamic coefficients and other calculations

Terminology III

**Constructed Diameter,** $D_c$
- Maximum diameter of the parachute (measured along the gore radial seam) of the parachute

**Conical Parachute Base Angle,** $\mu$

**Vent Diameter,** $D_v$

**Vent Area,** $S_v$
- Constructed area of the vent
- Although related, the vent area and vent diameter ($D_v$) are not always related by the simple relationship between the area and diameter of a circle (see following example for a conical parachute)
- $S_v$ is typically ~1% of $S_0$
Terminology IV

**Geometric Porosity, \( \Delta_g \)**
- Ratio of total open areas (e.g., Vent Area) to the Nominal Area
- Usually expressed as a percentage

**Total Porosity, \( \Delta_t \)**
- The sum of the geometric porosity and an equivalent porosity due to fabric permeability
- Fabric permeability (i.e., flow through the fabric material) is converted to an “equivalent” open area of the parachute to determine the porosity due to fabric permeability
- Usually expressed as a percentage

The geometric and total porosity have a significant effect on the performance of the parachute (e.g., drag, stability, peak opening load). Consideration of total porosity is important in the design and testing of parachutes for planetary missions since there can be significant differences between the total porosity in an Earth test and actual flight.

Terminology V

**Example: Conical Parachute**

\[
S_0 = \lambda \frac{D_c^2}{4} \sqrt{1 + \tan^2 \mu}
\]
\[
D_0 = \sqrt{\frac{4S_0}{\lambda}}
\]
\[
S_v = \lambda \frac{D_v^2}{4} \sqrt{1 + \tan^2 \mu}
\]
\[
\lambda_g = \frac{S_v}{S_0}
\]
Terminology VI

Projected Area, $S_p$
- Projected area of the inflated parachute
- Sometimes used as reference area for aerodynamic coefficients in parachutes for which it is difficult to define $S_0$ (e.g., Guide Surface parachutes)

Projected Diameter, $D_p$
- Maximum projected diameter of the parachute based on $S_p$:

$$D_p = \sqrt{\frac{4S_p}{\pi}}$$

Suspension Line Length, $L_s$
- Typically $L_s/D_0 = 1$ to 2

Parachute Types

Solid Textile Parachutes
- Parachutes with canopies fabricated mainly from cloth materials
- Typically these types of parachutes have no openings other than the vent
- Relatively easy to manufacture

Slotted Textile Parachutes
- Parachutes with canopies fabricated from either cloth materials or ribbons
- These types of parachutes have extensive openings through the canopy in addition to the vent
- Can be expensive to manufacture
- Most common parachute type used in planetary exploration missions
### Solid Textile Parachutes I

<table>
<thead>
<tr>
<th>Type</th>
<th>Constructed Shape</th>
<th>Inflated Shape Coef. $D_C/D_D$</th>
<th>Drag Coef. $D_D/D_D$</th>
<th>Opening Load Factor $C_D$ (Inf. Mass)</th>
<th>Average Angle of Oscillation $\theta$</th>
<th>General Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>![Image]</td>
<td>.67</td>
<td>.75</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Descent</td>
</tr>
<tr>
<td>Circular</td>
<td>![Image]</td>
<td>.67</td>
<td>.75</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Descent</td>
</tr>
<tr>
<td>Conical</td>
<td>![Image]</td>
<td>.93</td>
<td>.75</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Descent</td>
</tr>
<tr>
<td>Bi-Conical</td>
<td>![Image]</td>
<td>.90</td>
<td>.75</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Descent</td>
</tr>
<tr>
<td>Tri-Conical</td>
<td>![Image]</td>
<td>.90</td>
<td>.75</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Descent</td>
</tr>
</tbody>
</table>

### Solid Textile Parachutes II

<table>
<thead>
<tr>
<th>Type</th>
<th>Constructed Shape</th>
<th>Inflated Shape Coef. $D_C/D_D$</th>
<th>Drag Coef. $D_D/D_D$</th>
<th>Opening Load Factor $C_D$ (Inf. Mass)</th>
<th>Average Angle of Oscillation $\theta$</th>
<th>General Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemispherical</td>
<td>![Image]</td>
<td>.71</td>
<td>.62</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Descent</td>
</tr>
<tr>
<td>Guide</td>
<td>Surface (Ribbed)</td>
<td>.63</td>
<td>.62</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Stabilization Drogue</td>
</tr>
<tr>
<td>Guide</td>
<td>Surface (Ribless)</td>
<td>.66</td>
<td>.63</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Pilot, Drogue</td>
</tr>
<tr>
<td>Annular</td>
<td>![Image]</td>
<td>1.04</td>
<td>.96</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Deceleration</td>
</tr>
<tr>
<td>Cross</td>
<td>![Image]</td>
<td>1.15</td>
<td>.66</td>
<td>to</td>
<td>$\pm 10^\circ$</td>
<td>Deceleration</td>
</tr>
</tbody>
</table>
Slotted Textile Parachutes

<table>
<thead>
<tr>
<th>Type</th>
<th>Constructed Shape</th>
<th>Inflated Shape</th>
<th>Drag Coef.</th>
<th>Opening Load Factor</th>
<th>Average Angle of Oscillation</th>
<th>General Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Ribbon</td>
<td></td>
<td></td>
<td>D_C/D_D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Ribbon</td>
<td></td>
<td></td>
<td>D_P/D_D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Ribbon (Varied Porosity)</td>
<td></td>
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<td></td>
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<tr>
<td>Ribbon (Hemisf)</td>
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<tr>
<td>Ringlot</td>
<td></td>
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<tr>
<td>Ringsail</td>
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<tr>
<td>Disc-Gap-Band</td>
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</tbody>
</table>

*Supersonic

Drag vs Stability Trade Space I

- Solid Textile Parachutes
- Slotted Textile Parachutes

Displacement Angle (AAD) vs $C_{D_0}$

- Disk-Gap-Band
- Conical Ribbon
- Ringsail

Parachutes: Types and Functions
Drag vs Stability Trade Space II

- Graph generated by averaging $C_{d0}$ and Average Angle of Oscillation from previous tables
- General trend: increasing drag increases average angle of oscillation (decreased stability)
- Slotted textile parachutes provide better drag-stability trade space
- This chart does not address all important design trades! Other considerations include:
  - Heritage - what data/experience do we already have?
  - Drag area vs mass trade
  - Robustness - how well will this parachute hold up in the specific application?
  - Deployment and inflation reliability
  - Cost and ease of fabrication

*Parachute type selection is influenced by numerous considerations!*

Canopies for Planetary Exploration Missions

The most commonly used canopies in planetary exploration missions are:

- Guide Surface
- Conical Ribbon
- Disk-Gap-Band
- Ringsail

Each of these is discussed in more detail in the following charts
Guide Surface (Ribless) Parachutes

- Low drag ($C_D \sim 0.3$) with good stability ($0^\circ$ to $\pm 3^\circ$ AAO)
- Used in situations where stability is principal consideration (drogue, pilot)
- Abrupt transition at maximum projected diameter and subsequent flow separation is reason for stability characteristics
- Appropriate for subsonic applications
- Difficult to manufacture
- Used by Pioneer Venus (pilot)

Conical Ribbon Parachutes

- Moderate drag ($C_D \sim 0.5$) with good stability ($0^\circ$ to $\pm 3^\circ$ AAO)
- Appropriate for subsonic and supersonic applications
- Can be made very strong (especially if manufactured from Kevlar) and deployed at high dynamic pressure
- Relatively high weight per unit drag area
- Used by:
  - Pioneer Venus
  - Galileo
**Disk-Gap-Band Parachutes**

- Low-to-moderate drag ($C_{D0} \sim 0.4$ to $0.7$) with good-to-moderate stability ($\pm 5^\circ$ to $\pm 15^\circ$ AAO)
- Drag can be traded for stability by changing the gap and band heights
- Appropriate for subsonic and supersonic applications
- Strong heritage data at supersonic speeds in low density atmospheres key to its continued use
- Used by:
  - Viking
  - MPF
  - MPL
  - Beagle 2
  - MER
  - Huygens
  - Genesis
  - Stardust

**Ringsail Parachutes**

- High drag ($C_{D0} \sim 0.8$) with good-to-moderate stability ($\pm 5^\circ$ to $\pm 10^\circ$ AAO)
- Design tailored for optimum performance by varying canopy shape and distribution of geometric porosity throughout canopy
- Currently limited to subsonic applications
- Time consuming fabrication
- Relatively light weight per unit drag area
- Used by Beagle 2 and proposed for other missions
Stages

Design
  Qualification
  Flight Unit Fabrication
  Sterilization
  Spacecraft Integration
  Launch
  Cruise
  Entry
  Deployment
  Inflation
  Descent
  Release

Each stage imposes its own set of requirements and constraints on the parachute system

Drag - Definition

Drag - Force parallel to the free-stream velocity, \( V \)

Assuming quasi steady-state conditions (e.g., parachute is fully inflated) the parachute drag force \( F_p \) can be calculated from:

\[
F_p = qC_D S_0
\]

(using \( S_0 \) as reference area)

or

\[
F_p = qC_D S_p
\]

(using \( S_p \) as nominal area)
What does $C_{D0}$ depend on?

For a specific system (parachute, entry vehicle) in quasi-steady conditions:

$$C_{D0} = f(M, Re, Fr, Kp, c)$$

where,

- Mach Number, $M = V/a$
- Reynolds Number, $Re = \Delta V L / \mu$
- Froude Number, $Fr = V / (L g)^{1/2}$
- Kaplun Number, $Kp = k / \Delta V^2 L$
- Effective Porosity, $c = V_\Delta / V$

See “Symbols” section for a definition of all quantities used in this chart.

It is difficult to match all these nondimensional quantities in a test!

The Mach Number and Effective Porosity are the most important parameters in situations involving the static aerodynamic coefficients (e.g., $C_{D0}$) of parachutes.

**$C_{D0}$ vs M**

Viking Parachute Wind Tunnel Test Results in Wake of Aeroshell

Sources: Janzenko, I., Skalberg, S., and Faye-Petersen, R.: Scale Model Test Results of the Viking Parachute System at Mach Numbers from 0.1 Through 2.0, NASA CR-145077, 1971.

**Design Effects on $C_{D0}$**

**How does parachute design affect $C_{D0}$?**

**Canopy Type**
- Example: Ringsail parachutes have higher $C_{D0}$ than Guide Surface parachutes

**Geometric Porosity**
- Parachutes with smaller geometric porosity have a higher $C_{D0}$
- Example: Increasing gap size on a DGB parachute decreases $C_{D0}$

**Fabric Permeability**
- Reducing fabric permeability increases $C_{D0}$

---

**$C_{D0}$ vs Fabric Permeability**

*The effects of fabric permeability are significant in many parachute systems for planetary entry systems - they must be accounted for.*

Design Effects on \( C_{D0} \) II

How does parachute design affect \( C_{D0} \)?

**Suspension Lines Length**
- Increasing suspension line length increases \( C_{D0} \)

**Trailing Distance**
- Increasing trailing distance increases \( C_{D0} \)

**Forebody-to-Parachute Diameter Ratio**
- Reducing forebody-to-parachute ratio increases \( C_{D0} \)

*Due to wake effects of forebody on parachute

Wake Effects on \( C_{D0} \)

How Do We Obtain $C_{D0}$?

Re-Evaluation of Available Data

Flight Reconstruction

Wind Tunnel Testing

Flight Testing

Viking Drag Model

Terminal Descent Problem

**Basic Equations**
\[ F_P + F_{EV} = q(C_{D0}S_0 + C_{DEV}S_{EV}) \]
\[ q = \Delta V^2 / 2 \]
\[ F_P + F_{EV} = mg \]

**Parachute Sizing - Determine \( S_0 \)**
\[ C_{D0}, S_{EV}, C_{DEV}, q, m, \text{ and } g \text{ are known} \]
\[ S_0 = (m g / q - C_{DEV}S_{EV}) / C_{D0} \]

**Terminal Descent Velocity - Calculate \( V \)**
\[ S_0, C_{D0}, S_{EV}, C_{DEV}, \Delta, m, \text{ and } g \text{ are known} \]
\[ V = \left( 2 m g / [\Delta (C_{D0}S_0 + C_{DEV}S_{EV})] \right)^{1/2} \]

**Parameter Identification - Determine \( C_{D0} \)**
\[ S_0, S_{EV}, C_{DEV}, q, m, \text{ and } g \text{ are known} \]
\[ C_{D0} = (m g / q - C_{DEV}S_{EV}) / S_0 \]

2 DOF Trajectory Equations

\[ m\dot{V}_x = \gamma (F_P + F_{EV}) \cos\gamma \]
\[ m\dot{V}_z = \gamma (F_P + F_{EV}) \sin\gamma \gamma mg \]
\[ F_P + F_{EV} = q(C_{D0}S_0 + C_{DEV}S_{EV}) \]

- These trajectory equations can be solved analytically for some simple cases
- In general, these equations are solved numerically
  - Start by transforming them into a set of first-order coupled ordinary differential equations
  - Solve for specified set of initial conditions
Parachute Clusters

Total drag area of a parachute system can be increased by clustering parachutes

Advantages
• Easier to fabricate smaller canopies
• Drag area can be adjusted by adding or deleting canopies
• Redundancy
• Increased stability
• Shorter inflation time/distance

Disadvantages
• Slight loss of $C_{D0}$ (~5% for a three-canopy cluster)
• Problems with asynchronous inflation
• Heavier than a single canopy system

Dynamics - Importance to Planetary Missions

Dynamic behavior of the entry system during the parachute phase of descent and landing is important for numerous reasons, for example:

• Scientific observations (imaging)
• Sensor performance (radar)
• Separation events (heatshield)
• Initial conditions for propulsive terminal descent
• Attitude at rocket firing events
• Control of horizontal velocity
Model for Discussion

A simple model will be used for this discussion:
- Parachute and payload behave as a single unit
- Parachute is modeled as a rigid unit
- Payload generates no aerodynamic forces
- \( \Delta \): angle of attack; single degree of freedom in this simplified model
- \( N \): parachute normal force acting at parachute center of pressure (CP)
- \( T \): parachute tangential force acting along axis of symmetry of parachute
- \( m \): parachute pitching moment
  - Shown about center of gravity, but other reference points such as suspension lines confluence point also used; do not confuse with mass “m”
- Dynamic derivatives (e.g., \( C_{ma} \), \( C_{me} \)) are ignored

Static Aerodynamic Coefficients

- \( C_N \), \( C_T \), \( C_m \) are static aerodynamic coefficients - functions of \( \Delta \)
  \[
  N = q S_0 C_N \quad T = q S_0 C_T \quad m = q S_0 D_0 C_m
  \]
- \( C_T \gg C_N \)
- \( C_T \) dominates drag behavior: \( C_{D0} = \sqrt{C_T^2 + C_N^2} \)
- Center of Pressure function of \( \Delta \)
  - However, CP assumed constant in present simplified analysis
- Pitching moment coefficient coefficient, \( C_m \), related to \( C_N \)
  \[
  C_m = -\frac{x_{CP}}{D_0} C_N
  \]
  where \( x_{CP} \) is distance from CP to reference point (typically the system center of mass or suspension lines confluence point)
- \( C_N \) and \( C_m \) control stability
Typical $C_T$, $C_N$, and $C_m$ vs $\Delta$

Trim and Stability

**Trim:** $C_m = 0$

- **Stable Trim Point:** $dC_m/d\Delta < 0$  (restoring moment)
- **Unstable Trim Point:** $dC_m/d\Delta > 0$  (diverging moment)
Stable and Unstable Parachutes

Possible Motions

- Gliding flight - “constant” $\Delta$
- Oscillation about single trim $\Delta$
- Oscillation from one trim $\Delta$ to another
- Coning
- Combination of the above

Other factors further complicate system motions:
- Wind shear
- Unsteady wake from payload
- Payload dynamics
- Attachment to payload
- Parachute self induced oscillations
Real World Motions - Wind Tunnel Test

Real World Motions - MER A Flight

time to rocket firing = 27.33 sec
altitude = 2932.7 m
Design Effects on Stability

Parachute choice and design can be used to affect stability:

- Guide surface parachute is more stable than a Ringsail parachute
- Increasing band height on DGB parachutes improves stability
- Increasing geometric porosity improves stability
- Increasing fabric permeability improves stability

*Stability considerations may drive choice of parachute and its design*

Multi-DOF Dynamics Models

Complex multi-DOF dynamics models are often created to investigate stability issues

- Static aero coefficients
- Dynamic aero coefficients
- Physical mass and moments of inertia
- Apparent mass
- System components elasticity

*There is still significant room for improvement in these dynamics models!*
Deployment I

Definition

• Process by which the parachute is exposed to the airstream so that inflation can start
• Starts with the parachute in its deployment bag within the entry vehicle
• Ends with the parachute stretched-out (but not inflated) and completely out of its deployment bag, streaming behind the entry vehicle

Deployment Methods Discussed
• Extractor Rocket
• Pilot Parachute
• Mortar

Deployment II

A good deployment system will:
- Keep the parachute under tension
- Prevents “dumping” of the canopy (i.e., uncontrolled emergence from the deployment bag)
- Keep the parachute from tangling
- Minimize inertial deployment loads (i.e., snatch loads)
- Prevent significant inflation before the parachute is completely out of its deployment bag
- Be reliable (i.e., works every time, in the same way)
- Will operate properly at a variety of deployment conditions (e.g., combinations of M and q)
- Can be qualified through a reasonable testing program

Planetary parachutes use lines-first deployment systems
Deployment III

Lines-First Deployment

Extractor Rocket

• Rocket used to extract pilot or main parachute
• Used in Soviet Mars 2 and 3 missions
• Low recoil force
• Reliable
• Insensitive to deployment conditions (e.g., M and q)
Pilot Parachute I

Genesis System

Mortar-Deployed Drogue/Pilot Parachute at \( M \approx 1.4, H \approx 33 \text{ km} \)

Descent Under Drogue/Pilot Parachute

Drogue/Pilot-Deployed Parafoil

Descent Under Parafoil

Pilot Parachute II

- Used in numerous missions:
  - Mars 2 and 3
  - Pioneer Venus
  - Genesis
  - Stardust
  - Huygens

- Low recoil force

- Allows extracted parachute to be packed in almost any shape

- Added complexity (more than one parachute, deployment system needed for pilot parachute)

- May have problems with bag strip velocity

- May be sensitive to deployment conditions
**Mortar I**

- Cover
- Sabot
- Tube
- Gas Generator
- Attachment Lugs (3)
- Rails (3)

**Mortar II**

- Mortar mounted on the backshell of the entry vehicle
- Mortar ejects parachute pack at high velocity (100 to 130 ft/s)
- Parachute emerges from deployment bag in a lines-first sequence
- Deployment bag separates from parachute at end of deployment leaving parachute stretched-out and ready for inflation
Drop Test with Mortar Deployment

Wind Tunnel Test with Mortar Deployment
Mortar Remarks

- Used in all US missions to Mars
- Simple and reliable
- Relatively easy to qualify
- Low bag-strip velocity
- Insensitive to deployment conditions
- High recoil force
- Parachute must be packed to high density (typically 40 to 45 lbm/ft³)
- Mortar tube must be long enough to provide sufficient stroke for parachute pack acceleration
  - Parachute pack length to diameter ratio 1.0 to 2.5
- Inflexible with regards to parachute pack geometry and dimensions
  - Can be problematic wrt space allocation inside entry vehicle

Snatch Loads

As the parachute bag re-accelerates to the entry vehicle velocity, inertial forces are generated

These inertial forces are known as snatch loads
Inflation

- Process by which the parachute is filled (i.e., opens)

- Starts with the parachute stretched-out and completely out of its deployment bag, streaming behind the entry vehicle

- Ends with first full-inflation of the parachute

Inflation Process

a) Opening of canopy mouth (start of inflation)

b) Air mass moves along canopy

c) Air mass reaches crown of canopy

d) Influx of air expands crown

e) Expansion of crown resisted by structural tension and inertia

f) Enlarged inlet causes rapid filling

g) Skirt over-expanded, crown depressed by momentum of surrounding air mass

Subsonic Inflation

- At subsonic speeds, inflation is often modeled as occurring over a constant number of parachute diameters (i.e., multiples of \( D_0 \)) for a given parachute type
- Parachute is “scooping” a given volume of air to inflate
- For the most part, experimental data supports this assumption
- Thus if inflation occurs at a constant velocity, \( V \), the inflation time, \( t_{\text{inf}} \), can be estimated from:
  \[
  t_{\text{inf}} = \frac{n_{\text{inf}} D_0}{V}
  \]
  where \( n \) depends on the parachute type and geometry (typically \( n_{\text{inf}} \sim 6 \) to 15)
- If \( V \) varies significantly during inflation, the equations of motion must be integrated to obtain the inflation time for a given inflation distance

Supersonic Inflation

- At supersonic speeds, inflation is often modeled as occurring over a fixed time, proportional to the parachute diameter but independent of Mach number (in the range \( 1.5 \leq M \leq 2.5 \))
- For the most part, experimental data supports this assumption
- Thus,
  \[
  t_{\text{inf}} = K_{\text{inf}} D_0
  \]
  where \( K_{\text{inf}} \) depends on the parachute type and geometry (for a Viking-type DGB, \( K_{\text{inf}} \sim 0.02 \) s/m)
- Inflation (from bag strip to full inflation) is very fast at supersonic speeds! For the Viking DGB with \( D_0 = 16 \) m, \( t_{\text{inf}} \sim 0.32 \) s.
Infinite-Mass Inflation

- If inflation is of the infinite mass type, there will be little deceleration and reduction in the dynamic pressure during inflation.
  - Peak opening load will occur at full inflation.
- Infinite-mass inflation can happen when inflation occurs so rapidly that there is no time for significant deceleration of the entry vehicle during inflation.
- Parachute inflation in thin atmospheres at supersonic speeds is often of the infinite mass type -> Mars!
- Infinite-mass inflation is difficult to obtain at subsonic speeds at low Earth altitudes - this presents a challenge to the qualification of supersonic parachutes at low Earth altitudes.
- To obtain infinite-mass inflation at low Earth altitudes:
  - Payload mass must be large or,
  - Test must be conducted in a wind tunnel.

Infinite-Mass Inflation Example

![Graph showing Load vs. Time from Mortar Firing (s)](image-url)

- **MER Drop Test - 8,000 lbm Test Vehicle**
- **Load / 1,000 (lb)**
- **Time from Mortar Firing (s)**
- **Normalized Dynamic Pressure (pd)**
- **Peak opening load and full inflation**
- **Load**
- **q**
Infinite-Mass Inflation Film

Finite-Mass Inflation

- If the payload has “finite-mass,” there will be substantial deceleration and reduction in the dynamic pressure during the inflation
  - Peak opening load will not occur at full inflation

- This is the typical situation when parachutes are inflated at low Earth altitudes

- It is more difficult to accurately predict the opening loads in a finite-mass inflation
Finite-Mass Inflation Example

Opening Loads

Accurate calculation of opening loads are critical for:
• Stress analysis of parachute
• Stress analysis of entry vehicle
• Calculating acceleration of payload
• Specification of on-board accelerometers

Three opening loads analysis methods are discussed here:
• Pflanz’s Method
• Inflation Curve Method
• Apparent Mass Method
Pflanz’s Method Description

- Simple, first-order, design book type method
- Requires least knowledge of the system as compared to other methods
- Version presented here assumes no gravity - limits application to shallow flight path angles at parachute deployment (can be extended to account for gravity and steeper flight path angles)
- Neglects entry vehicle drag
- Yields only peak opening load

Pflanz’s Method Equations

\[ F_{\text{peak}} = q_1 C_{D0} S_0 C_X X_1 \]

where \( X_1 = f(A, n) \) and \( A = 2 m_{EV} / C_{D0} S_0 \Delta V_1 t_{\text{inf}} \)

Variables definition

- \( F_{\text{peak}} \) - peak opening load
- \( q_1 \) - dynamic pressure at start of inflation
- \( C_{D0} \) - parachute full-open drag coefficient
- \( S_0 \) - parachute nominal area
- \( C_X \) - opening load factor (from test data or tables in pages 24 through 26)
- \( X_1 \) - force reduction factor accounting for deceleration during inflation (see figure 5-51 of Knacke: Parachute Recovery Systems Design Manual)
- \( A \) - ballistic parameter
- \( n \) - inflation curve exponent (dependent on canopy type, see Knacke: Parachute Recovery Systems Design Manual, p. 5-58)
- \( m_{EV} \) - mass of entry vehicle
- \( \Delta \) - atmospheric density
- \( V_1 \) - velocity at start of inflation
- \( t_{\text{inf}} \) - inflation time (see inflation section for guidelines)
Pflanz’s Method Example

MER A - Spirit

\[ q = 729 \text{ Pa} \]
\[ C_{D0} = 0.400 \text{ (at } M = 1.75) \]
\[ D_0 = 14.1 \text{ m} \]
\[ S_0 = 156 \text{ m}^2 \]
\[ C_X = 1.45 \]
\[ m_{EV} = 827 \text{ kg} \]
\[ \Delta = 0.00863 \text{ kg/m}^3 \]
\[ V_1 = 411 \text{ m/s} \]
\[ t_{inf} = 0.282 \text{ s (from previous discussion on supersonic inflation)} \]
\[ A = 26.5 \]
\[ n = 2 \text{ (for DGB parachutes)} \]
\[ X_1 = 0.98 \text{ (i.e., very close to infinite mass inflation!)} \]
\[ \Delta \]
\[ F_{peak} = 64,641 \text{ N (within 10% of best estimate)} \]

Parachutes: Opening Loads 83

Inflation Curve Method Description

• An explicit version of Pflanz’s method

• Assumes a drag area growth function with opening load factor

• Only as accurate as the assumed drag area growth function and the opening load factor

• Requires determination of the trajectory

• Easy to implement in trajectory analysis programs

• Yields parachute force-time history

Parachutes: Opening Loads 84
Apparent Mass Method Description

- As the parachute inflates it carries with it a certain amount of air mass both within and around it - this air mass is known as the apparent mass.

- Accelerating the apparent mass requires force, which is generated by the parachute.

- Thus, the apparent mass is reflected in \( F_p \), the parachute force.

- The apparent mass varies with the state of the parachute during inflation.

- Although apparent mass opening loads methods are more physically sound and general, they are difficult to implement due to the large number of unknowns.

- Implementation in trajectory analysis is required.
Apparent Mass Method Equations

Basic equation: \[ F_p = qC_D S + \frac{d}{dt} \left( (m_p + m_a) V \right) + m_p g \sin \gamma \]

After differentiating: \[ F_p = qC_D S + (m_p + m_a) \frac{dV}{dt} + \frac{dm_p}{dt} V + m_p g \sin \gamma \]

- \( F_p \): parachute force
- \( q \): dynamic pressure
- \( C_D S \): parachute drag area (function of time)
- \( m_a \): apparent mass
- \( m_p \): parachute mass
- \( V \): velocity
- \( g \): acceleration of gravity
- \( \Delta \): flight path angle (positive above horizon)

Key difficulties in implementing apparent mass opening load methods lie in modeling \( C_D S \) and \( m_a \)

Reefing

Opening loads can be controlled by temporarily restricting canopy at the skirt - this is known as reefing

- Reefing line(s) threaded through rings at parachute skirt
- Reefing line(s) length controls degree of reefing and drag area
- Reefing line is cut allowing parachute to continue inflation
- Reefing can be performed in multiple stages
- Reefing is also an effective method for drag area control
- Added complexity and possible failure modes need to be considered in design
Materials I

Most commonly used materials for planetary parachutes:

- Nylon
  - Good strength
  - Often used in fabric form
  - 480°F melting point
  - Poor ultraviolet light resistance

- Dacron
  - Good strength
  - Often used in fabric form
  - 485°F melting point

- Nomex
  - Moderate strength
  - Often used in fabric form
  - 800°F melting point
  - Used mainly in higher temperature applications

continued…

Materials II

- Kevlar
  - High strength
  - Most used in lines and webbing form
  - 850°F melting point
  - Poor ultraviolet light resistance
  - Used mainly for suspension lines, bridles, risers, and reinforcements
  - Has significantly reduced parachute mass as compared to the mainly-Nylon systems of the 1970’s

- Teflon
  - Often used as low-friction liner for deployment bags to avoid friction burns

- New Materials
  - Spectra
  - Vectran
  - Zylon
Mass and Volume

Determining the mass of a planetary parachute system can be done in various ways:

- Estimating mass based on historical data
- Bottoms-up mass estimate from system drawings
- Measuring weight of prototype and final systems

Historical Ringsail Parachute Mass Data

\[
\frac{m_p}{S_0} = 0.1055 \text{ kg/m}^2
\]

Testing I

Types of testing performed during a planetary parachute system design and development

Materials
- Strength & Stiffness
- Environmental (e.g., heat, UV, radiation, chemical)
- Fabric Permeability
- Joint and Seam

Wind Tunnel Testing
- Drag Coefficients
- Other Aerodynamic Coefficients
- Parachute Dynamics
- Parachute Strength

continued…
Testing II

Flight Testing (Low- and High-Altitude)
- Drag Coefficient
- Other Aerodynamic Coefficients
- Parachute Dynamics
- Parachute Strength
- Deployment and Inflation
- System Operation and Performance

Ground Testing
- Mortar Performance
- Bag Strip
- Structural
- Vibration
- Thermal & Vacuum

Balloon / Rocket Flight Testing

Balloon / Rocket Flight Testing Film

Rocket Flight Testing

MER Low-Altitude Flight Testing

Parachute Drag and Dynamics

Structural Qualification

Parachutes: Testing

MER Low-Altitude Structural Qualification Flight Testing

Parachutes: Testing
MER Sub-Scale Wind Tunnel Testing

Drag Coefficient

Aero Static Stability Coefficients

MER Full-Scale Structural Qual Wind Tunnel Testing
Fluid-Structures Interaction (FSI) Analyses

- Analyses used currently to design, develop, and qualify parachutes are highly empirical - not derived from first principles
- Coupling of fluid (CFD) and structures (FEM) analyses to solve parachute problems has become viable
- CFD + FEM = FSI
- Potential benefits of FSI
  - Yield insights as to why parachutes work the way they do
  - Allow for the numerical exploration and optimization of the design before testing
  - Guide the scaling of sub-scale test results to full-scale flight
  - Guide the full-scale qualification testing of new designs
  - Expand the range of applicability of previous test results by numerical extrapolation

Additional Materials

Part III: Additional Materials

<table>
<thead>
<tr>
<th>Title</th>
<th>Slide No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbols</td>
<td>105</td>
</tr>
<tr>
<td>Acronyms</td>
<td>108</td>
</tr>
<tr>
<td>Glossary</td>
<td>109</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>116</td>
</tr>
<tr>
<td>Point of Contact</td>
<td>117</td>
</tr>
<tr>
<td>Bibliography</td>
<td>118</td>
</tr>
</tbody>
</table>
Symbols

\( a \) speed of sound
\( A \) ballistic parameter
\( c \) effective porosity
\( C_{\text{ DV}} \) drag coefficient of the entry vehicle based on \( S_{\text{DV}} \) as the reference area
\( C_{\text{DP}} \) drag coefficient based on projected area
\( C_{\text{PS}} \) parachute drag area
\( C_{\text{DP0}} \) drag coefficient based on nominal area
\( C_n \) pitching moment coefficient
\( C_n' \) normal force coefficient
\( C_{n,\text{d}} \) derivative of \( C_n \) with respect to \( d\alpha/dt \)
\( C_{n',\text{d}} \) derivative of \( C_n' \) with respect to \( d\alpha/dt \)
\( C_T \) tangential force coefficient
\( D_e \) constructed diameter
\( D_i \) projected diameter
\( D_0 \) nominal diameter
\( F_{\text{DV}} \) drag force generated by the entry vehicle
\( F_p \) drag force generated by the parachute
\( F_{\text{peak}} \) peak opening load
\( Fr \) Froude number
\( g \) acceleration of gravity
\( k \) stiffness parameter
\( K_{\text{Su}} \) supersonic inflation constant
\( Kp \) Kaplin number
\( L \) reference length
\( L_s \) suspension line length
\( H \) altitude

Additional Materials: Symbols
Symbols

\[\alpha\] angle of attack
\[\Delta\] flight path angle (positive above horizon)
\[\Delta p\] differential pressure across fabric
\[\Delta_{g}\] geometric porosity
\[\Delta_{t}\] total porosity
\[\mu\] conical parachute base angle, viscosity
\[\Delta\] atmospheric density

Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAO</td>
<td>Average Angle of Oscillation</td>
</tr>
<tr>
<td>AFFDL</td>
<td>Air Force Flight Dynamics Laboratory</td>
</tr>
<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Mechanics</td>
</tr>
<tr>
<td>CP</td>
<td>Center of Pressure</td>
</tr>
<tr>
<td>DGB</td>
<td>Disk-Gap-Band</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree-of-Freedom</td>
</tr>
<tr>
<td>EDL</td>
<td>Entry, Descent, and Landing</td>
</tr>
<tr>
<td>EV</td>
<td>Entry Vehicle</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FSI</td>
<td>Fluid Structures Interaction</td>
</tr>
<tr>
<td>IAD</td>
<td>Inflatable Aerodynamic Decelerator</td>
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<tr>
<td>MER</td>
<td>Mars Exploration Rovers</td>
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<tr>
<td>MPF</td>
<td>Mars Pathfinder</td>
</tr>
<tr>
<td>MPL</td>
<td>Mars Polar Lander</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NA&amp;SD</td>
<td>NASA Aeronautics and Space Database</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet light</td>
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</tbody>
</table>
Glossary

Aerocapture – an orbit insertion maneuver in which the drag generated by an entry vehicle as it flies through the atmosphere of a planet or moon is used to reduce the entry vehicle’s kinetic energy so that it is captured into orbit.

Aerodynamic Decelerator – a device that uses drag to dissipate a payload’s kinetic energy and velocity.

Aeroshell – an enclosure that protects a payload from the rigors of entry.

Airbag – an inflatable textile bag used to cushion the impact of a payload.

Angle of Attack – in two dimensions, the angle between the longitudinal axis of an entry vehicle or parachute and its velocity through a fluid.

Angle of Oscillation – the angular displacement of a parachute’s axis of symmetry from the vertical or direction of travel.

Apex – the furthest downstream (i.e., top) portion of a parachute.

Apparent Mass – the mass of fluid, both within and around a parachute canopy, affected by the parachute. The apparent mass has an influence on the forces and moments generated by the parachute.

Apparent Mass Method – a method of calculating parachute opening loads that incorporates the effects of apparent mass.

Backshell – the downstream facing portion of an aeroshell.

Bag-Strip Velocity – the relative velocity between the parachute and the deployment bag during deployment.

Ballistic Coefficient – the ratio of mass to drag area of an entry vehicle or other component (e.g., heatshield).

Ballute – a type of aerodynamic decelerator consisting of an inflatable structure that is either attached to the entry vehicle through one or more risers (i.e., a trailing ballute) or is directly attached around the edges of the entry vehicle (i.e., an attached ballute). The inflating fluid can be provided by either a gas generator or by capturing a portion of the airflow (i.e., a ram-air ballute). The term ballute is a combination of balloon and parachute. Ballutes are also sometimes referred to as inflatable aerodynamic decelerators (IAD). Ballutes have been proposed for a variety of purposes from entry to supersonic deceleration. I discourage the use of the term ballute since it is applied to a wide variety of disparate devices. I recommend using the term inflatable
aeroshell to describe devices that are deployed and inflated prior to entry and must withstand the heat of entry, and inflatable aerodynamic decelerator for devices deployed and inflated at Mach numbers of five or less.

**Band** – the component of a Disk-Gap-Band parachute whose constructed shape consists of a (fabric) cylinder. The upstream edge of the band is the skirt of a Disk-Gap-Band parachute.

**Bridle** – a multiple-leg textile component used to attach the parachute to the payload.

**Canopy** – the main drag producing portion of a parachute.

**Cluster** – an arrangement of parachutes in which two or more identical canopies are used simultaneously.

**Conical Ribbon Parachute** – a type of slotted textile parachute with a conical constructed shape consisting of ribbons in the circumferential and radial directions.

**Coning** – one possible motion of a parachute/payload system in which both the parachute and the payload rotate in circles and the combination traces two cones.

**Constructed Diameter** – the diameter of a parachute when it is held in its constructed shape (e.g., the base diameter of the cone describing the constructed shape of a conical parachute, the diameter of the hemisphere describing the constructed shape of a hemispherical parachute).

**Crown** – the top portion of a parachute canopy from its maximum diameter to the apex.

**Deployment** – the process by which a parachute is exposed to the airstream so that inflation can start. Deployment starts with the parachute in its deployment bag and ends with the parachute completely out of its deployment bag and stretched-out (but not inflated) while streaming behind the entry vehicle.

**Deployment Bag** – a bag containing the parachute whose main purpose is that of effecting an organized deployment.

**Disk** – the component of a Disk-Gap-Band parachute whose constructed shape consists of a circular (fabric) disk.

**Disk-Gap-Band Parachute** – a type of slotted textile parachute whose constructed shape consists of a flat disk and a cylindrical band with a gap between the disk and the band.

**Drag** – the component of aerodynamic force parallel to the airstream generated by a body such as a parachute or entry vehicle.

Additional Materials: Glossary
Drag Coefficient – a nondimensional quantity defined as the drag of a body divided by its reference area and dynamic pressure.

Drogue Parachute – a parachute whose main purpose is to stabilize the payload.

Dumping – uncontrolled and/or unorganized emergence of a parachute from its deployment bag.

Dynamic Pressure – one-half the product of fluid density times the airspeed squared.

Effective Porosity – a measure of canopy porosity due to fabric permeability.

Extractor Rocket – a deployment system in which the deployment bag and parachute are pulled away from the vehicle by means of a rocket.

Finite-Mass Inflation – an inflation of a parachute occurring such that the change in dynamic pressure is relatively large during inflation. For a parachute, the peak opening load will often occur before full inflation during a finite-mass inflation. The term finite-mass inflation arises from the observation that if a payload’s mass is low (in a constant atmospheric density, gravity-free environment) the dynamic pressure will drop significantly during inflation since the drag of the parachute will decelerate the payload. See infinite-mass inflation for the converse situation.

Forebody – a body suspended in front of a parachute.

Froude Number – a nondimensional number expressing the ratio of inertial to gravity forces.

Gap – the open portion of a Disk-Gap-Band parachute whose constructed shape consists of a cylinder joining the disk to the band by means of suspension lines.

Gas Generator – a pyrotechnic device that creates gas at high pressure behind the sabot of a mortar to eject the parachute in its deployment bag. Also, a pyrotechnic device that creates gas to inflate an airbag, an inflatable aeroshell, or an inflatable aerodynamic decelerator.

Geometric Porosity – the ratio of open areas in a parachute’s canopy to the nominal area. Usually expressed in percentage.

Gliding – one possible motion of a parachute/payload system in which there is significant forward motion in addition to the descent.

Gore – the segment of a circular parachute canopy between the suspension lines.

Guide Surface Parachute – a type of solid textile parachute offering high stability, as measured by its angle of oscillation, but having a low drag coefficient.

Additional Materials: Glossary
**Heatshield** – the upstream facing portion of an aeroshell. The main role of the heatshield is to protect the payload from the heat of entry.

**Infinite-Mass Inflation** – an inflation of a parachute occurring such that the change in dynamic pressure is relatively modest during inflation. For a parachute, full inflation and the peak opening load will occur nearly simultaneously during an infinite-mass inflation. The term infinite-mass inflation arises from the observation that if a payload were to be of infinite mass (in a constant atmospheric density, gravity-free environment) the dynamic pressure would not vary during inflation since the drag of the parachute would be incapable of decelerating the payload. In practical situations infinite-mass inflations occur only when the payload is massive, and/or the atmospheric density is low, and/or in a wind tunnel.

**Inflatable Aerodynamic Decelerator** – a type of aerodynamic decelerator consisting of an inflatable structure that is either attached to the entry vehicle through one or more risers (trailing type) or is directly attached around the edges of the entry vehicle (attached type). The inflating fluid can be provided by either a gas generator or by capturing a portion of the airflow (i.e., ram-air). Inflatable aerodynamic decelerators are not intended to withstand the heat of entry. They are deployed and inflated at Mach numbers of five or less. See ballute and inflatable aeroshell for descriptions of related devices.

**Inflatable Aeroshell** – a type of aeroshell consisting of an inflatable structure directly attached around the edges of the payload to become part of the entry vehicle. Inflatable aeroshells are deployed and inflated (via one or more gas generators) before entry, and are intended to withstand the heat of entry. See ballute and inflatable aerodynamic decelerator for descriptions of related devices.

**Inflation** – the filling of a parachute with fluid. Inflation starts at the end of deployment and concludes with a fully filled parachute.

**Inflation Curve Method** – a method of calculating parachute opening loads that makes assumptions as to how the drag area of the parachute increases during inflation.

**Kaplan Number** – a nondimensional parameter expressing the ratio of material stiffness to fluid pressure forces.

**Lines-First Deployment** – a deployment procedure in which the bridles, risers, and suspension lines emerge from the deployment bag before the canopy.

**Mach Number** – the ratio of airspeed to the speed of sound of the fluid.

**Mortar** – a device used to eject a parachute at high speed from a vehicle to effect deployment.

Additional Materials: Glossary
**Nominal Area** – the constructed surface area of a parachute canopy including all openings such as the vent. Often used as a reference area for the aerodynamic coefficients of parachutes.

**Nominal Diameter** – a fictitious parachute diameter obtained by assuming that the nominal area of the parachute is that of a circle. Often used as a reference length for the aerodynamic coefficients of parachutes.

**Normal Force** – for a parachute, the component of aerodynamic force normal to its axis of symmetry.

**Normal Force Coefficient** – for a parachute, a nondimensional quantity defined as the normal force divided by the parachute’s reference area and dynamic pressure.

**Opening Loads** - the forces generated by a parachute during inflation.

**Parafoil** – a non-circular gliding parachute whose shape resembles that of a wing.

**Peak Opening Load** – the largest force generated by a parachute during inflation.

**Permeability** – a measure of the amount of fluid that flows through a fabric.

**Pflanz’s Method** - a simplified method of calculating a parachute’s peak opening loads.

**Pilot Parachute** – a parachute used to deploy another parachute. The pilot parachute is usually smaller than the parachute it is deploying.

**Pitching Moment** – for a parachute, the aerodynamic moment normal to its axis of symmetry. The pitching moment is expressed about a given location, for example the parachute’s suspension lines confluence point.

**Pitching Moment Coefficient** – for a parachute, a nondimensional quantity defined as the pitching moment divided by the parachute’s reference area, reference length, and dynamic pressure. The pitching moment coefficient is expressed about a given location, for example the parachute’s suspension lines confluence point.

**Projected Area** – the frontal area of a fully inflated parachute. Occasionally used as a reference area for the aerodynamic coefficients of parachutes.

**Projected Diameter** - a fictitious parachute diameter obtained by assuming that the projected area of the parachute is that of a circle. Occasionally used as a reference length for the aerodynamic coefficients of parachutes.

**Recoil Force** – the reaction force generated by a mortar while deploying a parachute.
Reefing – a method of parachute drag area and opening loads control during inflation. In a reefed parachute the skirt’s inflated diameter is restricted by a reefing line threaded through a series of rings sewn along the skirt. To allow the parachute to reach full inflation the reefing line is severed by a reefing line cutter. Multiple stages of reefing can be used, thus controlling to some extent the inflation of the parachute.

Reefing Line – a braided cord threaded through a series of rings along the skirt of a parachute to restrict the skirt’s inflated diameter and thus control drag and opening loads.

Reefing Line Cutter – a pyrotechnic device used to cut a reefing line. Reefing line cutters (typically 2 to 3 per reefing line) are usually sewn along the skirt of the parachute.

Rigid Aerodynamic Decelerators – a non-textile aerodynamic decelerator (e.g., drag ring, rotor).

Ringsail Parachute – a type of slotted textile parachute consisting of concentric fabric rings and sails (essentially rings with extra fullness) with gaps between them. Ringsail parachutes offer a good combination of drag and stability.

Riser – a single-leg textile component used to attach the parachute to the payload. Also, a textile component used to gather several suspension lines into a single leg.

Sabot – the piston that pushes the parachute out of a mortar. On one side of the sabot lies the parachute in its deployment bag, while on the other side the high-pressure gas created by the gas generator is pushing on the sabot.

Skirt – the upstream edge of a parachute canopy.

Slotted Textile Parachutes – a family of parachutes with concentric slots that allow air (or some other fluid) to flow through the canopy.

Snatch Load – the peak inertial load generated by a deploying parachute as it re-accelerates to the speed of the payload.

Solid Textile Parachutes – a family of parachutes whose canopies lack concentric openings (besides the vent) that allow air (or some other fluid) to flow through. Solid textile parachutes are usually manufactured using fabric materials.

Static Aerodynamic Coefficients – the aerodynamic coefficients of a body measured at a constant angle of attack with zero pitch and yaw rates.

Suspension Lines – braided cord connecting the skirt of the parachute to the payload.

Additional Materials: Glossary
**Suspension Lines Confluence Point** – a point in space where the suspension lines would theoretically come together if they were to continue upstream. In most parachutes the suspension lines are gathered by groups in risers – thus, the suspension lines often do not physically meet at the suspension lines confluence point. The suspension lines confluence point is useful as a reference point for the pitching moment.

**Tangential Force** – for a parachute, the component of aerodynamic force along its axis of symmetry.

**Tangential Force Coefficient** – for a parachute, a nondimensional quantity defined as the tangential force divided by the parachute’s reference area and dynamic pressure.

**Textile Impact Attenuation Device** – an inflatable structure fabricated from textile materials and used to reduce the acceleration of a payload as it contacts the ground (e.g., airbags).

**Total Porosity** - the sum of the geometric porosity and an equivalent porosity due to fabric permeability. Fabric permeability (i.e., fluid flow through the fabric material) is converted to an “equivalent” open area of the parachute to determine the porosity due to fabric permeability.

**Trailing Distance** – the distance between the largest diameter of an entry vehicle and the skirt of the parachute.

**Trim Point/Angle of Attack** – the angle of attack at which the pitching moment of a parachute is zero.

**Tube** – the main cylindrical component of a mortar. The tube contains the parachute and its deployment bag and serves as the barrel through which the parachute (in its deployment bag) is accelerated by the sabot due to the fluid pressure created by the gas generator.

**Vent** – a circular opening at the apex of a parachute through which air (or some other fluid) flows.

**Vent Area** – the constructed area of the vent.

**Vent Diameter** – the diameter of a circular vent. Note that the vent area and vent diameter are not always related by the simple relationship between the area and diameter of a circle.
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Point of Contact

Juan R. Cruz  
NASA Langley Research Center  
Exploration Systems Engineering Branch  
Mail Stop 489  
Hampton, VA 23681

757-864-3173 (voice)  
757-864-8675 (fax)

Juan.R.Cruz@NASA.GOV
Planetary Parachute Bibliography

Juan R. Cruz

NASA Langley Research Center
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Contents
1.0 Pre-Viking
  1.1 General
  1.2 Wind Tunnel Testing
  1.3 Flight Test Programs (PEPP, SPED, SHAPE and Others)\(^1\)

2.0 Viking
  2.1 General
  2.2 Wind Tunnel Testing
  2.3 Low Altitude Drop Tests (LADT)
  2.4 Balloon Launched Decelerator Tests (BLDT)
  2.5 Mortar Testing and Qualification
  2.6 Multi-Body Dynamic Analyses

3.0 Mars Pathfinder

4.0 Mars Exploration Rover
  4.1 General
  4.2 Wind Tunnel Testing
  4.3 Low Altitude Drop Tests
  4.4 Mortar Testing and Qualification

5.0 Pioneer/Venus, Galileo, Beagle 2, Genesis, Cassini/Huygens, Stardust, and Mars Science Laboratory

6.0 Other

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\(^1\) PEPP – Planetary Entry Parachute Program; SPED – Supersonic Planetary Entry Decelerator Program; SHAPE – Supersonic High Altitude Parachute Experiment

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1.0 Pre-Viking

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119


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### 2.3 Low Altitude Drop Tests (LADT)


### 2.4 Balloon Launched Decelerator Tests (BLDT)


Additional Materials: Bibliography


2.5 Mortar Testing and Qualification

2.6 Multi-Body Dynamic Analyses


3.0 Mars Pathfinder


4.0 Mars Exploration Rover

4.1 General


Additional Materials: Bibliography

126


4.2 Wind Tunnel Testing


4.3 Low Altitude Drop Tests


Additional Materials: Bibliography

127
4.4 Mortar Testing and Qualification


5.0 Pioneer/Venus, Galileo, Beagle 2, Genesis, Cassini/Huygens, Stardust, and Mars Science Laboratory


Additional Materials: Bibliography

128


6.0 Other


Additional Materials: Bibliography

129


Additional Materials: Bibliography
130