Parachute Seminar

3rd International Planetary Probe Workshop

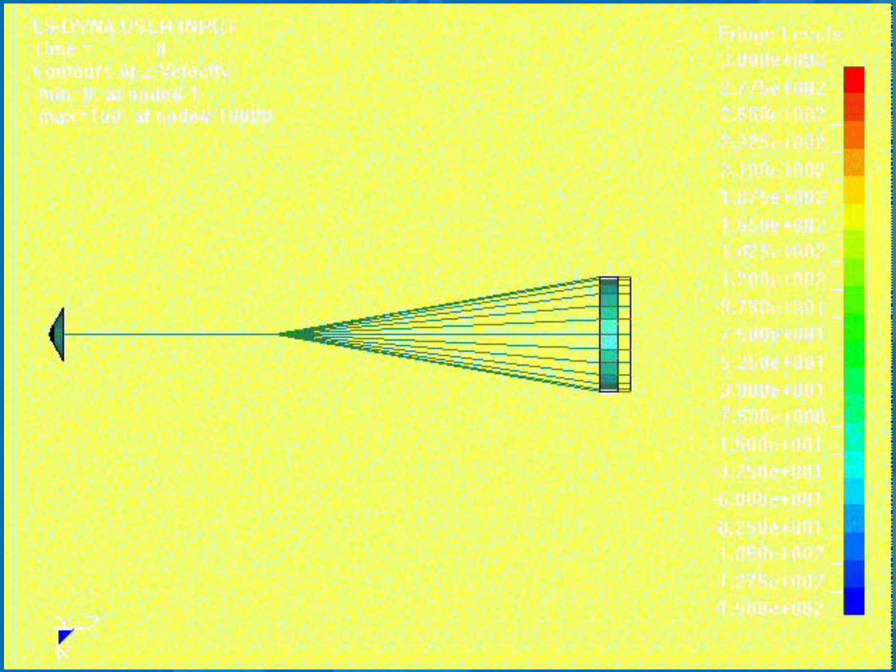
AERODYNAMICS 1 (Steady)

Steve Lingard
Vorticity Ltd
steve.lingard@vorticity-systems.com

Aerodynamics of Parachutes

- Primary role of a parachute is to produce drag
- Bluff, porous, flexible body
- Unsteady, separated, compressible flow
- Non-uniform upstream conditions
- Solution to all these problems beyond state of the art
- First simplification is to assume steady, incompressible flow

Steady Flow?



- Even “steady” parachute forces are really a time averaged

orticity

Parameters significant to parachute forces and moments

Quantity	Symbol	Dimensions M	L	T
Dependent Variable				
aerodynamic force	R	1	1	-2
aerodynamic moment	M	1	2	-2
Parachute Parameters				
nominal diameter	Do	0	1	0
line length	Ls	0	1	0
design ratios	Rd	0	0	0
mass of payload	ms	1	0	0
canopy nominal porosity	c	0	1	-1
canopy geometric porosity	λg	0	0	0
Fluid Parameters				
fluid density	ρ	1	-3	0
viscosity	μ	1	-1	-1
velocity of sound	a	0	1	-1
State Variables				
system velocity	V	0	1	-1
External Parameters				
gravity	g	0	1	-2
time	t	0	0	1

Important Dimensionless Parameters

Resultant force coefficient $\frac{R}{\rho V^2 D_o^2}$ and moment coefficient are $\frac{M}{\rho V^2 D_o^3}$

functions of nine dimensionless groups:

canopy design ratios: *Rd*

Mach number: $\frac{V}{a}$

fineness ratio: $\frac{L_s}{D_o}$

mass ratio: $\frac{m_s}{\rho D_o^3}$

Reynolds number: $\frac{\rho V D_o}{\mu}$

Froude number: $\frac{V^2}{g D_o}$

effective porosity: $\frac{c}{V}$

dimensionless time: $\frac{V t}{D_o}$

geometric porosity: λ_g

orticity

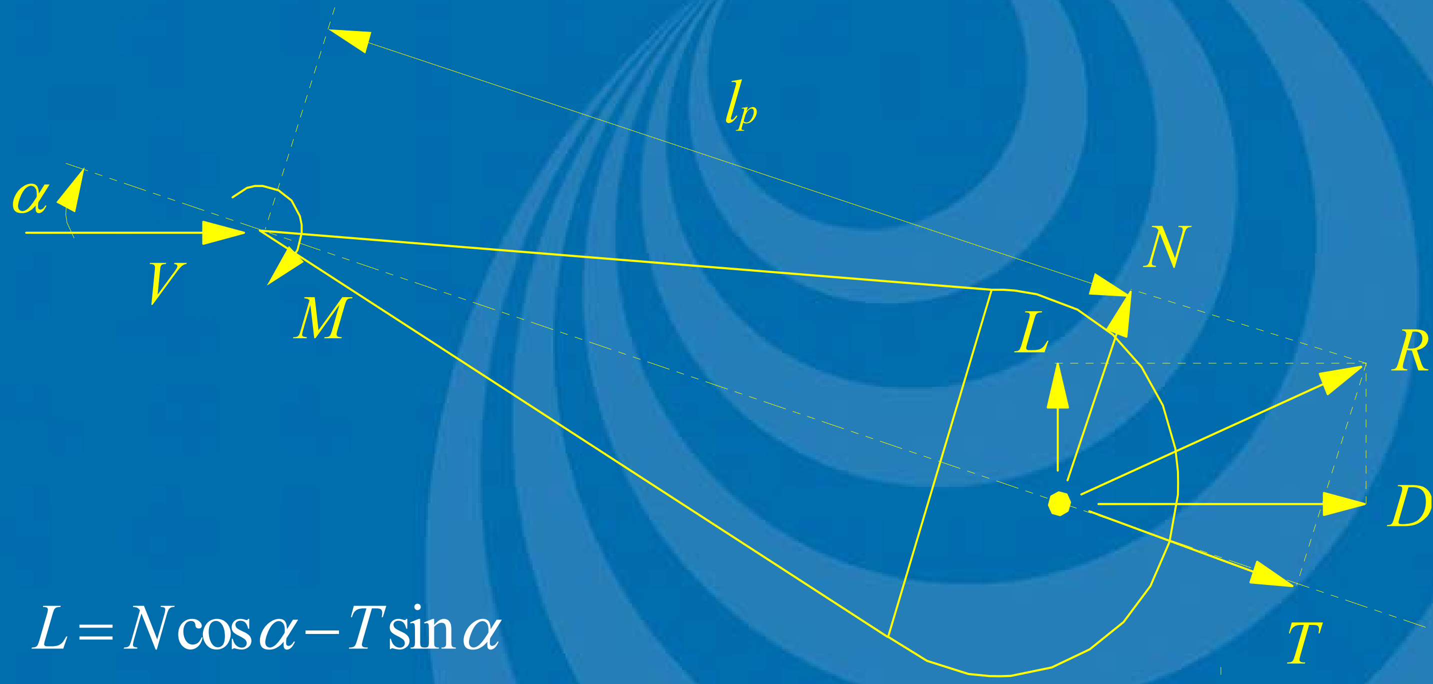
Body Forces

- Forces only generated by:

  pressure distribution p

  shear stress distribution τ

Aerodynamic Forces on a Parachute



$$L = N\cos\alpha - T\sin\alpha$$

$$D = N\sin\alpha + T\cos\alpha$$

$$N = L\cos\alpha + D\sin\alpha$$

$$T = D\cos\alpha - L\sin\alpha$$

orticity

Force Coefficients

Lift coefficient $C_L = \frac{L}{qS_o}$

Drag coefficient $C_D = \frac{D}{qS_o}$

Normal force coefficient $C_N = \frac{N}{qS_o}$

Tangent force coefficient $C_T = \frac{T}{qS_o}$

Moment coefficient $C_M = \frac{M}{qS_oD_o}$

q = dynamic pressure = $\frac{1}{2}\rho V^2$ S_o = nominal area $= \frac{\pi D_o^{\,2}}{4}$

orticity

Static Stability

$$C_M \approx -\frac{C_N l_p}{D_0}$$

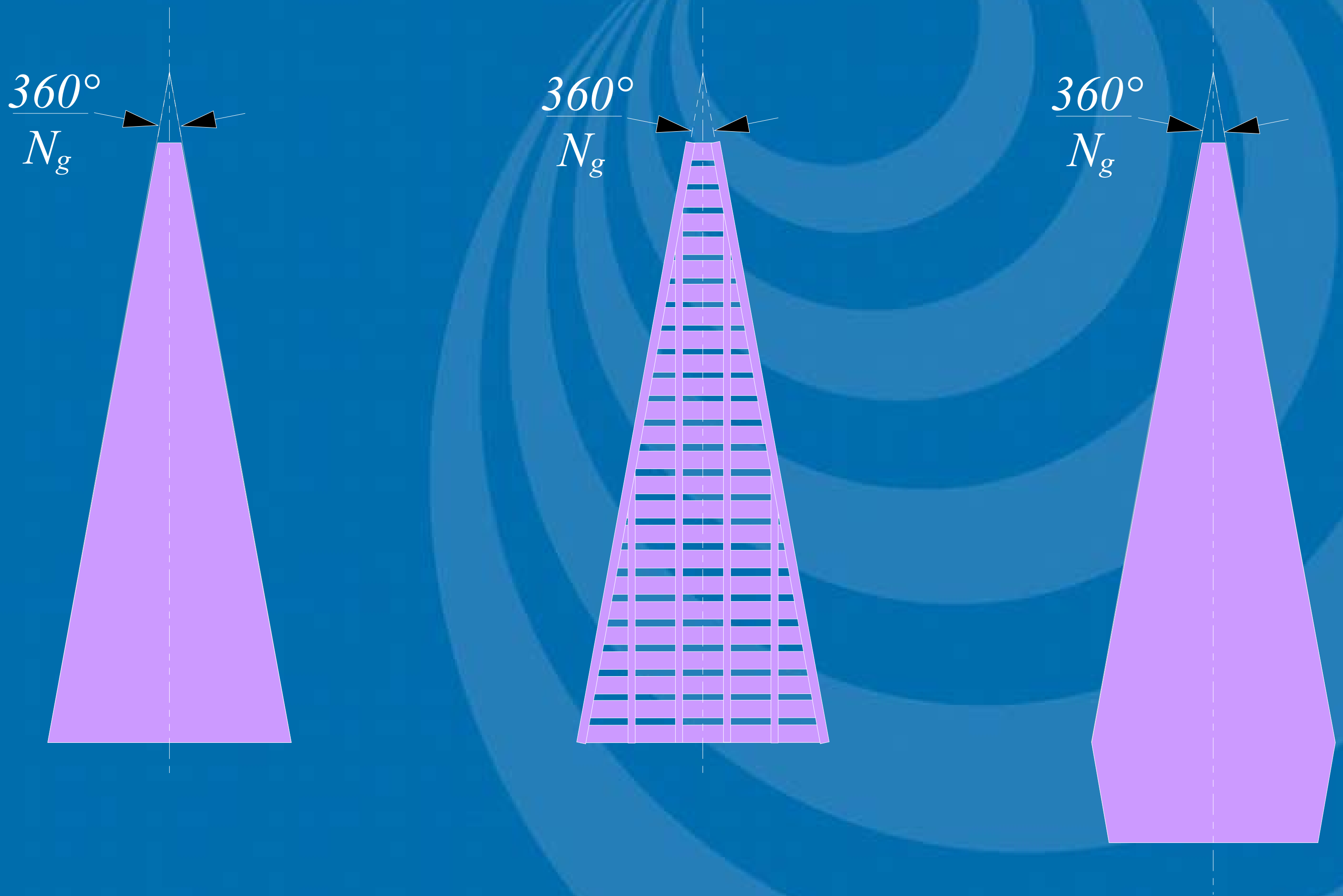
For static stability

$$C_N = 0 \text{ and } \frac{dC_N}{d\alpha} > 0 \text{ or}$$

$$C_M = 0 \text{ and } \frac{dC_M}{d\alpha} < 0$$

orticity

Diagram of Typical Parachute Gore Shapes

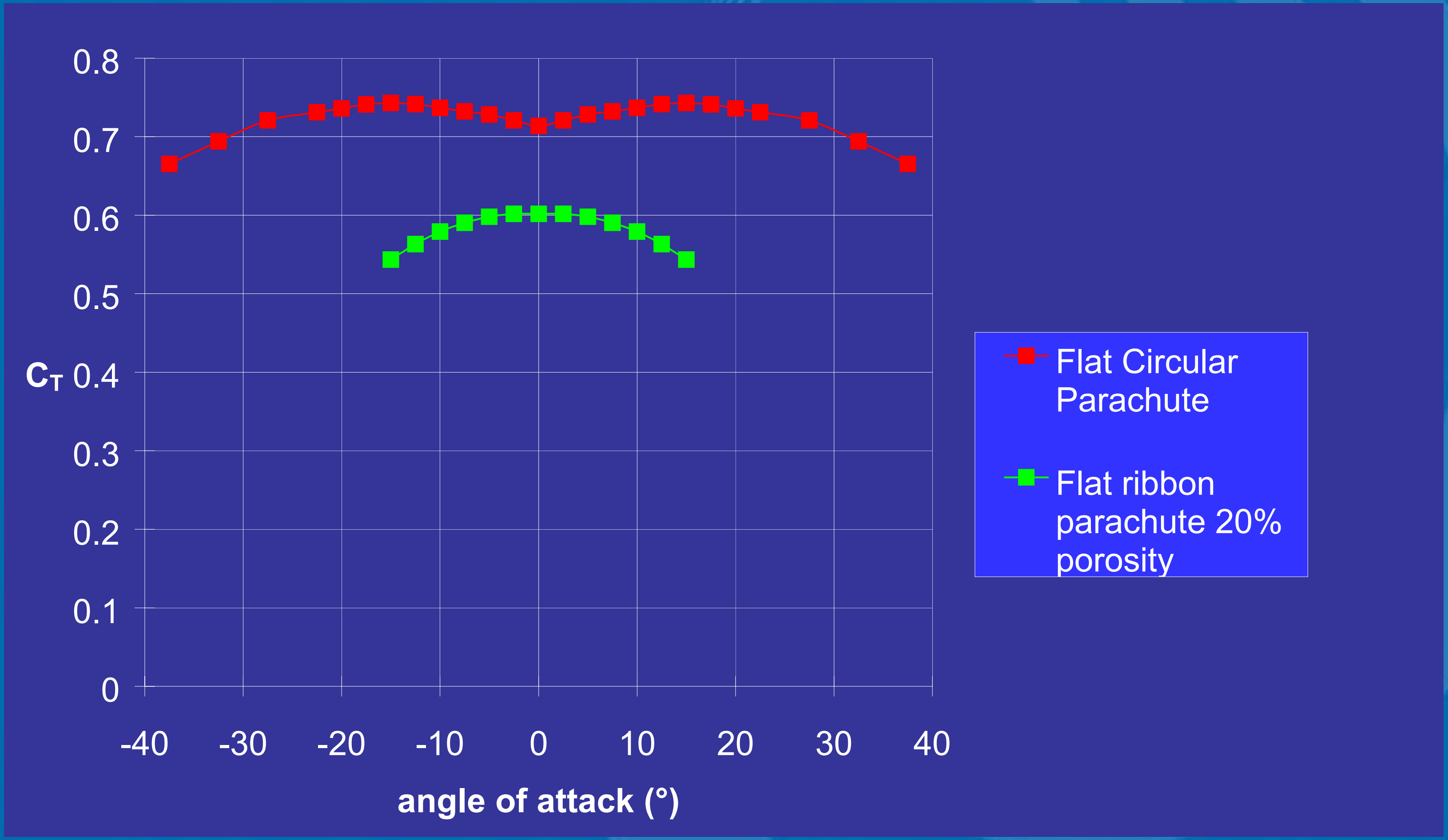


Solid flat circular

Flat ribbon

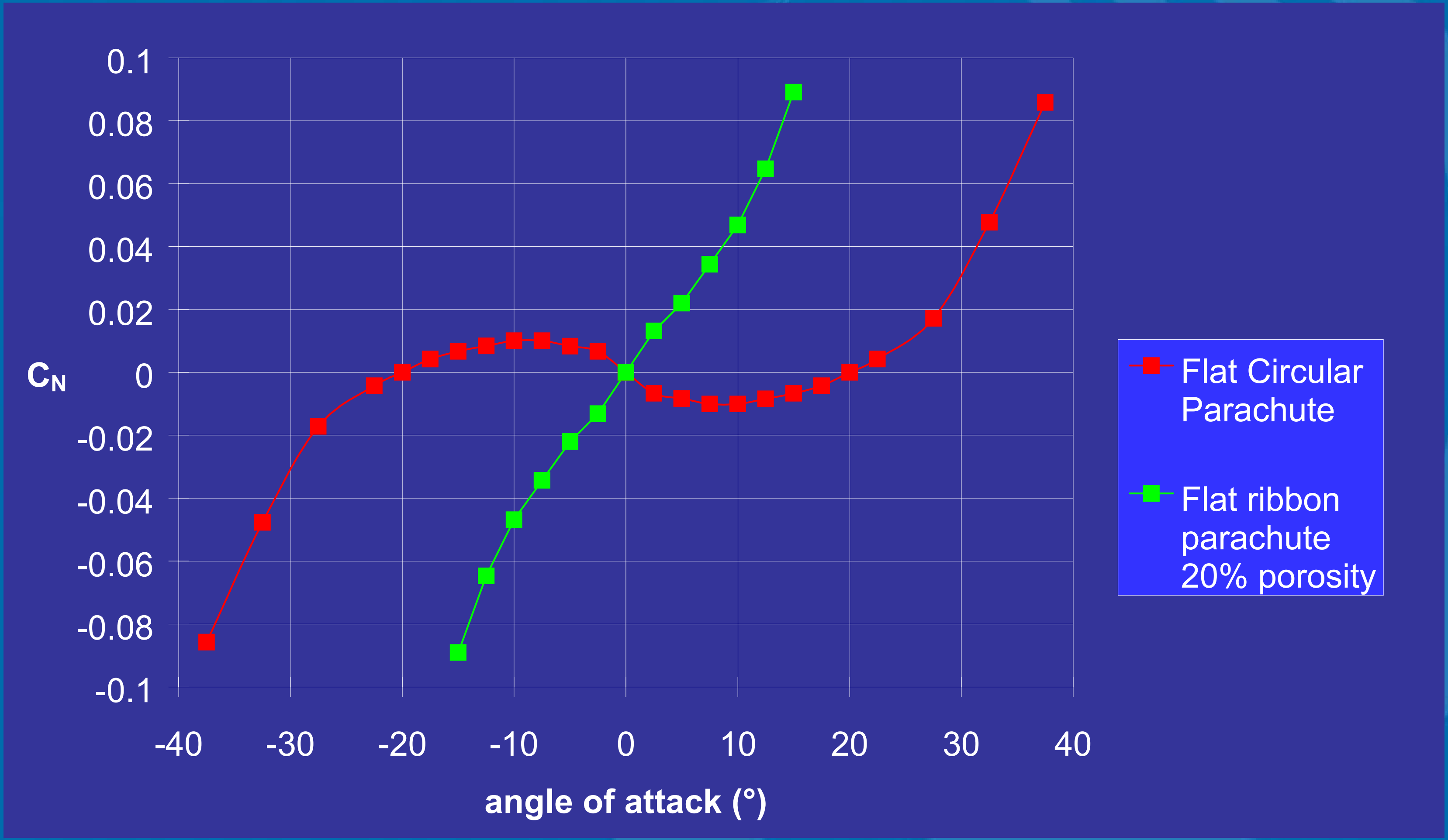
Solid flat extended skirt

Tangent force coefficient



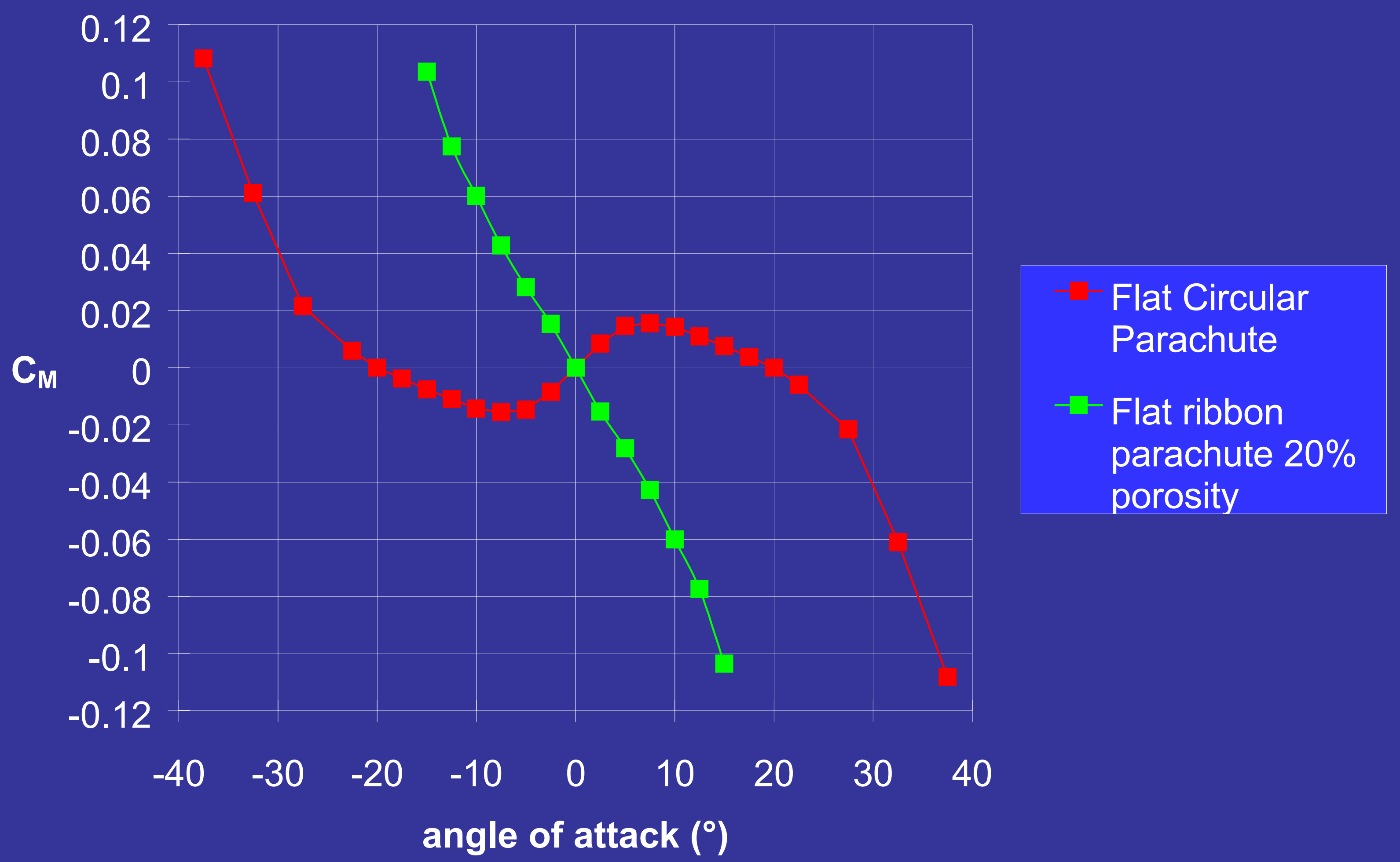
orticity

Normal Force Coefficient



orticity

Pitching Moment Coefficient



orticity

Design Ratios *Rd*

- Define the precise form of the parachute canopy in terms of gore shape and geometric porosity
- 30 different parachute types with variations within type
- detail design features influence performance to a greater or lesser extent
- two parameters independent of precise design have a predominant effect:

POROSITY

FINENESS RATIO

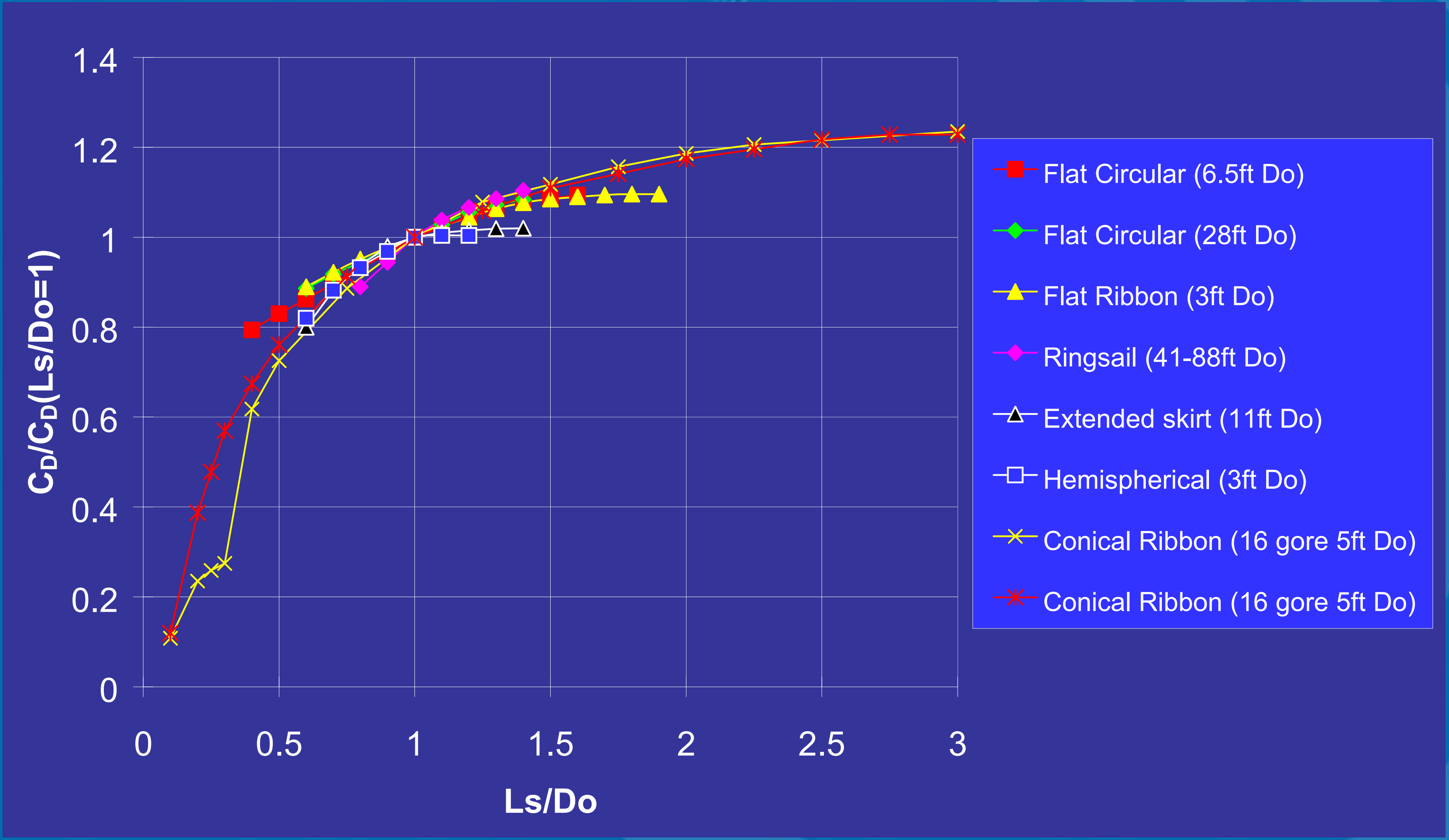
orticity

Fineness Ratio $\frac{L_s}{D_o}$

- ratio of line length to nominal diameter
- typically ranges from 0.8 - 2.0
- common value is 1.0

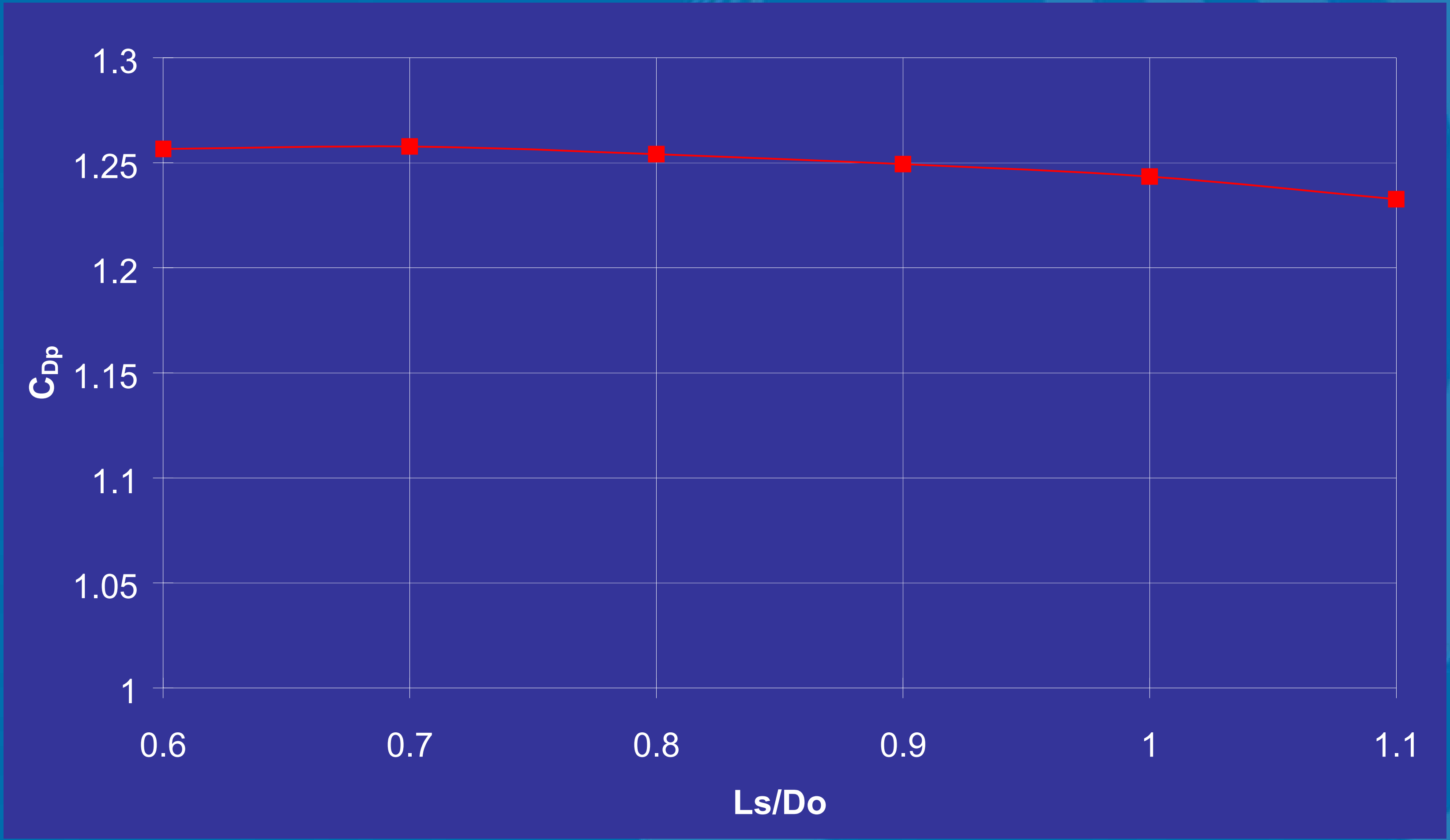
orticity

Variation of parachute drag coefficient based on nominal area with line length



orticity

Variation of Parachute Drag Coefficient Based on Projected Area With Line Length

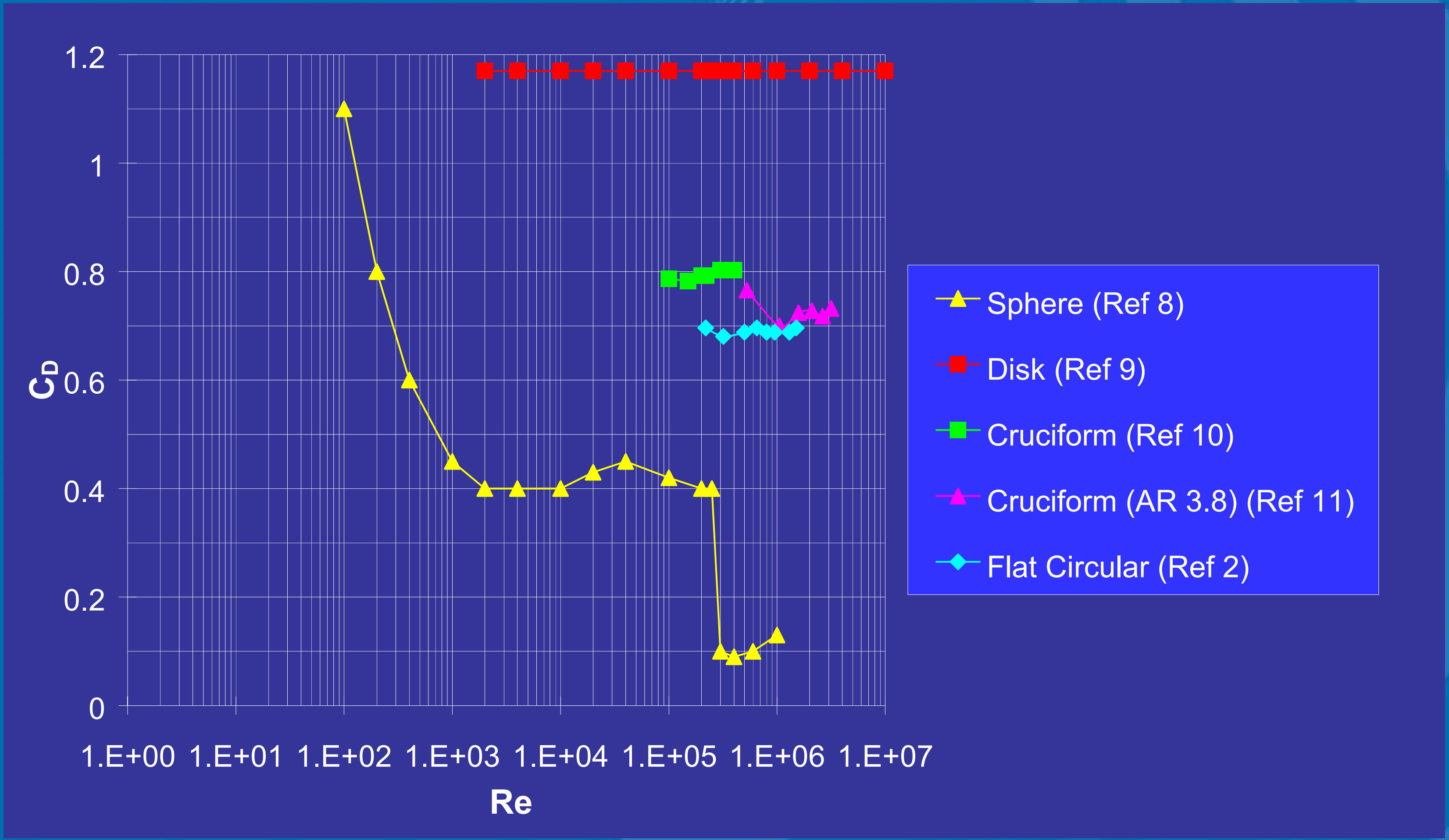


orticity

Reynolds Number $\frac{\rho V D_o}{\mu}$

- ratio of fluid inertial forces to viscous forces
- governs nature of boundary layer and separation - laminar or turbulent
- critical Reynolds number typically is 5×10^5
- laminar : lower friction forces, early separation
- turbulent : higher friction forces, delayed separation
- greatest significance below critical Reynolds number

Variation of Drag Coefficient With Reynolds Number



orticity

Reynolds Number

For typical parachute 5.5m/s descent velocity, nominal diameter 10m

standard sea level conditions $\rho = 1.225 kg/m^3,\ \mu = 1.79 \times 10^{-5} kg/(m.s)$

$$R_e = \frac{\rho V D_o}{\mu} = \frac{1.225 \times 5.5 \times 10}{1.79 \times 10^{-5}} = 3.76 \times 10^6$$

i.e. substantially supercritical

- parachutes have sharp edged separation therefore insensitive to R_e
- Reynolds number has secondary subtle effect
- IT MODIFIES POROSITY

orticity

Porosity

- GEOMETRIC POROSITY
  - λg is produced by physical gaps in the gore
  - λg is the ratio of the open area of the gore to the total gore area
- PERMEABILITY
  - λm derives from the flow passing through the canopy fabric
  - λm is defined as the volumetric flow rate of air per unit cloth area under a certain differential pressure Δp
- UK units are ft^3/ft^2s at 10 ins water pressure representing typical differential pressure during inflation
- USA units are ft^3/ft^2min at ½ ins water pressure, to represent differential pressure during steady descent

orticity

Permeability

Effective porosity is simply defined as:

$$c_e = \frac{u_o}{U}$$

where u_0 = velocity through the material

and $\Delta p = \frac{1}{2}\rho U^2$

For incompressible flow, from dimensional analysis

$$\Delta p = K_1 \rho u_0^2 + K_2 \mu u_0 \quad = \text{(pressure loss + viscous loss)}$$

$$u_o = -\frac{K_2 \mu}{2K_1 \rho} + \sqrt{\frac{K_2^2 \mu^2}{4K_1^2 \rho^2} + \frac{\Delta p}{K_1 \rho}}$$

orticity

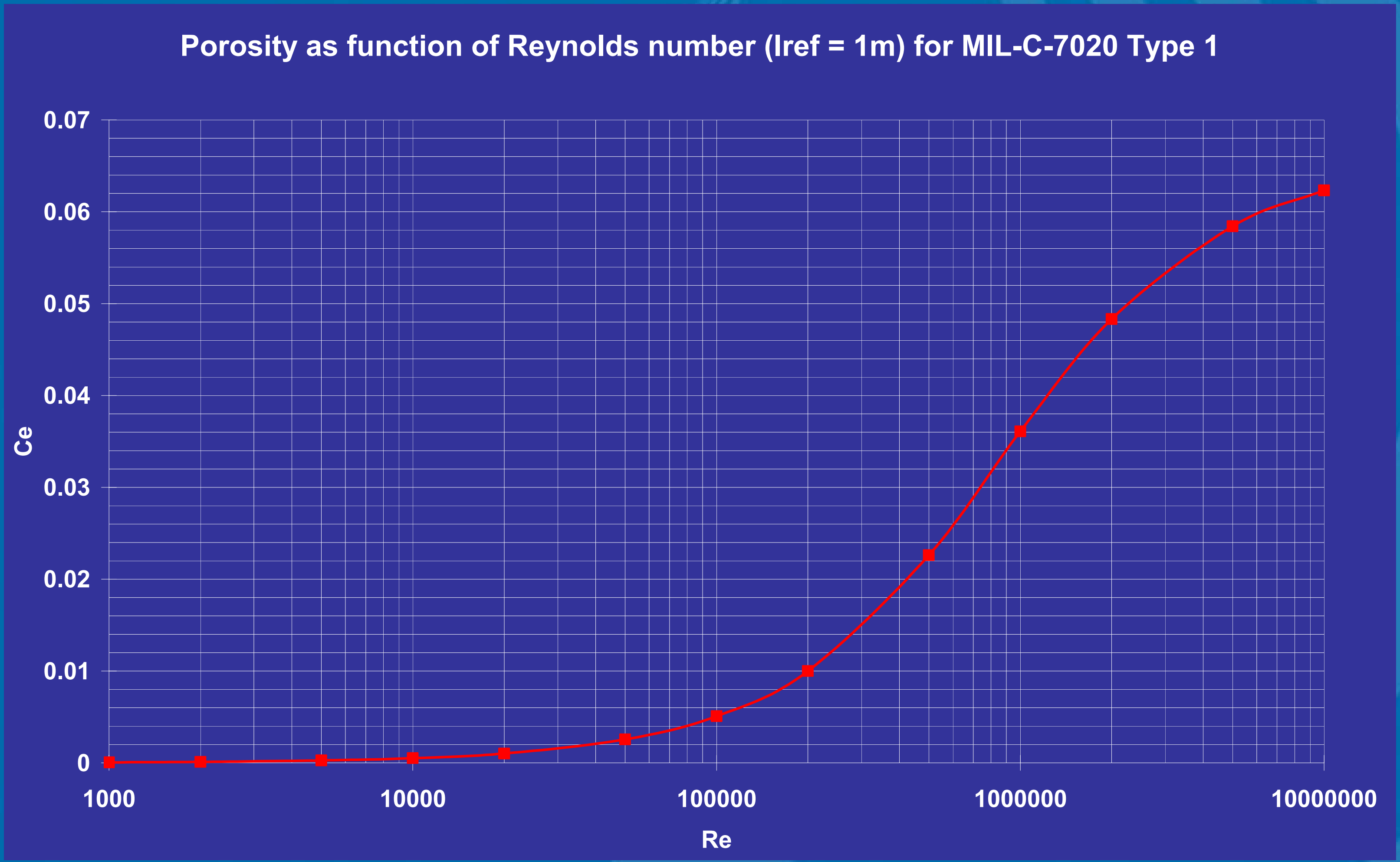
Permeability Contd

$$c_e = -\frac{K_2}{2K_1 R_e} + \sqrt{\frac{K_2^2}{4K_1^2 R_e^2} + \frac{1}{2K_1}}$$

where $R_e = \frac{\rho U}{\mu}$ = Reynolds number per unit length

- since effective porosity is a function of two constants, measuring porosity at a single differential pressure does not define the behavior of the material
- ideally we need to know both UK and US values i.e. for MIL-C-7020 Type 1: UK - 12 US - 100

Variation of Effective Porosity With Reynolds Number for Mil-C-7020 Type 1



orticity

Reynolds Number

- Mars
  - MER : Re = 6×10^4 for terminal descent
- Titan
  - Huygens
    - Main parachute Re = $1.4 \times 10^5 - 5 \times 10^4$
    - Stabilizing drogue Re = $5 \times 10^4 - 4 \times 10^6$

orticity

Effective porosity may be transformed to a geometric porosity equivalent

where S_p is canopy projected area and $D = \Delta p S_p$

then $D = qC_DS_o$ and $\Delta p = \dfrac{qC_DS_o}{S_p}$

Total porosity, λ_T, is simply defined as:

$$\lambda_T = \lambda_g + c_e(1 - \lambda_g)$$

with c_e measured at differential pressure Δp defined above.

- At high dynamic pressure the weave distorts and the flow passing through the cloth increases.
- The porosity of a canopy is an important parameter in many aspects of parachute behavior.

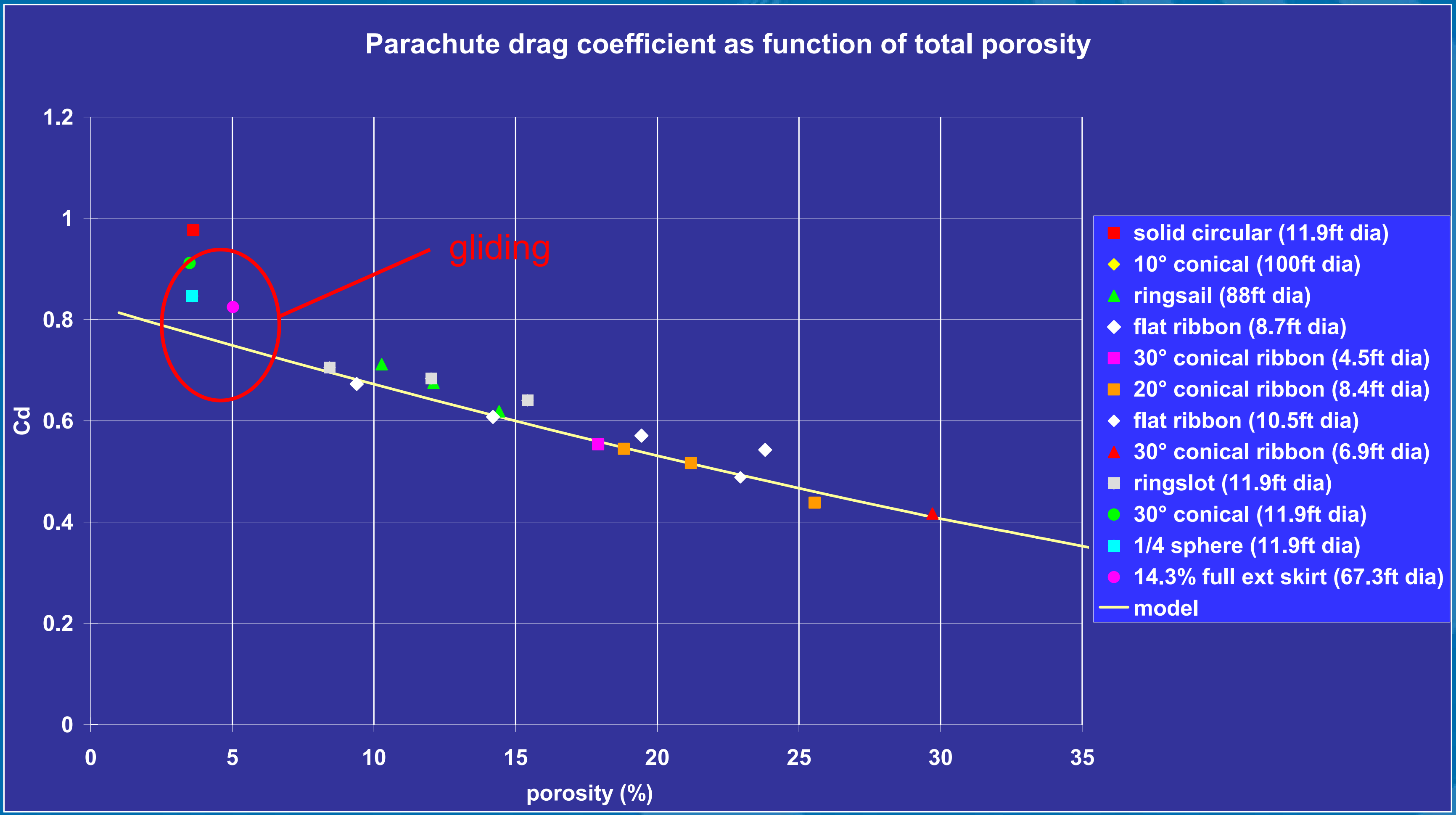
orticity

Increasing porosity:

- Reduces drag coefficient
- Increases parachute inflation time
- Reduces parachute inflation loads
- An over porous canopy may not open at all because its critical opening speed will be too low.
- Porosity also has a large effect on static stability
  - increasing porosity reduces the statically stable angle of attack
  - to achieve static stability at 0° a porosity of >18% is necessary or the open area of the canopy surface is >40% the mouth area

orticity

Influence of Porosity on Drag Coefficient

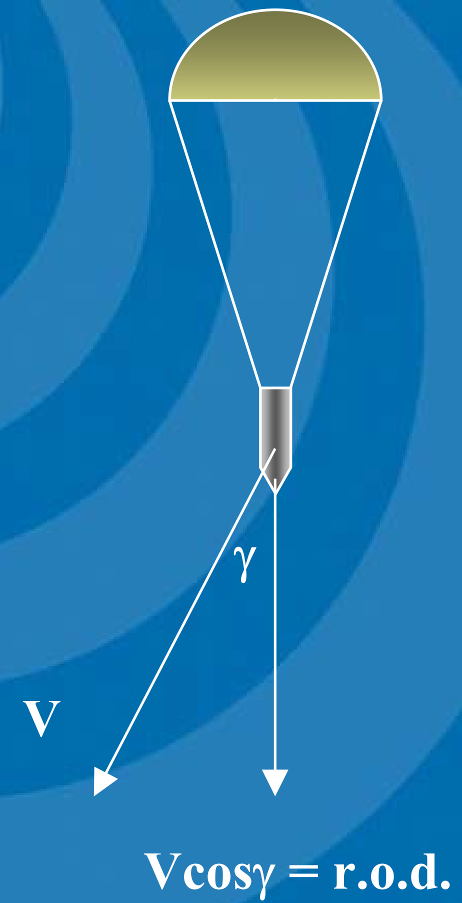


orticity

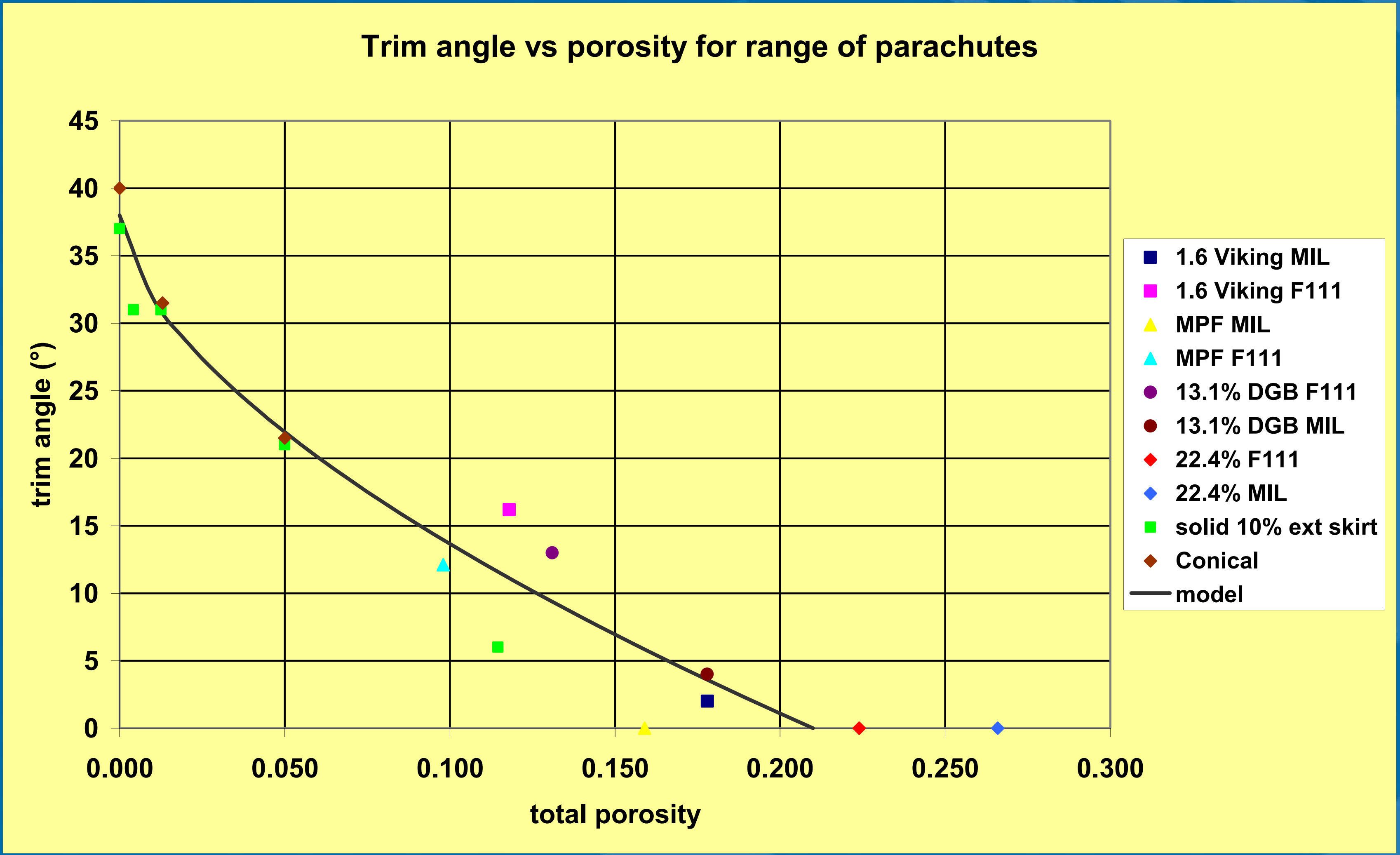
Drop test errors!

- Measured velocity = rate of descent ✗
- Calculated $C_d = C_d/\cos^2\gamma$ ✗

- Essential to check if glide is occurring
- Measured $C_d > 0.70$ almost certainly gliding



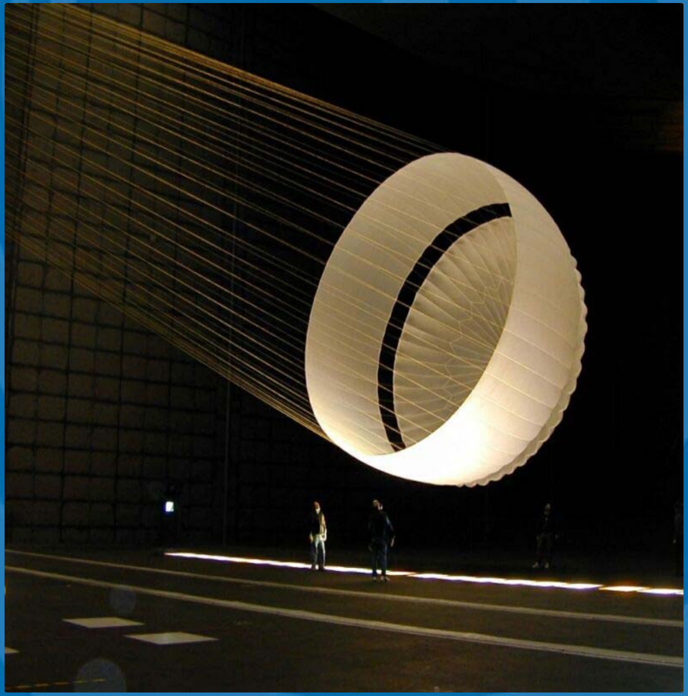
Trim angles



orticity

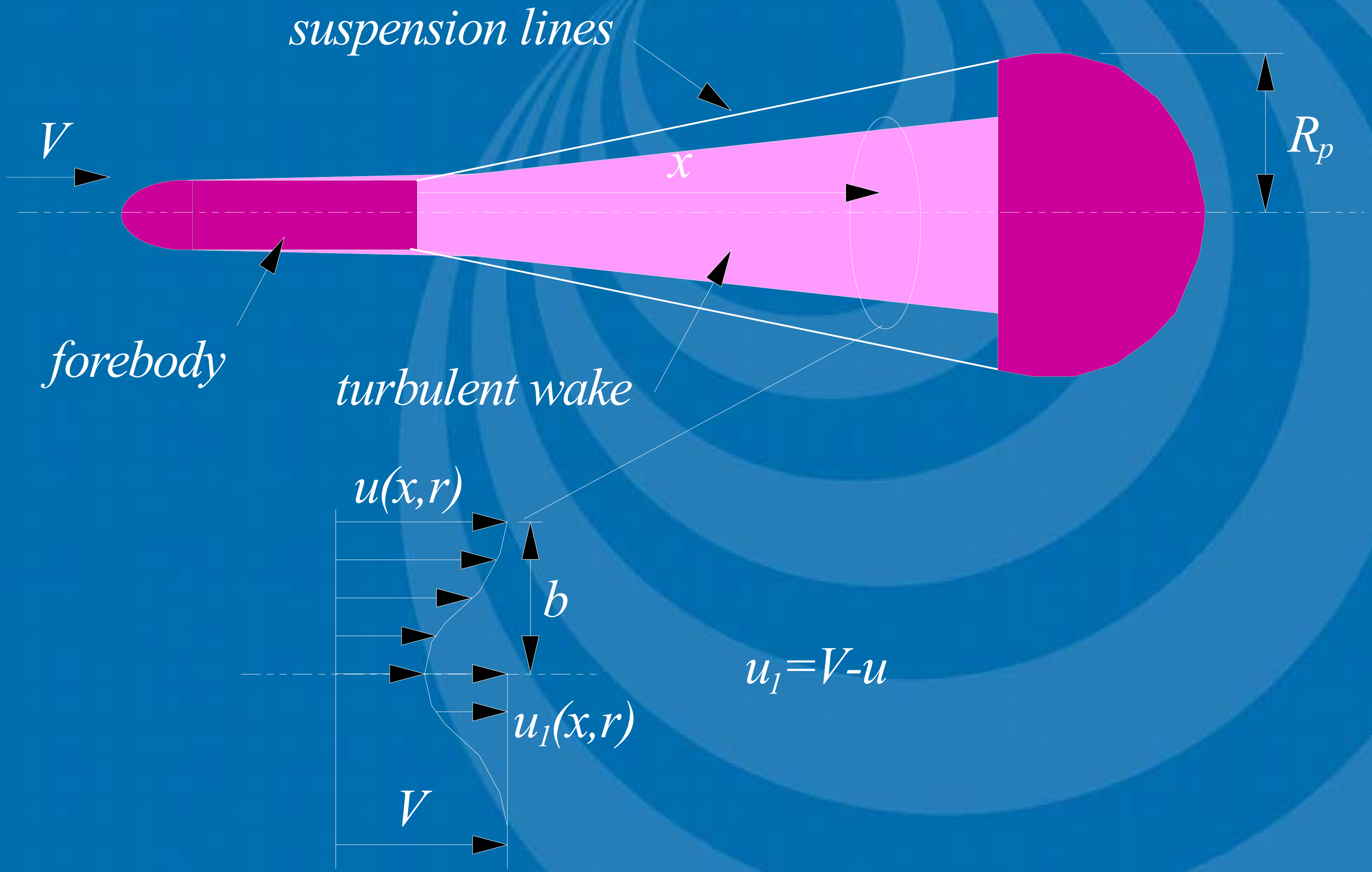
Extended skirt

- Alternative means of improving stability
- Reduces drag coefficient
- Less efficient than using geometric porosity
- Used effectively on
  - Mars Pathfinder
  - MER



orticity

Schematic Diagram of a Subsonic Turbulent Wake



orticity

Wake effects

Influence of wake is a function of:

- size of forebody compared to size of parachute D_B/D_P
- distance from base of forebody to parachute skirt x/D_B
- shape of the forebody C_{DB}
- Mach number

orticity

Wake Effects

width b of a turbulent axisymmetric wake is $b = k(C_{DB} S_B x)^{\frac{1}{3}}$

$$\frac{b}{D_B} = k\left(\frac{\pi}{4} C_{DB} \frac{x}{D_B}\right)^{\frac{1}{3}}$$

and the velocity decrement at the wake center line is: $U_1 = KV\left(\frac{C_{DB} S_B}{x^2}\right.$

$$\frac{U_1}{V} = K\left(\frac{C_{DB}\pi}{4(x/D_B)^2}\right)^{\frac{1}{3}}$$

where $C_{DB} =$ the forebody drag

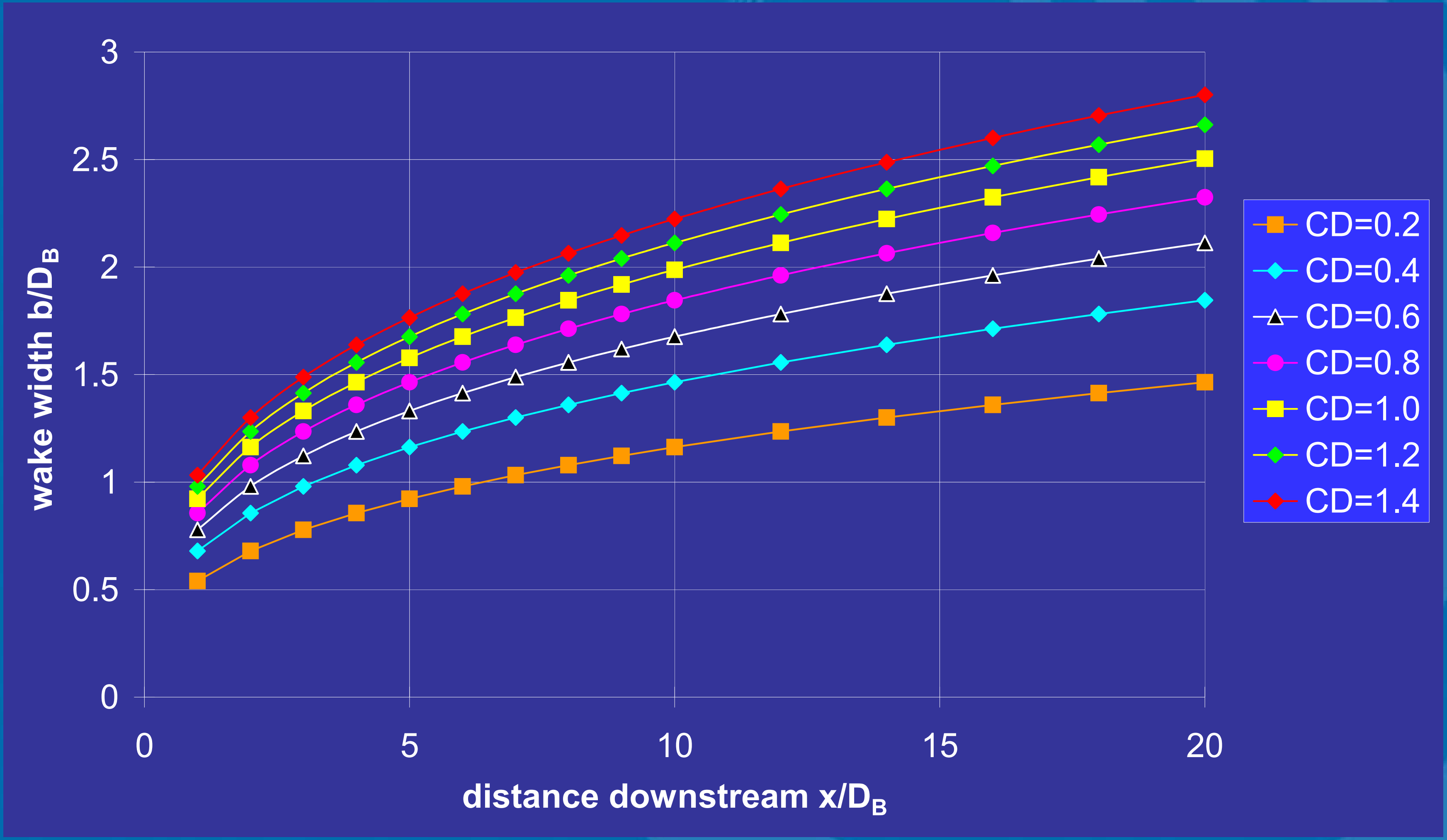
$S_B = \frac{\pi D_B^2}{4} =$ forebody reference area

$x =$ distance downstream from the base of the forebody

and k and K are constants.

orticity

Wake Width As a Function of Downstream Distance and Forebody Drag Coefficient



orticity

If the parachute diameter is larger than the wake drag loss = forebody drag

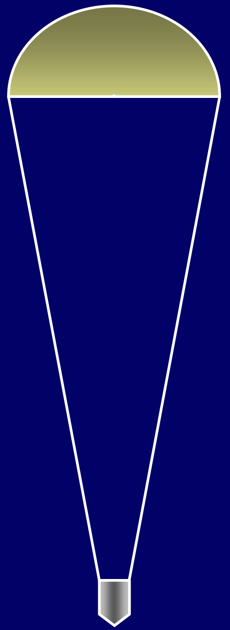
If parachute is immersed in the wake

$$\frac{C_D}{C_{D\infty}} = \frac{q_{eff}}{q_\infty} = \frac{1}{\pi R_p^2}\int_0^{R_p}\left(1-\frac{u_1}{V}\right)^2 2\pi r dr$$

where $$\frac{q_{eff}}{q_\infty} = 1 - \frac{2.476 C_{DB} S_B}{R_p^2}\left[\frac{\eta^2}{2} - \frac{4\eta^{3.5}}{7} + \frac{\eta^5}{5}\right]_0^{R_p/b}$$

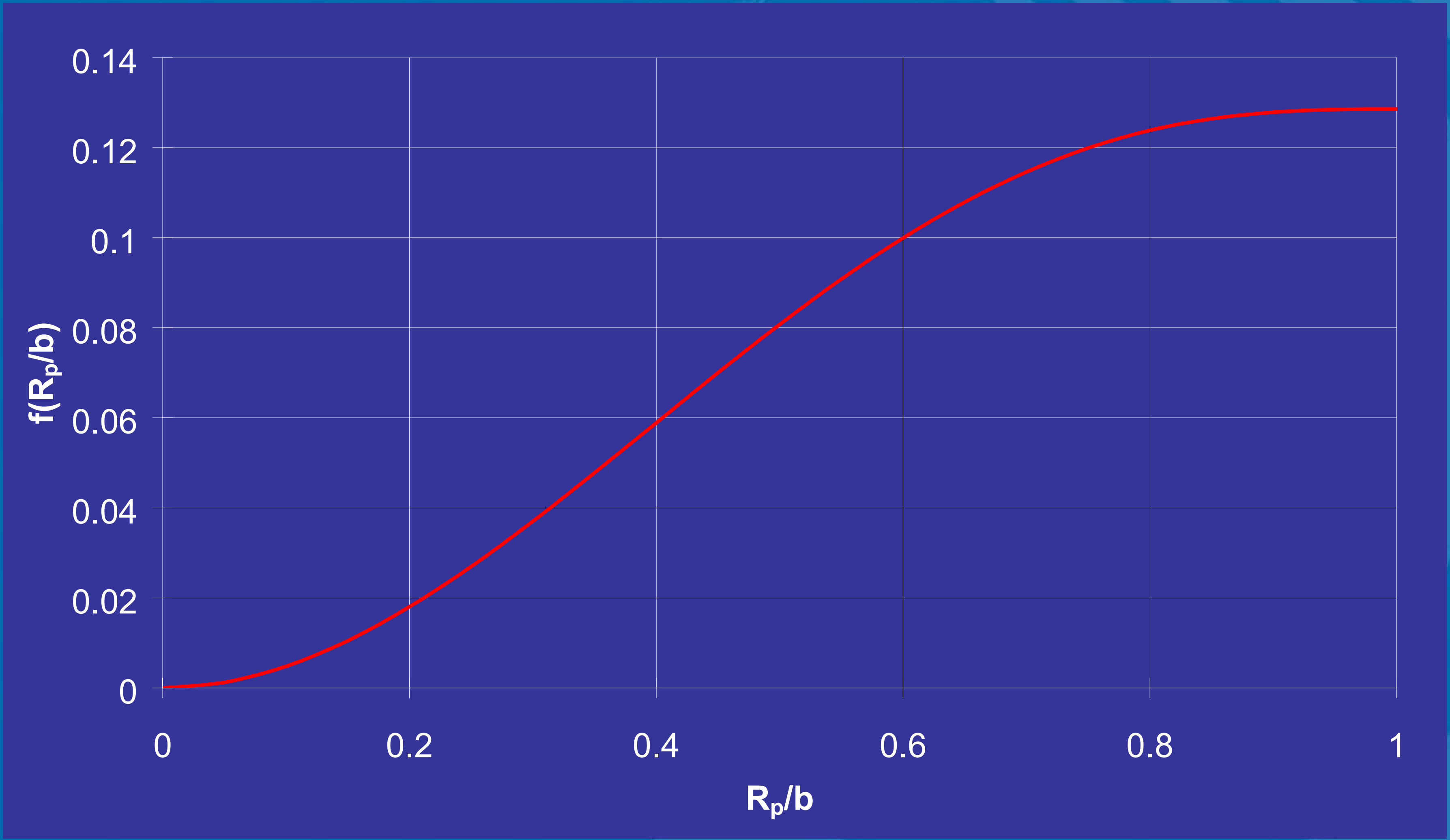
$$= 1 - \frac{2.476 C_{DB} S_B}{R_p^2} F(\eta)$$

$$\eta = r / b$$



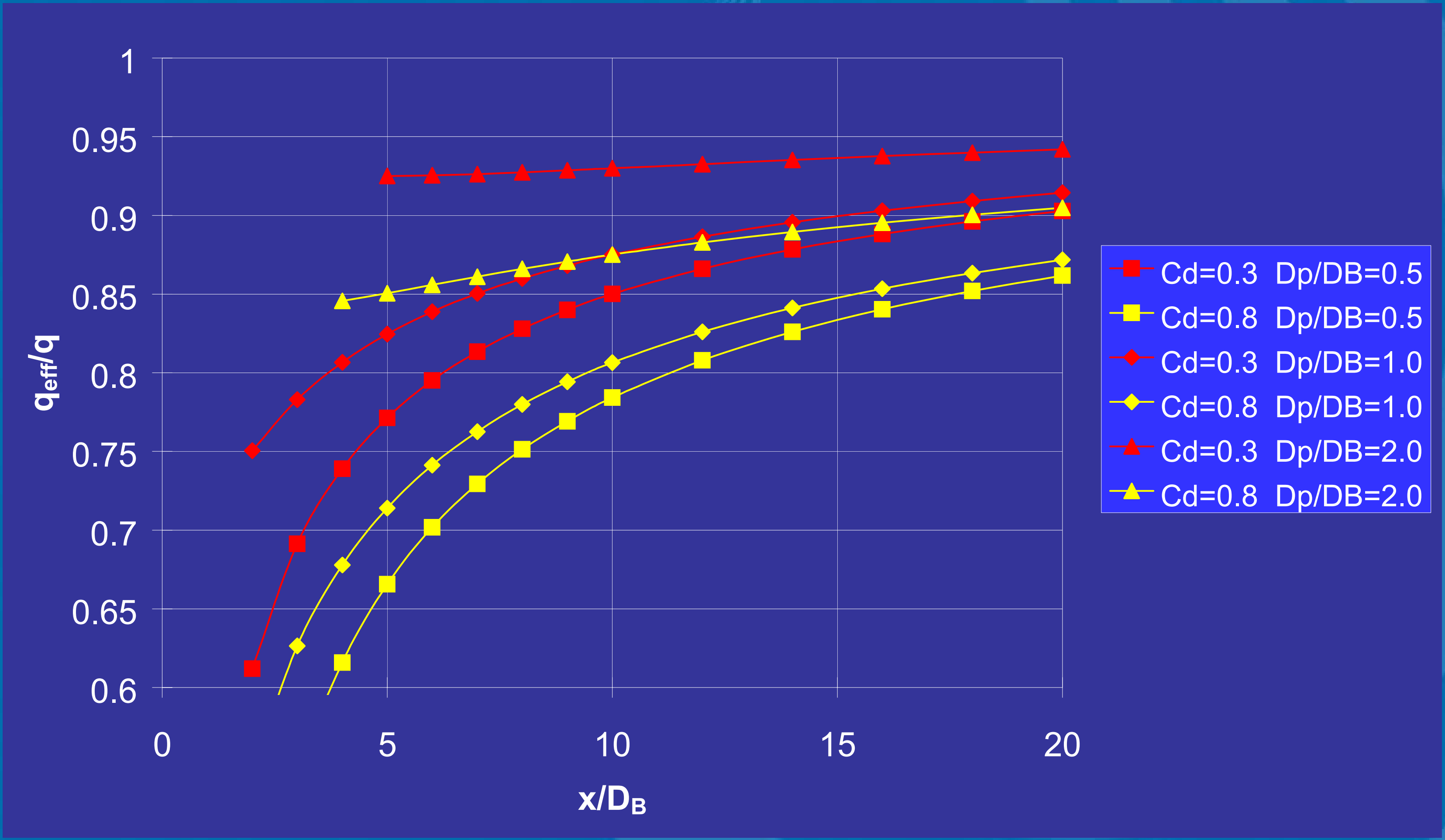
orticity

Function f(η) versus parachute projected diameter to wake diameter ratio



orticity

Wake Efficiency Factor As a Function of Trailing Distance, Parachute Size and Forebody Drag Coefficient



orticity

Pressure Distribution

- Pressure distribution is significant to understanding of drag and stress analysis
- The drag of a parachute is predominantly produced by the differential pressure over the canopy shear forces being second order.

$$D \approx - \oiint_{\text{canopy surface}} \mathbf{p}\, d\mathbf{S}$$

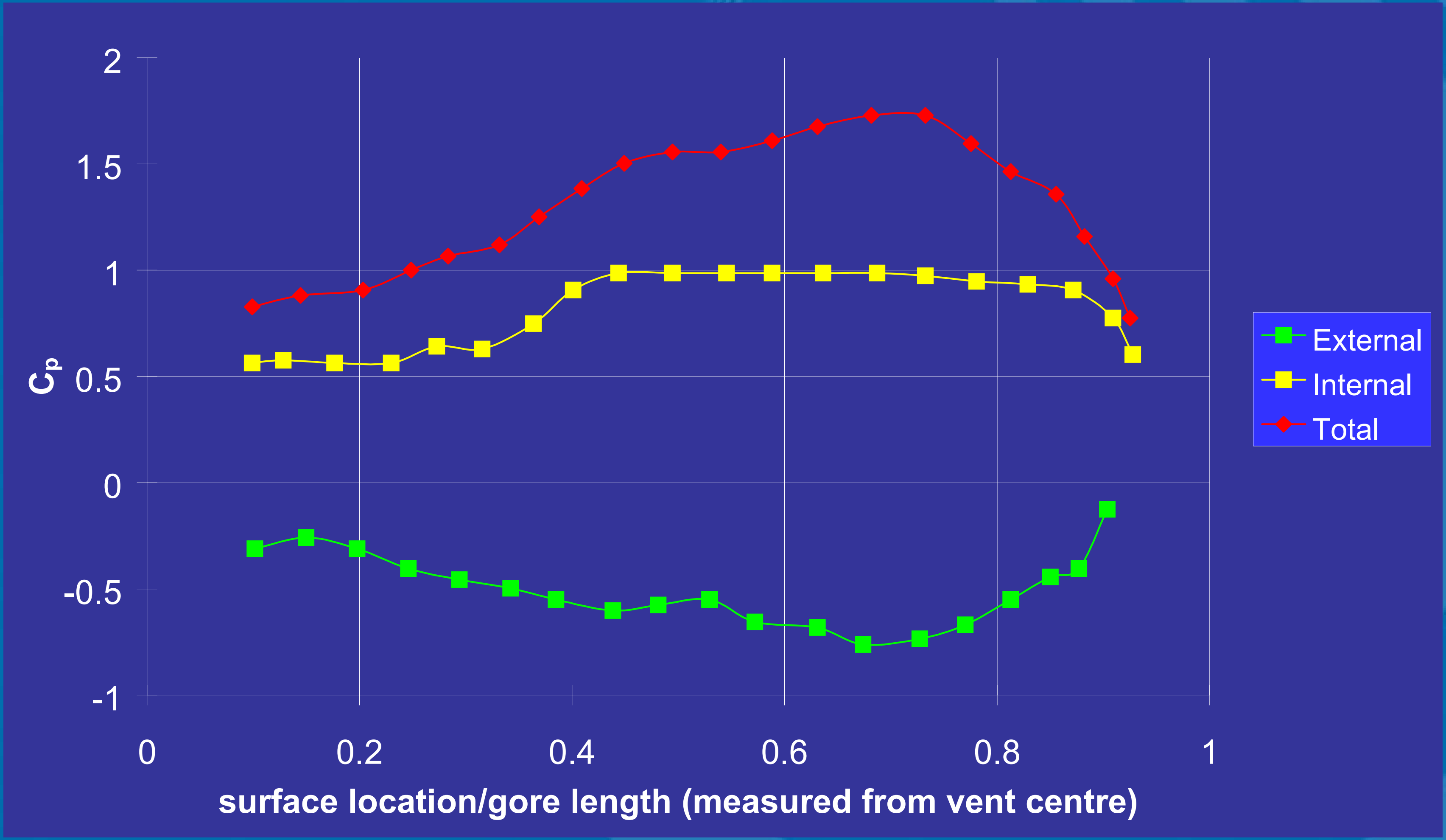
$$C_{pext} = (p_{ext} - p_{\infty}) / q_{\infty}$$

$$C_{pin} = (p_{in} - p_{\infty}) / q_{\infty}$$

$$C_{ptot} = (p_{in} - p_{out}) / q_{\infty}$$

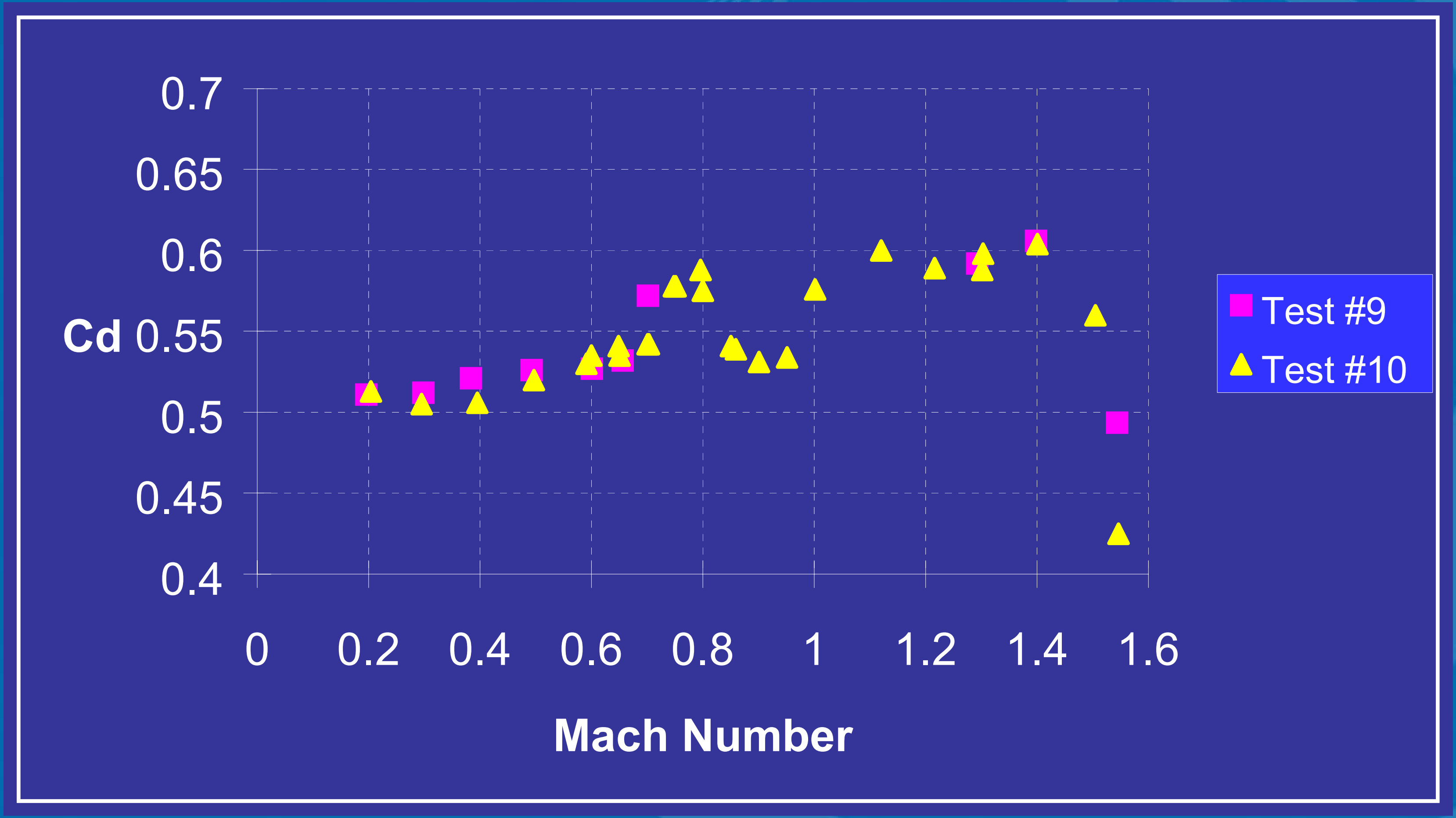
orticity

Typical Canopy Pressure Distribution for a 25% Geometric Porosity Ribbon Parachute



orticity

Variation of Drag Coefficient With Mach Number for a Disk-gap-band Parachute



orticity

Test Data

- High quality test data is important
- Data in literature is often incompletely defined
- Data sources
  - flight test
  - wind tunnel
- Flight test data
  - subject to atmospheric variations
  - ground relative
  - uncontrolled
  - instrumentation accuracy
  - D GPS + calibration chute
    - Large drop altitudes recommended

Wind Tunnel Test Data

Blockage correction

Solid wall wind tunnel correction factor

$$\frac{q}{q\infty} = 1 + 1.85\frac{C_D S}{S_t}$$

q = effective dynamic pressure to be used to non-dimensionalize the drag

$q\infty$ = free stream dynamic pressure

$C_D S$ = measured drag area

S_t = tunnel section area.

- Model scaling
  - stiffness
  - porosity

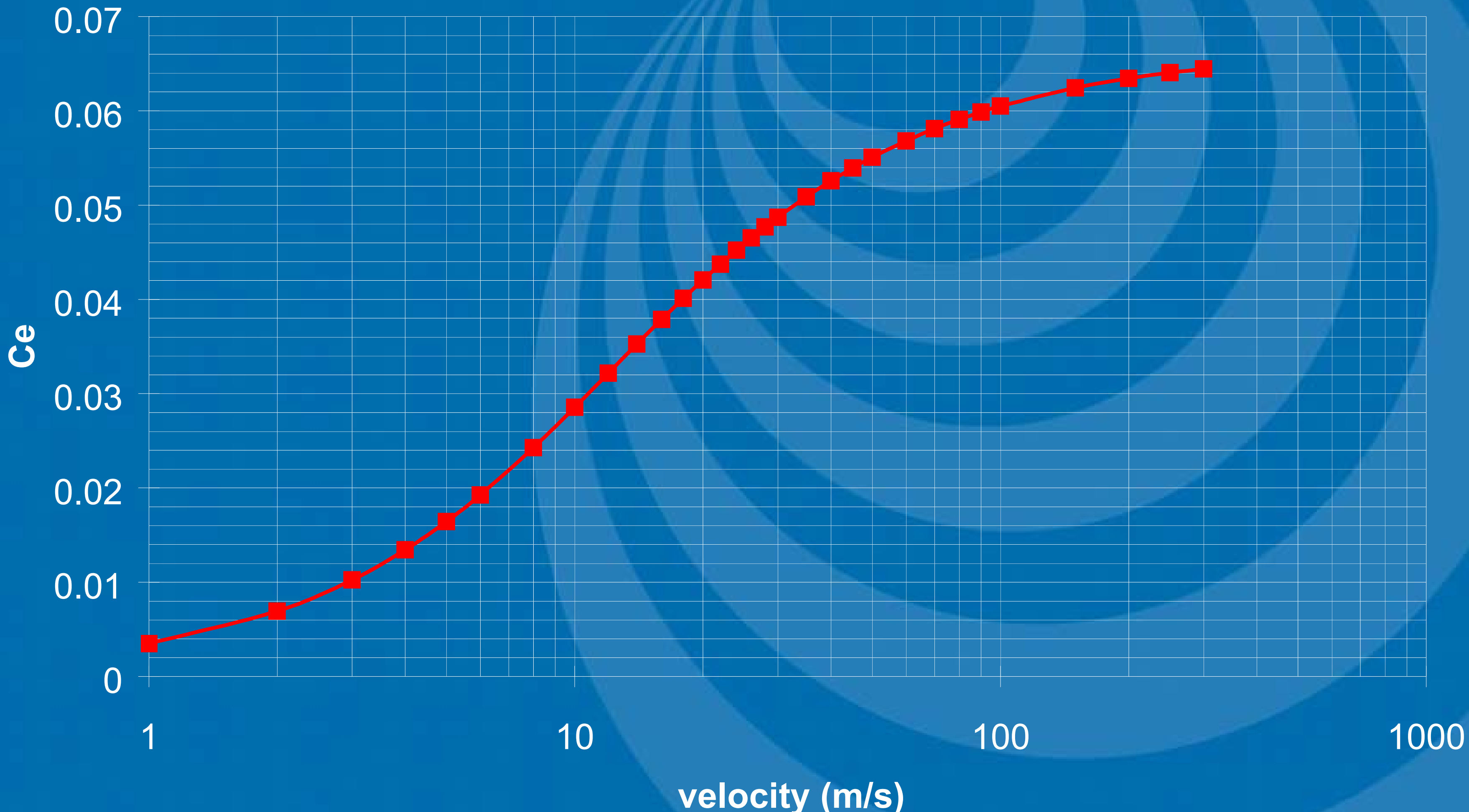
orticity

Test Data Summary

- always use the original source of the data to obtain all relevant information with regard to configuration and accuracy;
- always ensure you know the limitations of flight test data;
- always correct wind tunnel data for blockage and be aware of Reynolds number effects;
- always ensure that the configuration tested is as close as possible to that to which you wish to apply the data.

?

Variation of Effective Porosity Free Stream Velocity for Mil-C-7020 Type 1



orticity