Recovery Systems: Parachutes 101

Material taken from: Parachutes for Planetary Entry Systems

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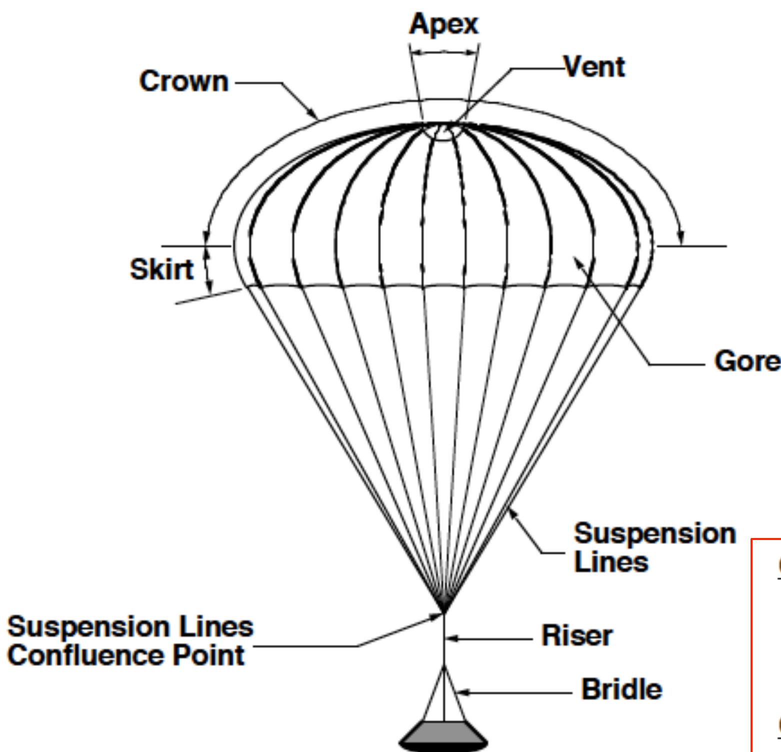
Also, Images from:

Knacke, T. W.: Parachute Recovery Systems Design Manual, Para Publishing, Santa Barbara, CA, 1992.
and
Ewing, E. G., Bixby, H.W., and Knacke, T.W.: Recovery System Design Guide, AFFDL-TR-78-151, 1978.

Basic Terminology



__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

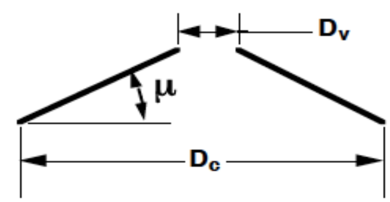
__Nominal Diameter__, D_0
- Fictitious diameter based on S_0:

$$D_0 = \sqrt{\frac{4S_0}{\pi}}$$

- Often (but not always!) used as reference length for aerodynamic coefficients and other calculations

__Constructed Diameter__, D_c
- Maximum diameter of the parachute (measured along the gore radial seam) of the parachute

__Conical Parachute Base Angle__, μ

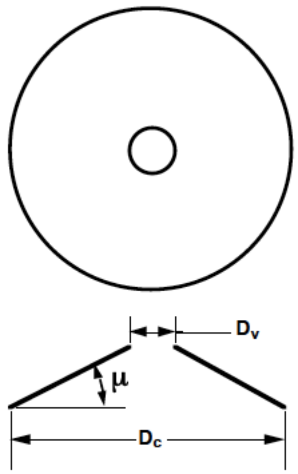


__Vent Diameter__, D_v

__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

Basic Terminology (2)

Example: Conical Parachute



$$S_0 = \lambda \frac{D_c^2}{4}\sqrt{1+\tan^2\mu}$$

$$D_0 = \sqrt{\frac{4S_0}{\lambda}}$$

$$S_v = \lambda \frac{D_v^2}{4}\sqrt{1+\tan^2\mu}$$

$$\lambda_g = \frac{S_V}{S_0}$$

For our purposed conical and elliptical parachutes are same thing"

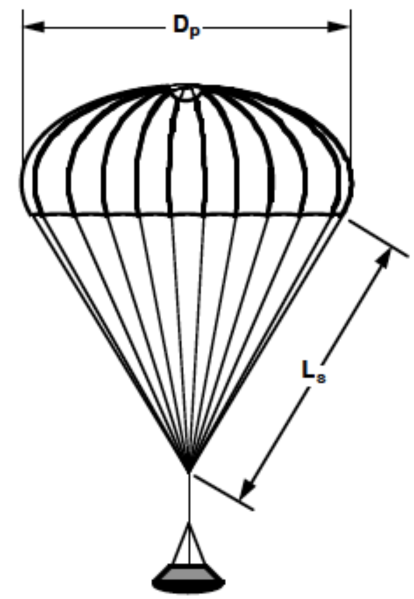
Projected Area, S_p

- 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

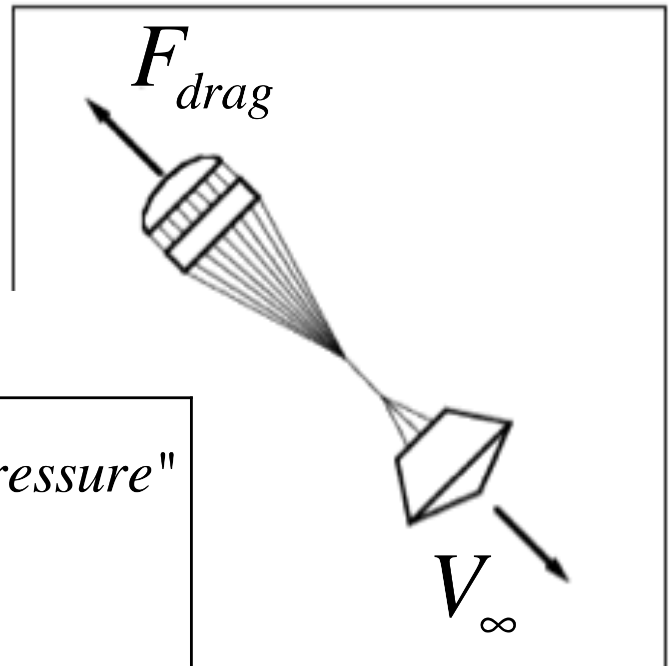
- Typically L_s/D_0 = 1 to 2

Basic Terminology (3)

Drag

Drag - Force parallel to the free-stream velocity,

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

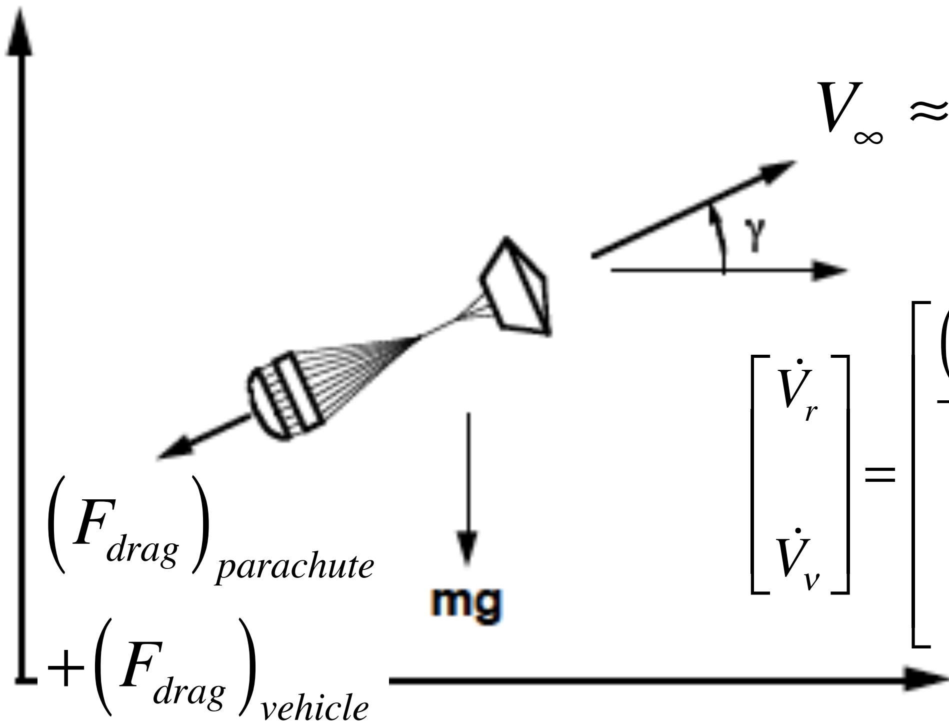


$$F_{drag} = \bar{q} \cdot C_D \cdot S_0$$

$$\rightarrow \begin{cases} \bar{q} = \frac{1}{2}\rho \cdot V_\infty^{\ 2} \text{ "incompressible dynamic pressure"} \\ C_D = \text{"drag coefficient"} \\ C_D \cdot S_0 = \text{"drag area"} \end{cases}$$

Basic Terminology (4)

In general, under parachute, 2-DOF equations of motion are ….
(ignore centrifugal & Coriolis forces)



$$V_\infty \approx \sqrt{V_r^2 + V_v^2}$$

$$\begin{bmatrix} \dot{V}_r \\ \dot{V}_v \end{bmatrix} = \begin{bmatrix} \dfrac{\left(F_{drag}\right)_{parachute} + \left(F_{drag}\right)_{vehicle}}{m} \cdot \sin\gamma - g \\ -\dfrac{\left(F_{drag}\right)_{parachute} + \left(F_{drag}\right)_{vehicle}}{m} \cdot \cos\gamma \end{bmatrix}$$

Vehicle decelerates very rapidly in horizontal direction

Basic Terminology (4)

"Terminal Velocity" .. Equilibrium velocity where parachute + vehicle are no longer accelerating

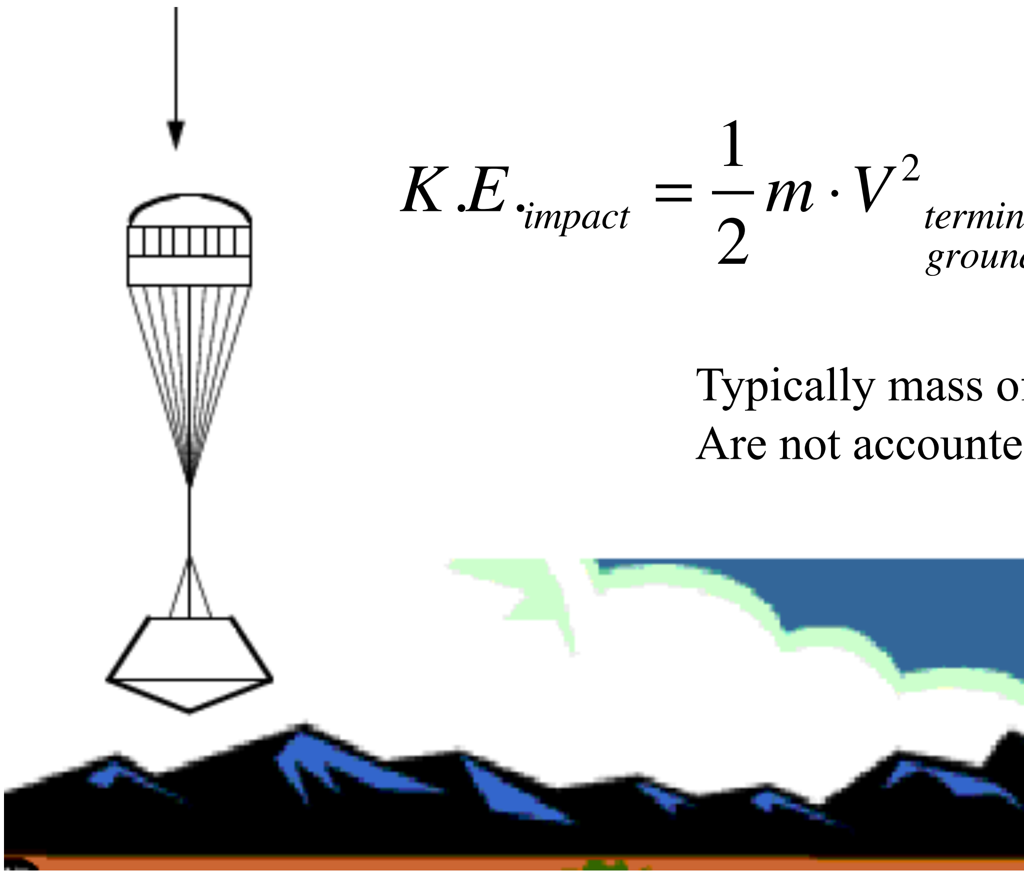
$$\begin{bmatrix} \dot{V}_r \\ \\ \dot{V}_v \end{bmatrix} \rightarrow \begin{bmatrix} 0 \\ \\ 0 \end{bmatrix} \rightarrow \begin{bmatrix} \gamma \approx 90^\circ \\ \left(F_{drag}\right)_{parachute} + \left(F_{drag}\right)_{vehicle} = m \cdot g \end{bmatrix}$$

$$\frac{1}{2}\rho \cdot V_{terminal}{}^2 \cdot \left[\left(C_D \cdot S_0\right)_{parachute} + \left(C_D \cdot S_0\right)_{vehicle}\right] = m \cdot g$$

$$V_{terminal} = \sqrt{\frac{2 \cdot m \cdot g}{\rho} - \left[\left(C_D \cdot S_0\right)_{parachute} + \left(C_D \cdot S_0\right)_{vehicle}\right]}$$

Basic Terminology (5)

"Impact Energy" .Kinetic Energy of "hard object" striking ground



$$K.E._{impact} = \frac{1}{2} m \cdot V^2_{\substack{terminal \\ ground}}$$

Typically mass of soft items like canopy
Are not accounted for in impact energy

Parachute Types

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

Guide Surface Parachute

We'll be using solid parachutes

Slotted Textile Parachutes

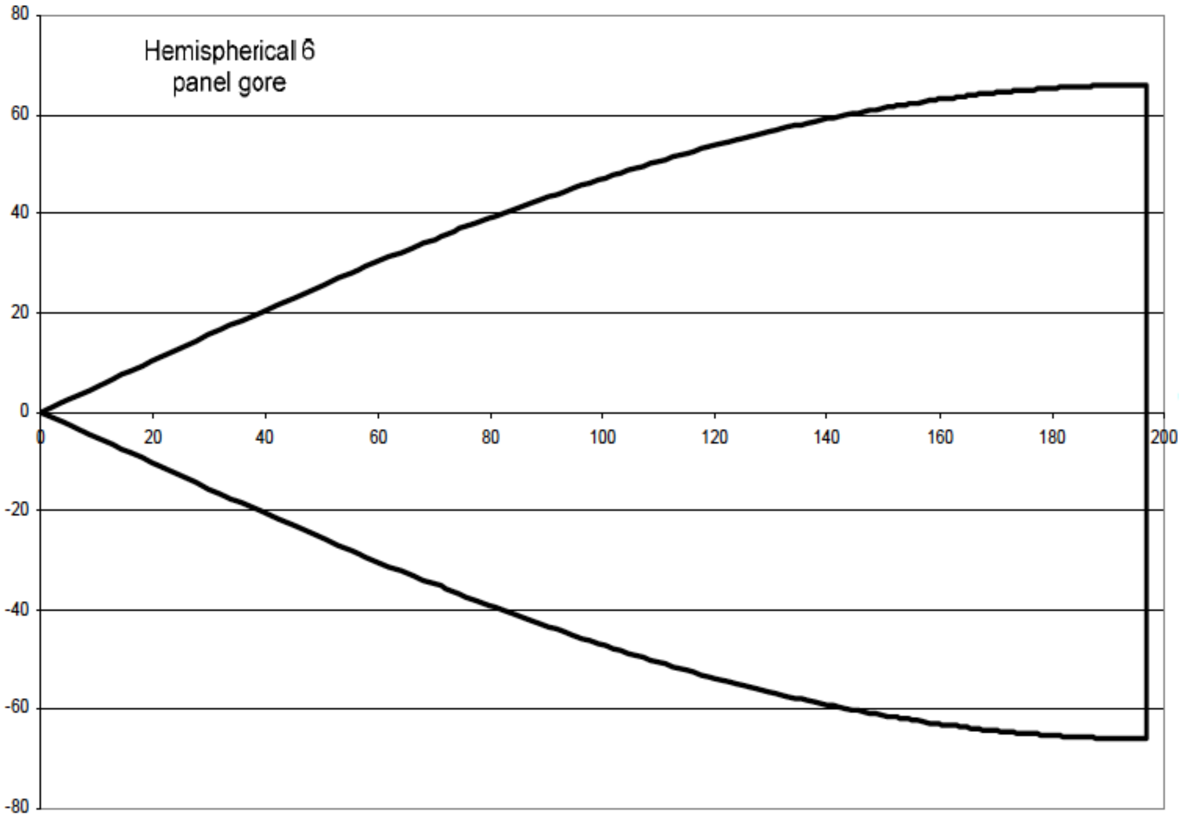
- Parachutes with canopies fabricated from either cloth materials or ribbons
- These types of parachutes have extensive openings through the canopy in addition to the vent
- Can be expensive to manufacture
- Most common parachute type used in planetary exploration missions

Galileo Ribbon Parachute

MER DGB Parachute

Parachute Shapes

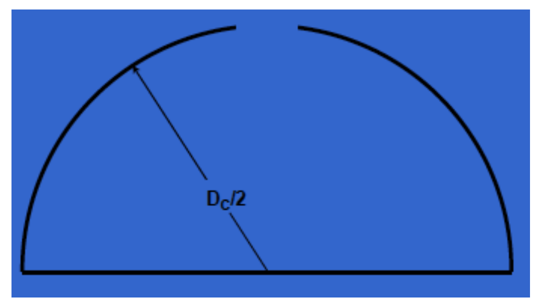
- **Hemispherical parachute:**
  - Deployed canopy takes on the shape of a hemisphere.
  - Three dimensional hemispherical shape divided into a number of 2-D panels, called gores



Gore pattern for 6 gore 252mm dia hemispherical parachute

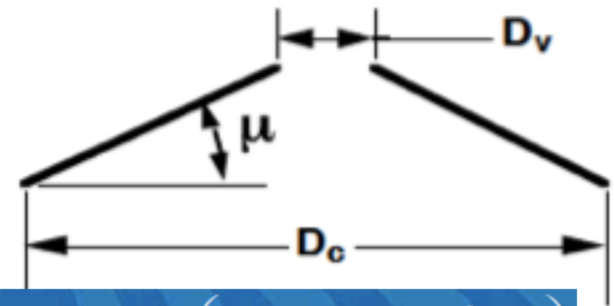
- Angle subtended on the left hand side of the pattern is 60 degrees

- When all six gores are joined they complete the 360 degree circle.



Parachute Shapes (2)

- **Conical Parachute**
  - 2-D Canopy shape in form of a triangle



- For conical parachutes $D_C = D_O\sqrt{\cos\mu}$ $\left(\mu = \text{cone } \frac{1}{2}\angle\right)$

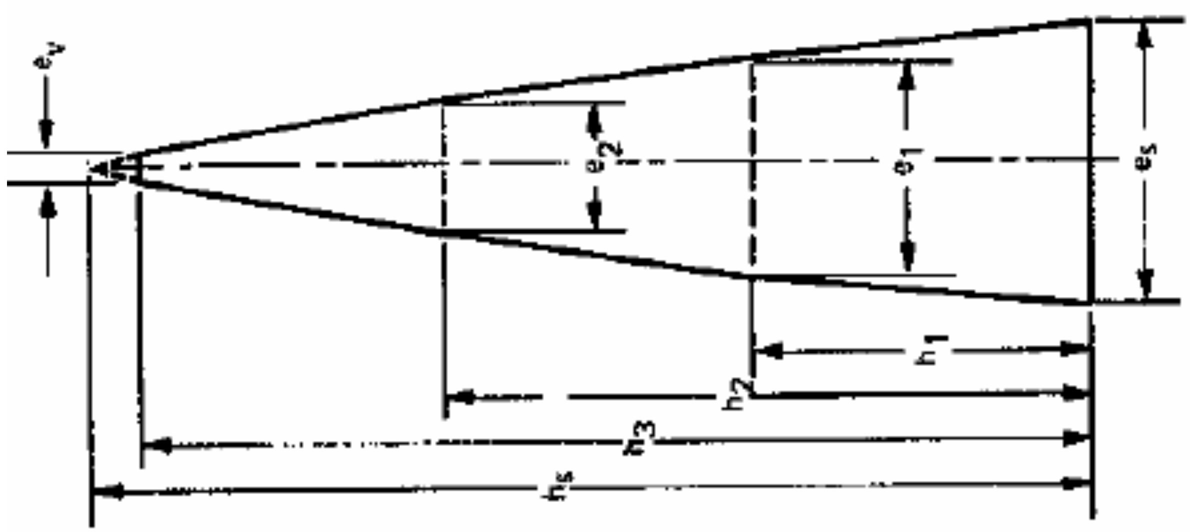
- For 10° conical parachute:
  - $D_O = 1.008\ D_C$

- For 20° conical parachute:
  - $D_O = 1.03\ D_C$

- For 30° conical parachute:
  - $D_O = 1.07\ D_C$

Parachute Shapes (3)

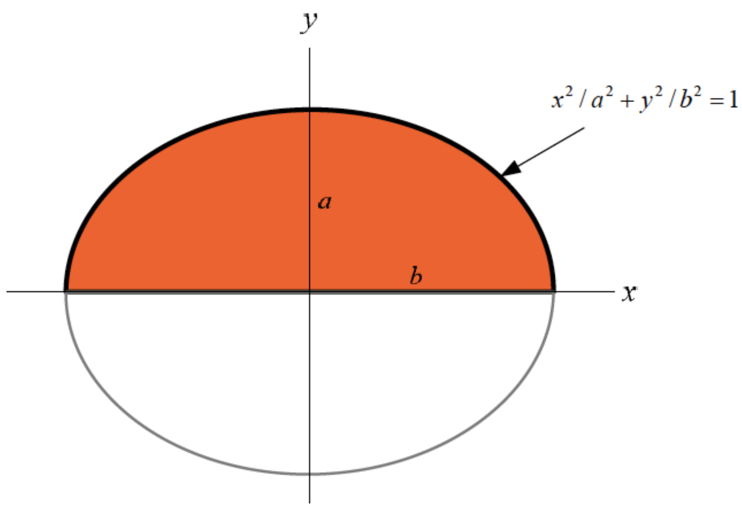
- **Conical Parachute Gore Shape**
  - 2-D Canopy shape in form of a triangle

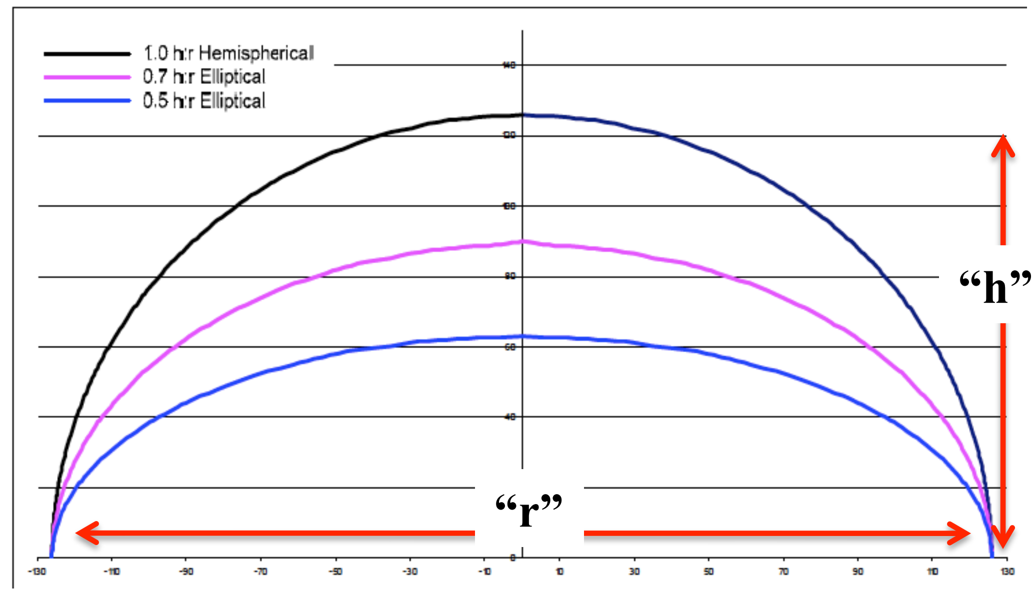


- ***Higher drag coefficient than hemispherical parachutes, but also less stability***

Parachute Shapes (4)

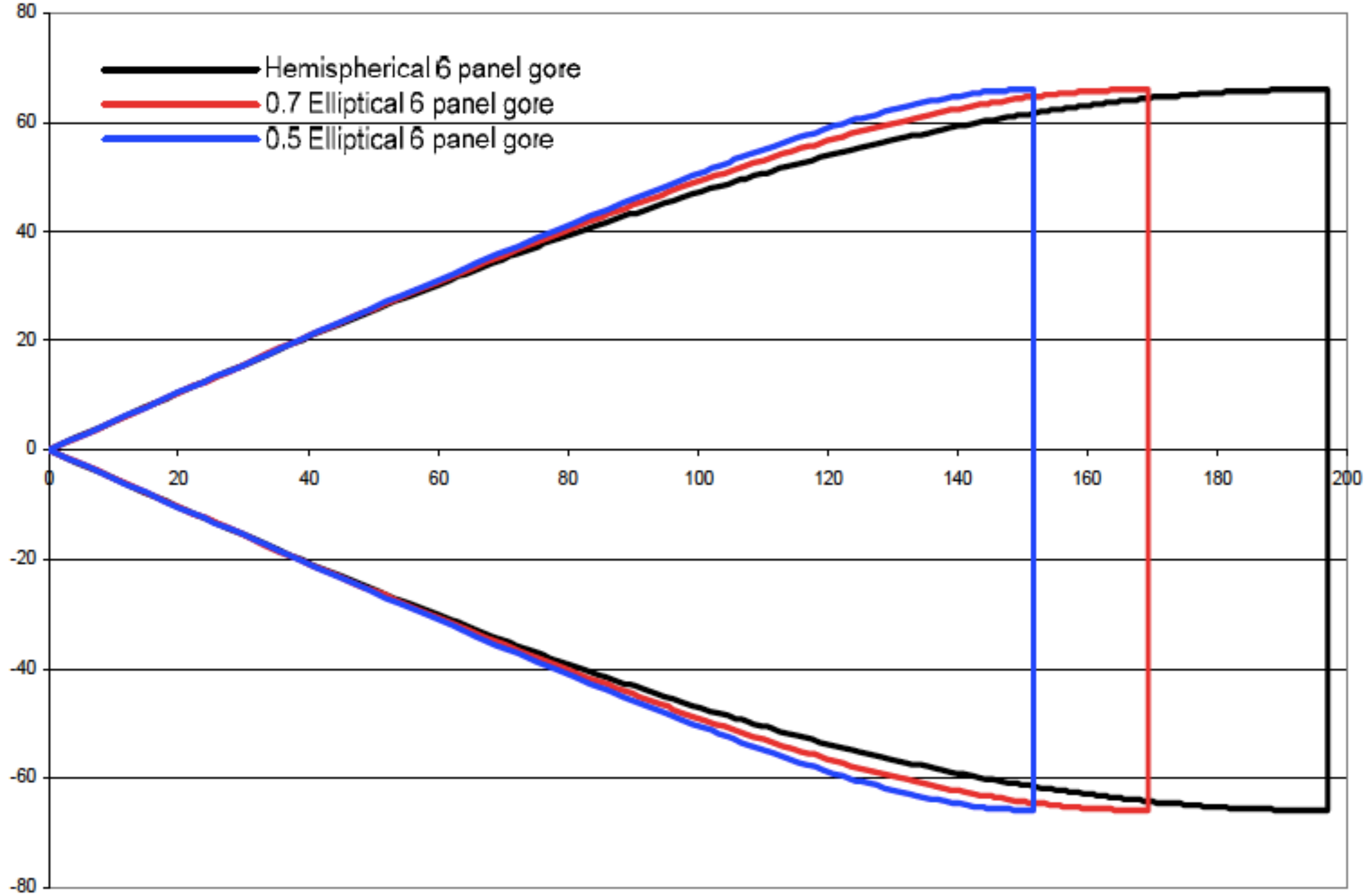
- **Elliptical parachute:**
  - Parachute where vertical axis is smaller than horizontal axis
  - A parachute with an elliptical canopy has essentially the same CD as a hemispherical parachute, but with less surface material





Canopy profile for different height / radius ratios

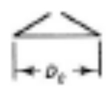
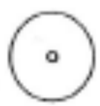
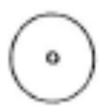
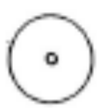
Parachute Shapes (5)



Comparison of gore shapes for different height : radius ratios

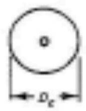
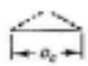
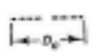
Parachute Types (2)

Solid Textile Parachutes

Type	Constructed Shape: Plan	Constructed Shape: Profile	$\frac{D_c}{D_o}$	Inflated Shape $\frac{D_p}{D_o}$	Drag Coef. C_{D_o} Range	Opening Load Factor C_X (Inf. Mass)	Average Angle of Oscillation	General Application
Flat Circular			1.00	.67 to .70	.75 to .80	~1.8	±10° to ±40°	Descent
Conical			.93 to .95	.70	.75 to .90	~1.8	±10° to ±30°	Descent
Bi-Conical			.90 to .95	.70	.75 to .92	~1.8	±10° to ±30°	Descent
Tri-Conical			.90 to .95	.70	.80 to .96	~1.8	±10° to ±20°	Descent
Hemispherical			.71	.66	.62 to .77	~1.6	±10° to ±15°	Descent

Parachute Types (3)

Slotted Textile Parachutes

Type	Constructed Shape: Plan	Constructed Shape: Profile	Constructed Shape: $\frac{D_c}{D_o}$	Inflated Shape: $\frac{D_p}{D_o}$	Drag Coef. C_{D_o} Range	Opening Load Factor C_X (Inf. Mass)	Average Angle of Oscillation	General Application
Flat Ribbon			1.00	.67	.45 to .50	~1.05	0° to ±3°	Drogue, Descent, Deceleration
Conical Ribbon			.95 to .97	.70	.50 to .55	~1.05	0° to ±3°	Descent, Deceleration
Conical Ribbon (Varied Porosity)			.97	.70	.55 to .65	1.05 to 1.30	0° to ±3°	Drogue, Descent, Deceleration
Ribbon (Hemisflo)			.62	.62	.30* to .46	1.00 to 1.30	±2°	Supersonic Drogue
Ringslot			1.00	.67 to .70	.56 to .65	~1.05	0° to ±5°	Extraction, Deceleration
Ringsail			1.16	.69	.75 to .90	~1.10	±5° to ±10°	Descent
Disc-Gap-Band			.73	.65	.52 to .58	~1.30	±10° to ±15°	Descent

*Supersonic

Example Calculation: Drogue Chute Terminal Velocity

$$h_{apogee} = h_{agl} + h_{\substack{launch \\ site}} =$$

$$(1609.23 + 240)_{meters} \simeq\approx 1850_{meters}$$

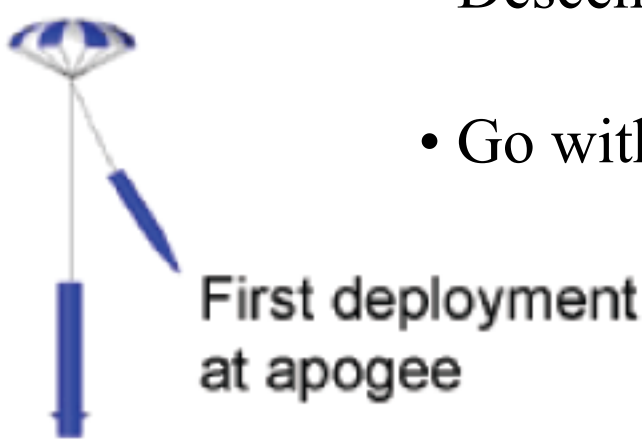
$$\rho_{apogee} = 1.0218_{\frac{kg}{m^3}}$$

$$g = \frac{\mu}{r^2} = \frac{3.9860044 \times 10^5{}_{\frac{km^3}{\sec^2}}}{(6371 + 1.85)^2{}_{km^2}} = 9.815_{\frac{m}{\sec^2}}$$

$$Maximum\ mass\ at\ apogee: m_{apogee} = m_{launch} - m_{fuel} = (14.188 - 1.76) = 12.428_{kg}$$

$$m_{apogee} \cdot g = 12.428 \cdot 9.815 = 121.975_{Nt}$$

Example Calculation: Drogue Chute Terminal Velocity (2)



- Descent rate under drogue, 50-100 ft/sec
- Go with minimum value ~ 15.24 m/sec (50 ft/sec)

"Vehicle Drag Area" ..
Rocket is broken into two pieces

$$\left(C_D \cdot S_0\right)_{vehicle} \approx 2\cdot\left[\left(C_D\right)_{rocket}\cdot\left(A_{ref}\right)_{rocket}\right] = \left(2\cdot 0.35\cdot 0.01589\right) \approx 0.0111_{m^2}$$

"Double up" nominal rocket drag area

Example Calculation: Drogue Chute Terminal Velocity (3)

- Parachute Drag Coefficient
- Elliptical Parachute .. Take median value

Solid Textile Parachutes

Type	Constructed Shape Plan	Constructed Shape Profile	$\frac{D_c}{D_o}$	Inflated Shape $\frac{D_p}{D_o}$	Drag Coef. C_{D_o} Range	Opening Load Factor C_X (Inf. Mass)	Average Angle of Oscillation	General Application
Conical			.93 to .95	.70	.75 to .90	~1.8	±10° to ±30°	Descent
Hemispherical			.71	.66	.62 to .77	~1.6	±10° to ±15°	Descent

$$\left(C_D\right)_{chute} \approx 0.76 \pm 0.115$$

Example Calculation: Drogue Chute Terminal Velocity (4)

- Calculate required chute area:

$$V_{terminal} = \sqrt{\frac{2 \cdot m \cdot g}{\rho} - \left[\left(C_D \cdot S_0 \right)_{parachute} + \left(C_D \cdot S_0 \right)_{vehicle} \right]}$$

$$\rightarrow \left(S_0 \right)_{parachute} = \frac{\dfrac{m \cdot g}{\frac{1}{2}\rho \cdot V_{terminal}{}^2} - \left(C_D \cdot S_0 \right)_{vehicle}}{\left(C_D \right)_{parachute}} =$$

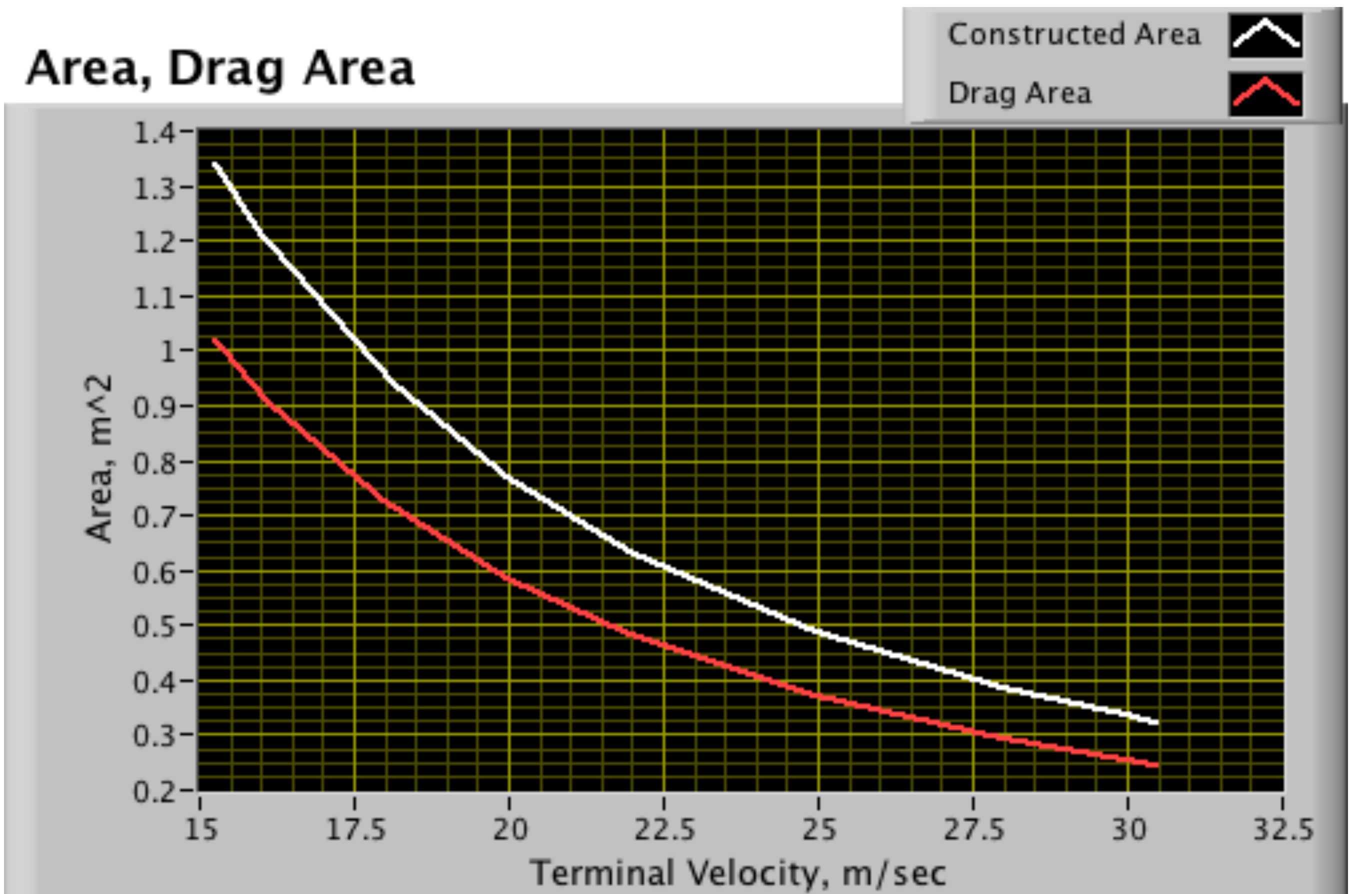
$$\frac{\dfrac{121.965}{\left(\frac{1}{2} 1.0218 \cdot 22.86^2 \right)} - 0.0111}{0.76}$$ **1.3378 m²**

$$D_0 = \sqrt{\frac{4 \cdot \left(S_0 \right)_{parachute}}{\pi}} =$$

$$\left(\frac{4 \cdot 1.33783}{\pi} \right)^{0.5} \frac{39.37}{12}$$ **= 4.28 ft**

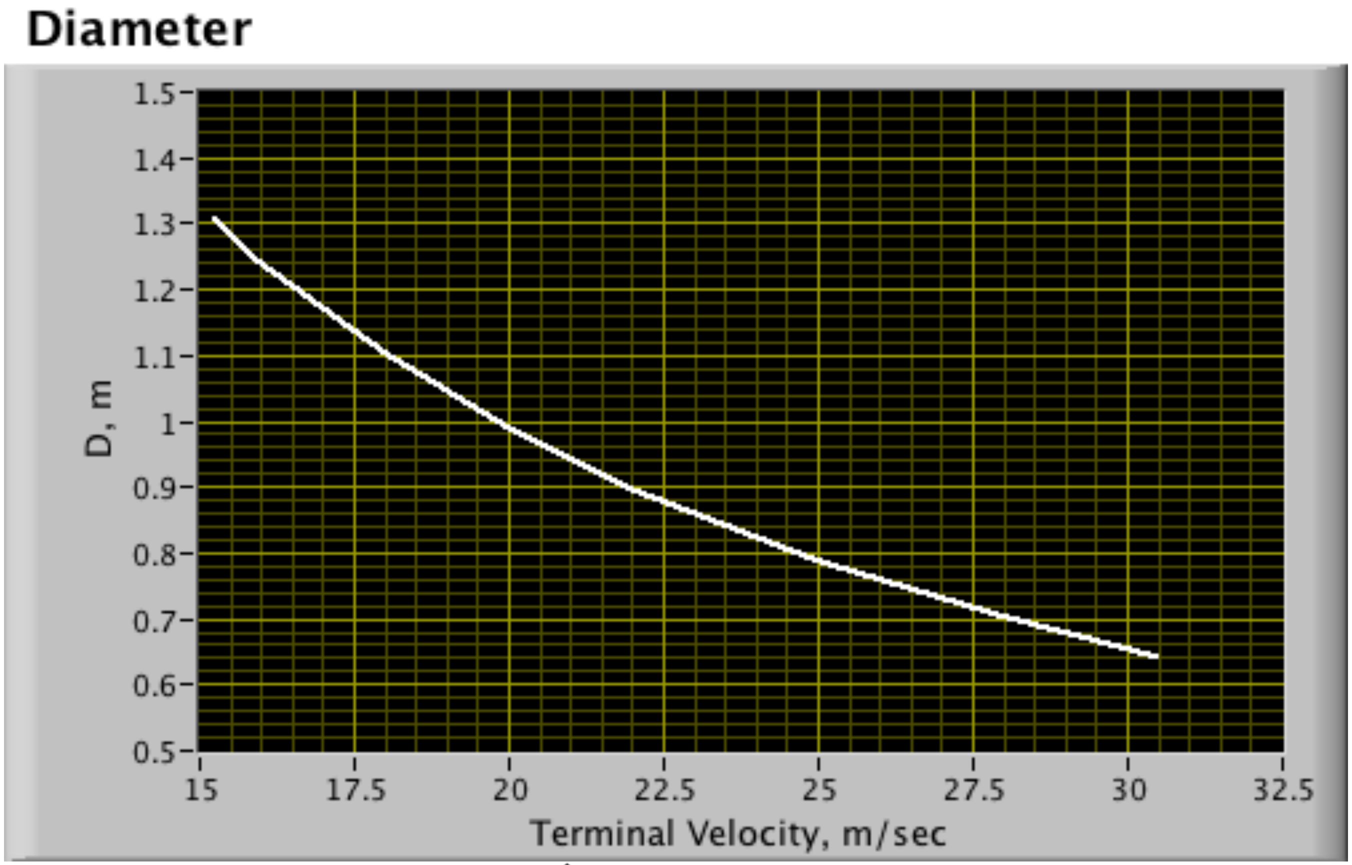
Example Calculation: Drogue Chute Terminal Velocity (5)

Drag Chute Areas Versus Terminal Velocity

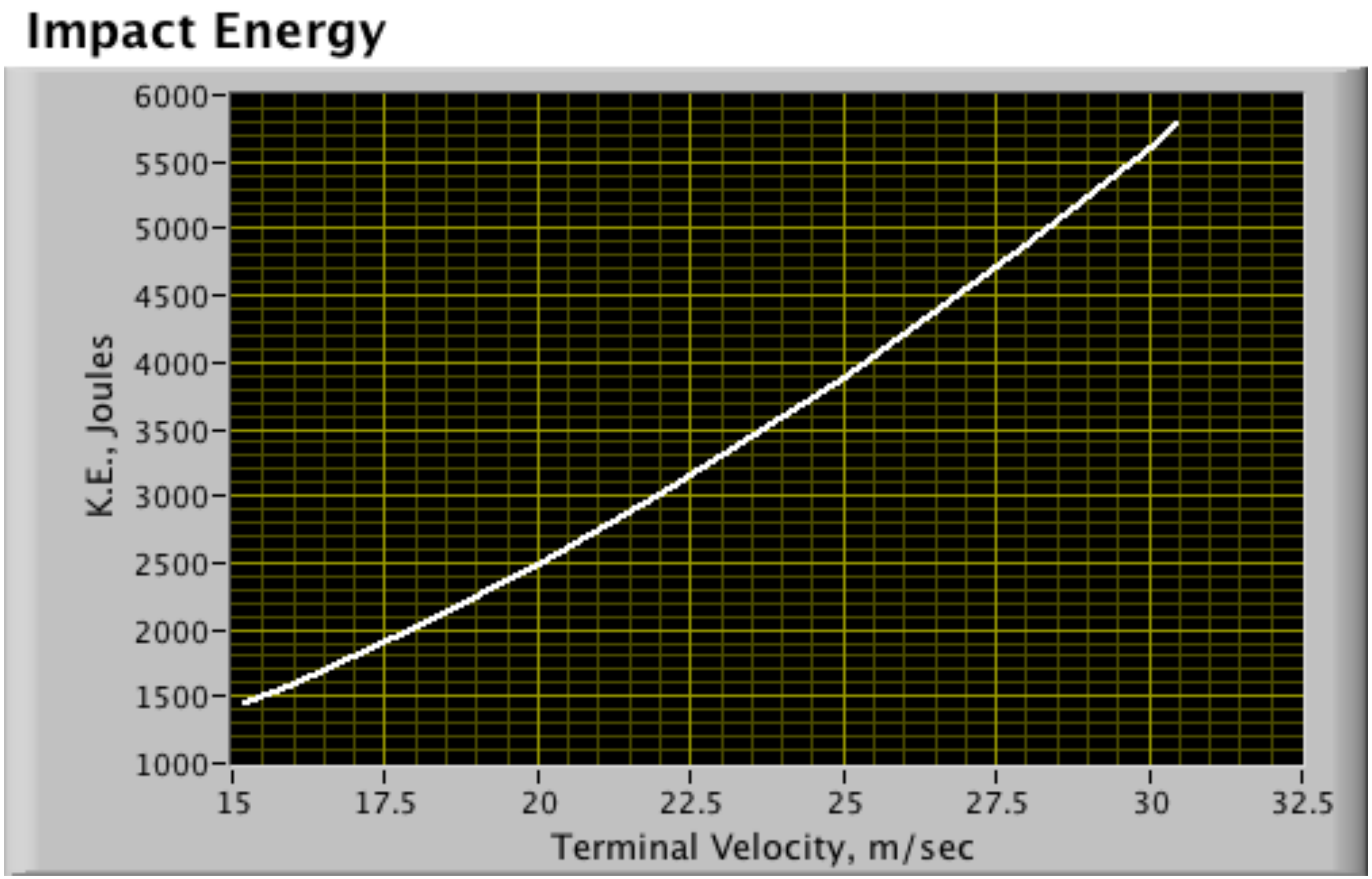


Example Calculation: Drogue Chute Terminal Velocity (6)

Drag Chute Diameter Versus Terminal Velocity



Example Calculation: Drogue Chute Terminal Velocity (7)



Parachute Opening Loads

Largest Tensile Load on Vehicle … often the Ultimate Design Load Driver

Accurate calculation of opening loads are critical for:

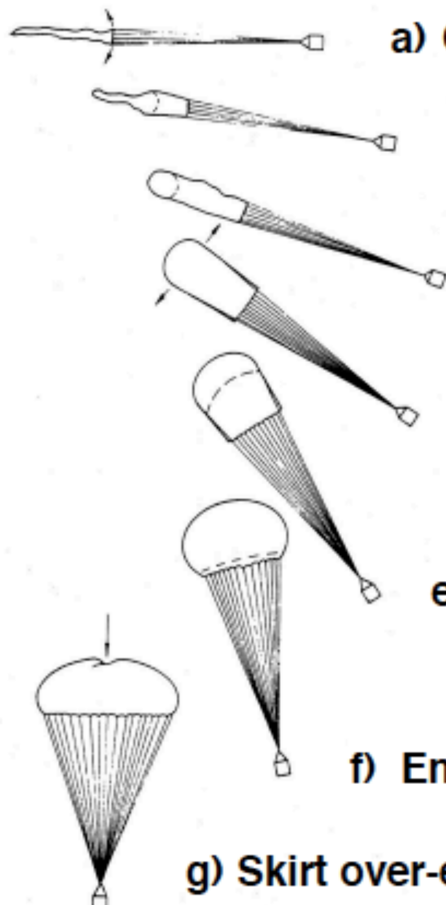
- Stress analysis of parachute
- Stress analysis of entry vehicle
- Calculating acceleration of payload
- Specification of on-board accelerometers

Three opening loads analysis methods are discussed here:

- Pflanz's Method ← *Design Tool*
- Inflation Curve Method ← *Verification Tool (Direct Simulation)*
- Apparent Mass Method

Parachute Opening Loads (2)

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

Parachute Opening Loads (3)

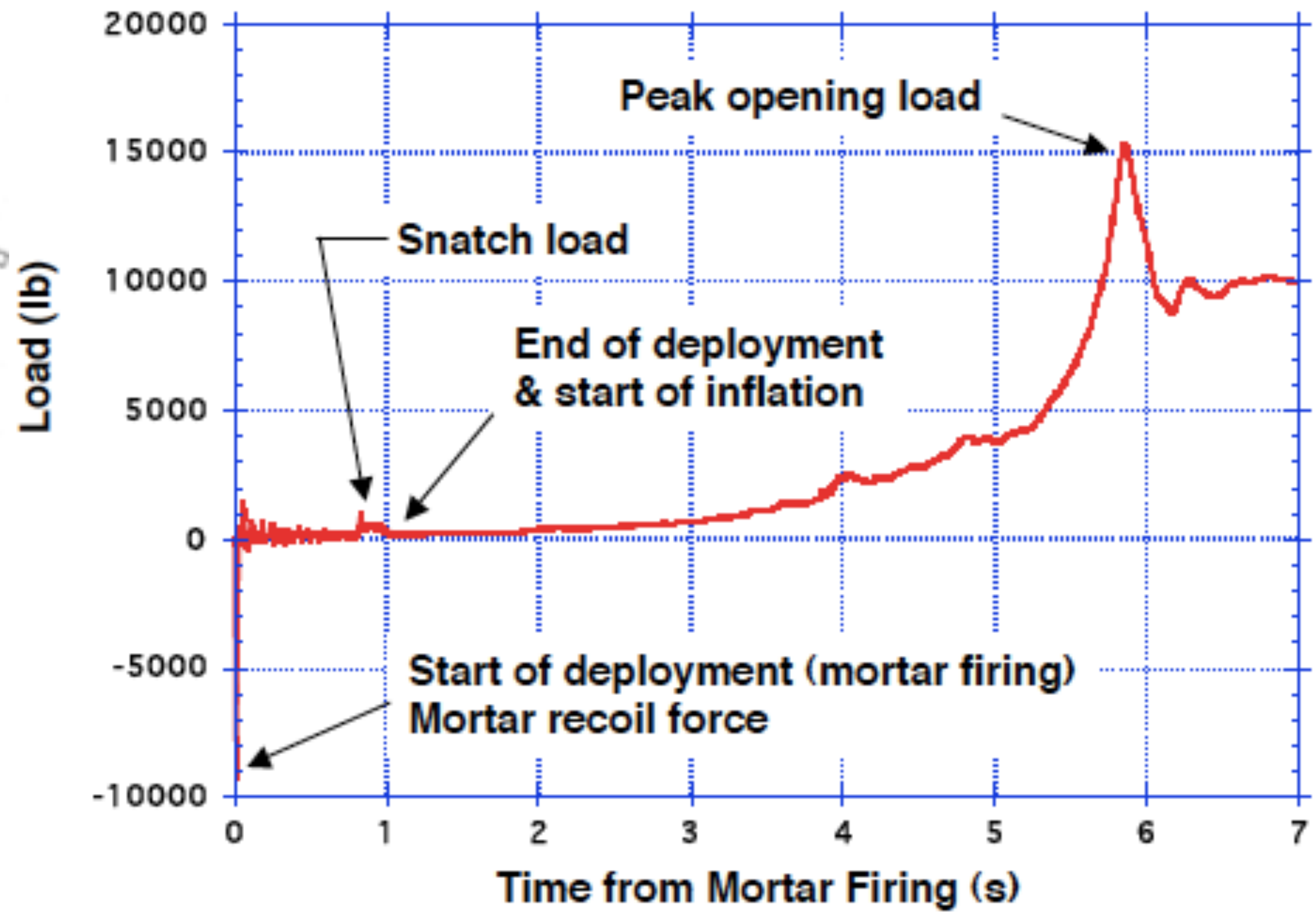
- At subsonic speeds, inflation is often modeled as occurring over a constant number of parachute diameters (i.e., multiples of D_0) for a given parachute type
- Parachute is "scooping" a given volume of air to inflate
- For the most part, experimental data supports this assumption
- Thus if inflation occurs at a constant velocity, V, the inflation time, t_{Inf}, can be estimated from:

$$t_{\inf} = n \cdot \frac{D_0}{V_1^{\,k}} \rightarrow \begin{array}{c} n = canopy\ fill\ constant \\ k = decceleration\ exponent \end{array}$$

where n depends on the parachute type and geometry (typically $n_{Inf} \sim 6$ 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

Parachute Opening Loads (4)



Parachute Opening Loads (5)

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

Parachute Opening Loads (6)

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

Pflanz's Method

- **Pflanz' (1942):**
  - -introduced analytical functions for the drag area

- **Simple, frst-order, design book type method**
  - -Requires least knowledge of the system compared to other methods
  - -Assumes no gravity acceleration – limits application to shallow fight path angles at parachute deployment
  - - Neglects entry vehicle drag
  - - Yields only peak opening load
  - - Allows for finite mass approximation

- **Doherr (2003) extended method to account for gravity and arbitrary fight path angles**

Pflanz's Method (2)

$$F_{\max} = \bar{q}_1 \cdot \left(C_D \cdot S_0\right) \cdot C_x \cdot X_1$$

where $X_1 = f(A, n)$ and $$A_{ballistic} = \frac{2 \cdot m}{\left(C_D \cdot S_0\right) \cdot \rho_1 \cdot V_1 \cdot t_{infl}}$$

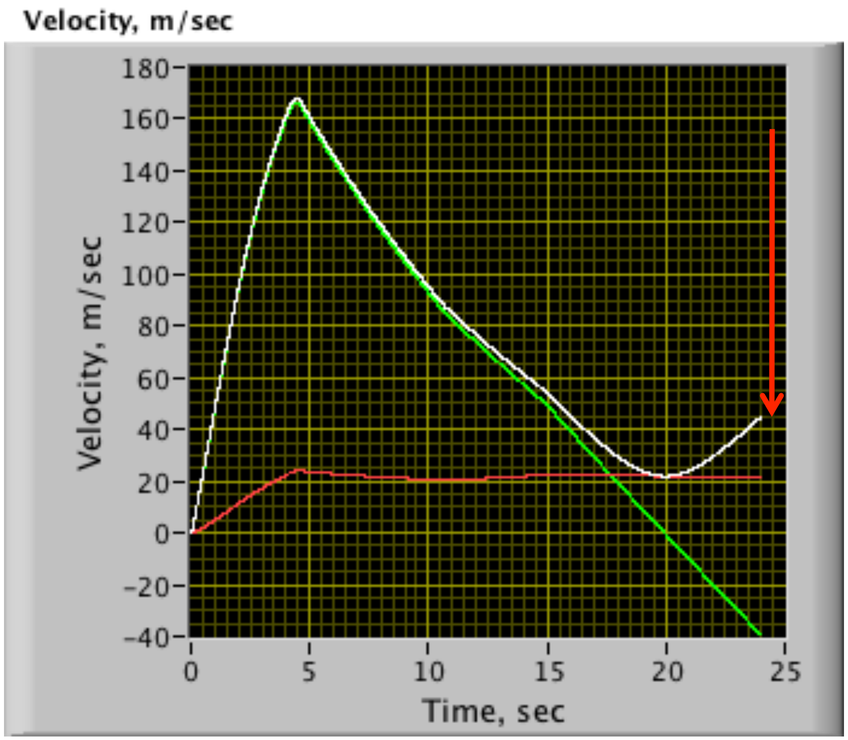
Variables definition

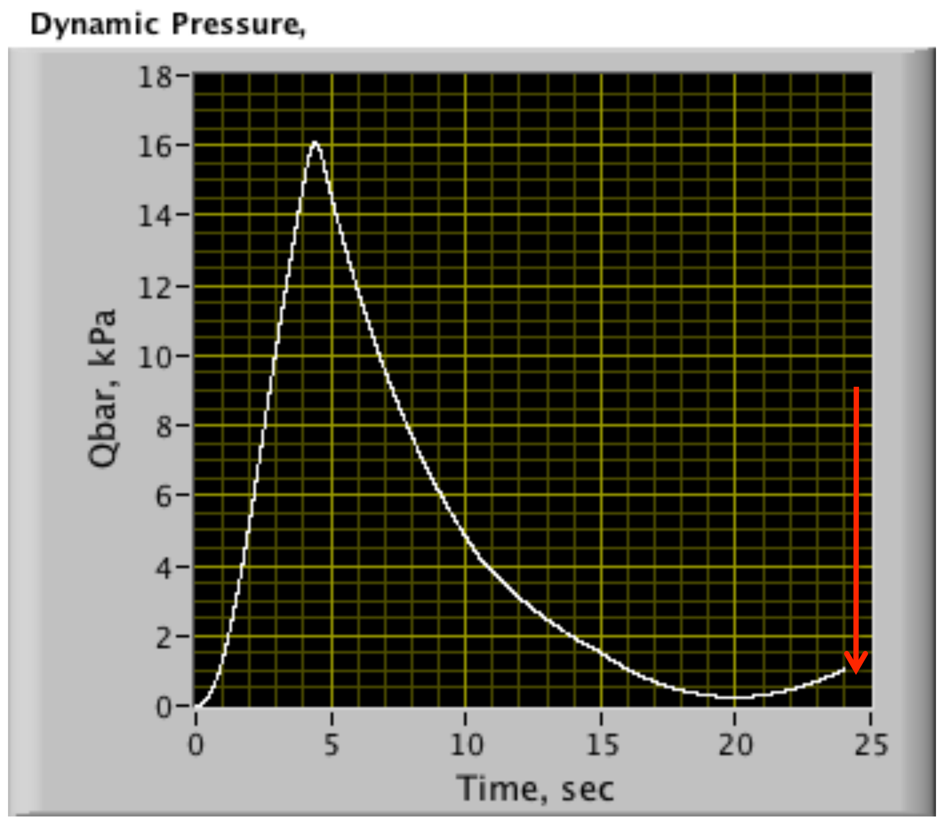
- F_{peak} - peak opening load
- q_1 - dynamic pressure at start of inflation
- C_{D0} - parachute full-open drag coefficient
- S_0 - parachute nominal area
- C_X - opening load factor (from test data or tables in pages 24 through 26)
- X_1 - force reduction factor accounting for deceleration during inflation (see figure 5-51 of Knacke: Parachute Recovery Systems Design Manual) *(finite mass inflation approximation)*
- 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
- Δ - atmospheric density
- V_1 - velocity at start of inflation
- t_{inf} - inflation time (see inflation section for guidelines)

Pflanz's Method (3)

- **Drogue Chute Opening Loads**

- **Assume "opening load "velocity at 4 seconds past apogee, ~45 m/sec**
- **Dynamic Pressure ~ 1.1 kPa**
- **Cx ~ 1.7**





Pflanz's Method (4)

Subsonic Inflation time …

$$t_{\text{inf}} = n \cdot \frac{D_0}{V_{open}^{\;k}} \rightarrow \begin{array}{l} n = canopy\ fill\ constant \\ k = decceleration\ exponent \end{array}$$

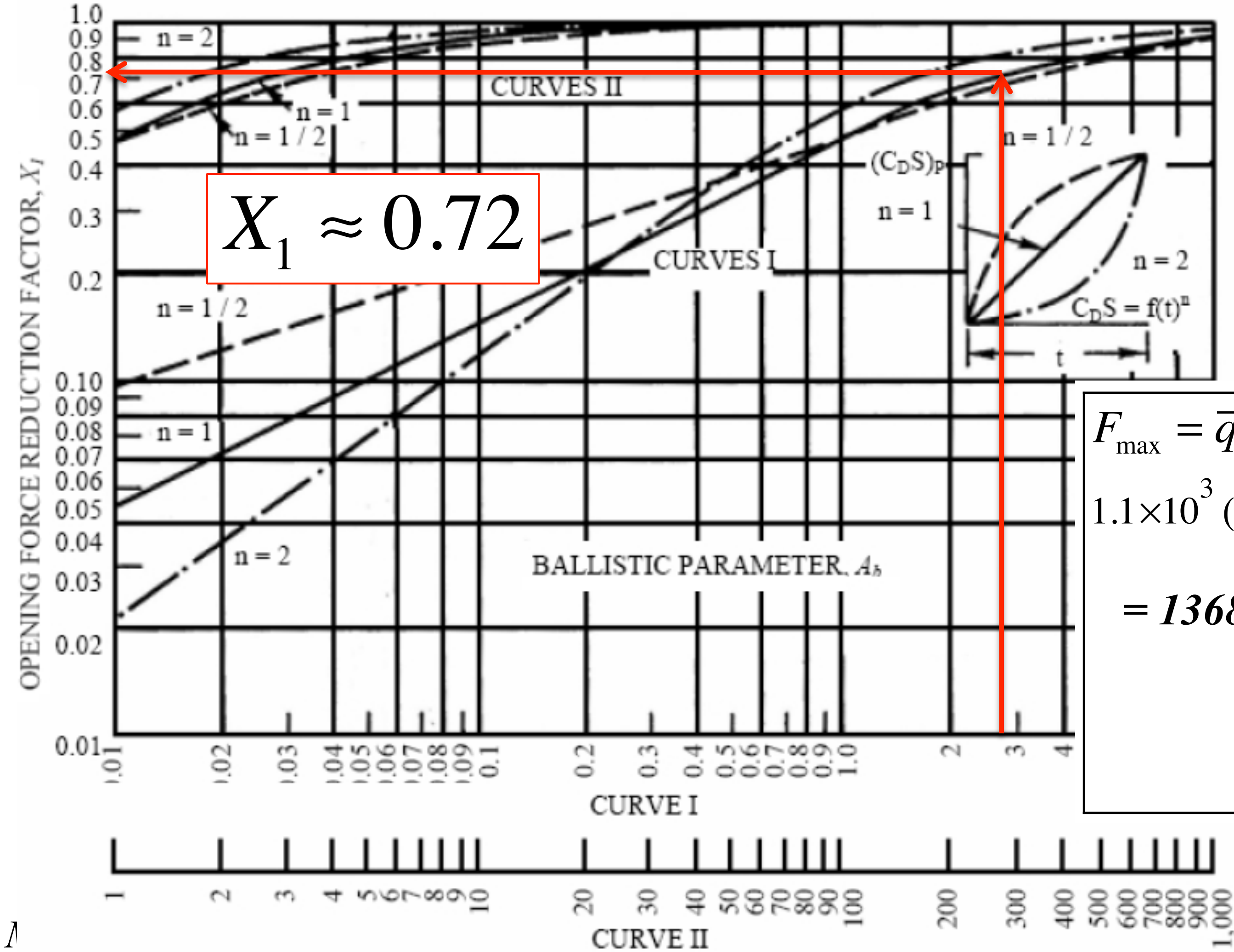
$$elliptical\ parachute \rightarrow \begin{array}{l} n \approx 4 \\ k \approx 0.85 \end{array}$$

$$t_{\text{inf}} = \frac{4\left(1.3378\,\frac{4}{\pi}\right)^{0.5}}{45^{0.85}} = 0.2053\ \text{sec}$$

$$A_{ballistic} = \frac{2 \cdot m}{\left(C_D \cdot S_0\right) \cdot \rho_1 \cdot V_1 \cdot t_{infl}} = \frac{2 \cdot 12.428}{(0.76 \cdot 1.3378)\ 1.0218 \cdot 45.0 \cdot 0.2053} = 2.590$$

Pflanz's Method (5)

$$A_{ballistic} = \frac{2 \cdot m}{\left(C_D \cdot S_0\right) \cdot \rho_1 \cdot V_1 \cdot t_{infl}} = 2.590$$



$$F_{max} = \bar{q}_1 \cdot \left(C_D \cdot S_0\right) \cdot C_x \cdot X_1 =$$

$$1.1 \times 10^3 \left(0.76 \cdot 1.3378\right) 1.7 \cdot 0.72$$

= 1368.9 Nt (307.7 lbf)

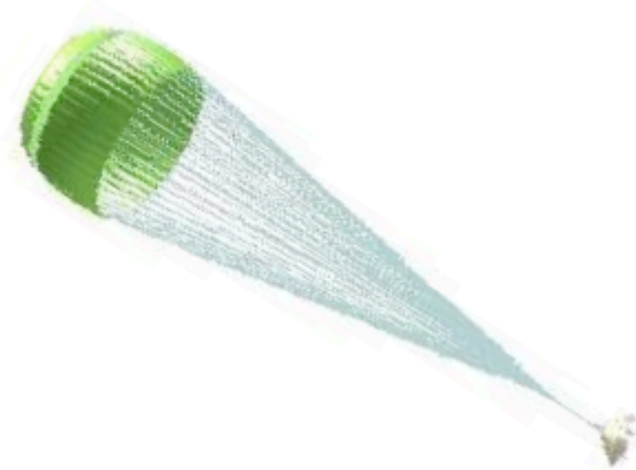
Pflanz's Method (6)

Pflanz's Method Example (2)

MER A - Spirit

q_1 = 729 Pa
C_{D0} = 0.400 (at M = 1.75)
D_0 = 14.1 m
S_0 = 156 m^2
C_X = 1.45

m_{EV} = 827 kg
Δ = 0.00863 kg/m^3
V_1 = 411 m/s
t_{inf} = 0.282 s (from previous discussion on supersonic inflation)



A = 26.5
n = 2 (for DGB parachutes)
X_1 = 0.98 (i.e., very close to infinite mass inflation!)

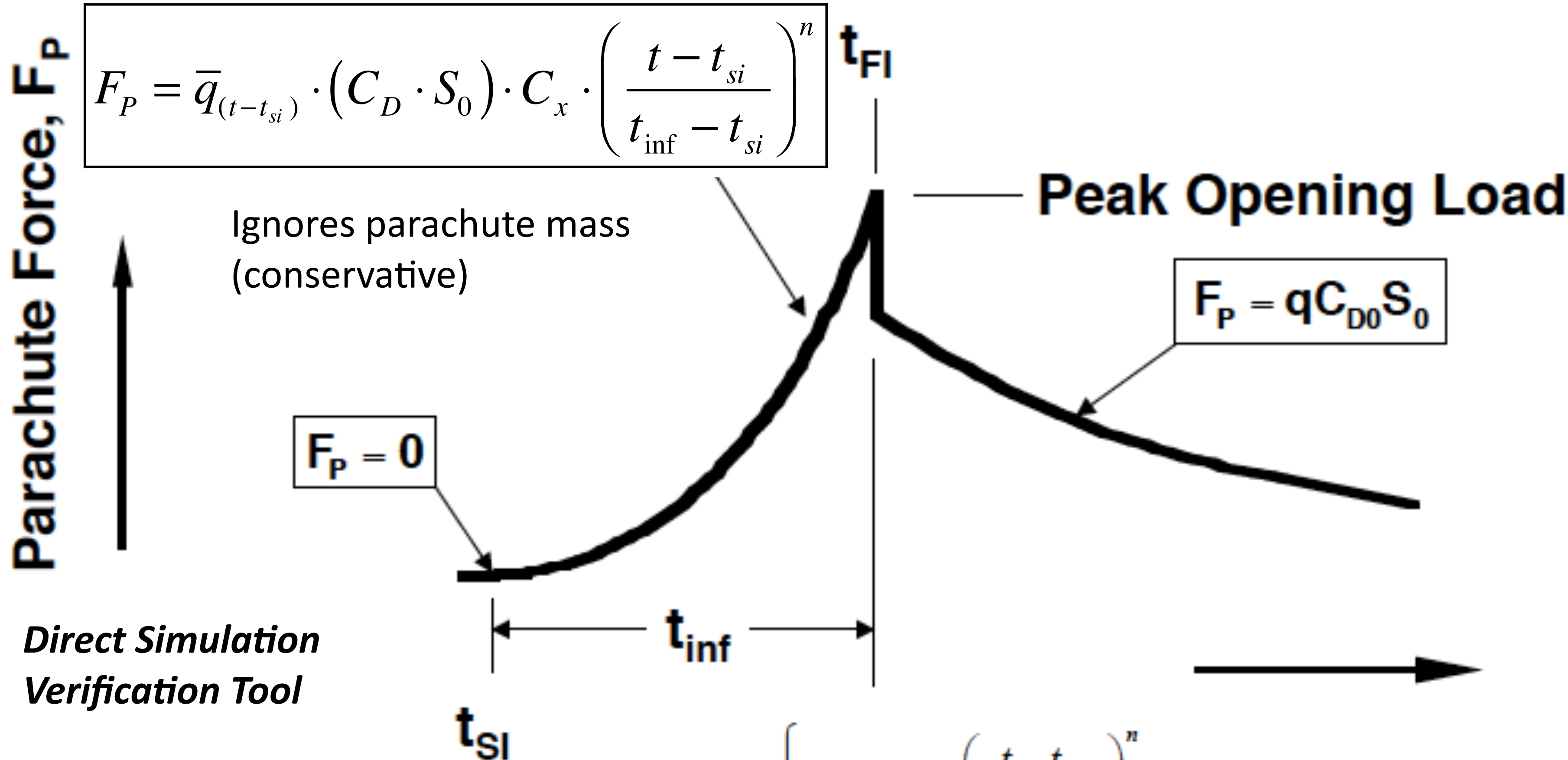
Δ

F_{peak} = 64,641 N (within 10% of best estimate)

Inflation Curve Method

$$F_P = \bar{q}_{(t-t_{si})} \cdot \left(C_D \cdot S_0\right) \cdot C_x \cdot \left(\frac{t - t_{si}}{t_{\inf} - t_{si}}\right)^n$$

Ignores parachute mass (conservative)



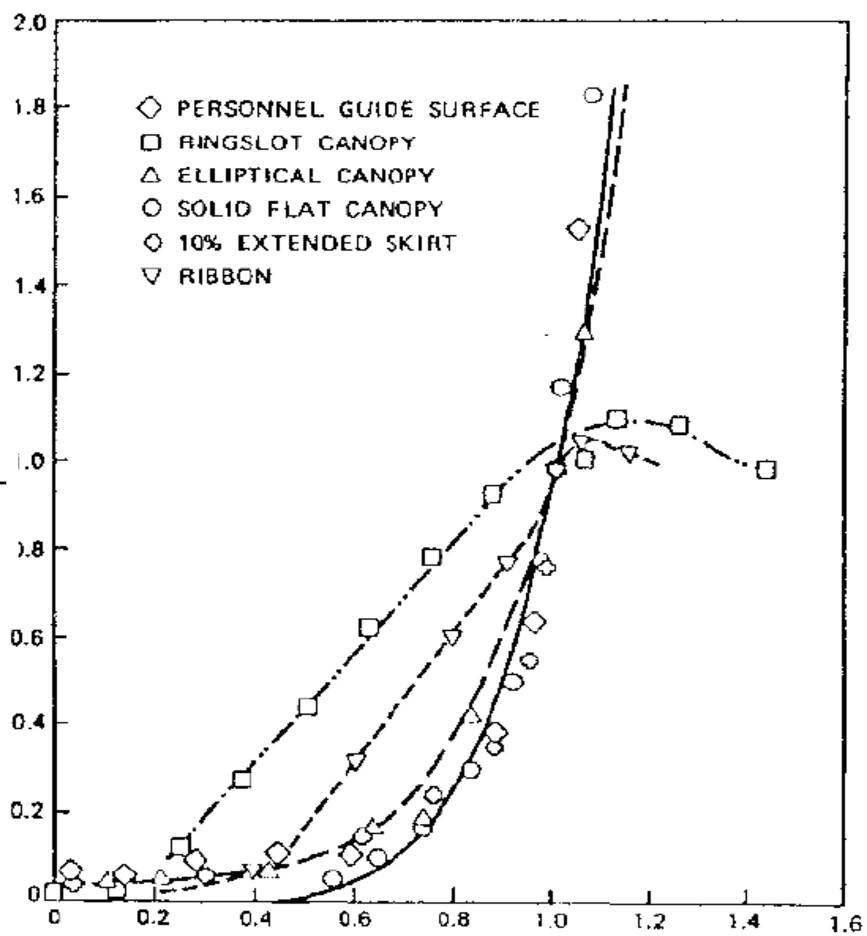
Direct Simulation Verification Tool

Allowing for parachute mass

$$F_p = \begin{cases} qC_{D,0}S_0C_x\left(\frac{t-t_{SI}}{t_{FI}-t_{SI}}\right)^n + m_p g \sin\gamma & t_{SI} \le t \le t_{FI} \\ qC_{D,0}S_0 + m_p g \sin\gamma & t > t_{FI} \end{cases}$$

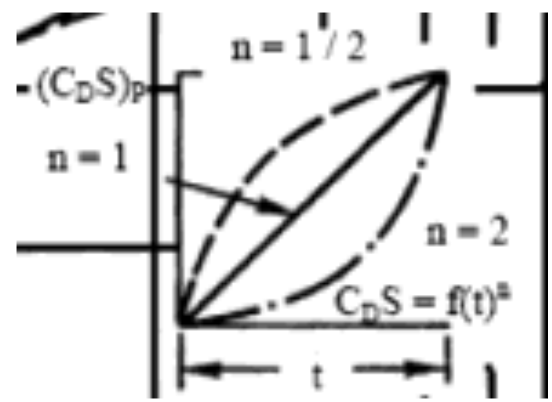
Inflation Curve Method (2)

$$\frac{\left(C_D \cdot S_0\right)_t}{\left(C_D \cdot S_0\right)_{steady}}$$



$$\left(\frac{t - t_{si}}{t_{\inf} - t_{si}}\right)$$

Inflation Data from Doherr




Questions??