Estimating Mass of Inflatable Aerodynamic Decelerators Using Dimensionless Parameters

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8th International Planetary Probe Workshop (IPPW-8)

Portsmouth, Virginia

June 6-10, 2011.

Acknowledgement

Thanks to Glenn Brown of HDT Engineering Services for verifying the revised derivation for the minimum inflation pressure for the stacked-toroid concept and Reuben Rohrschneider of Ball Aerospace for suggesting a simpler version of Eq. (19).

Outline

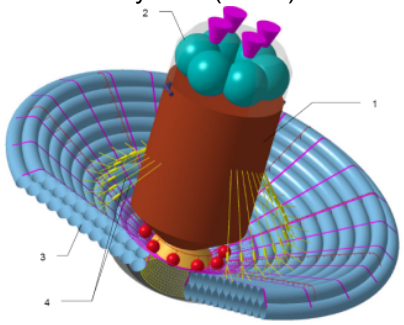
- Inflatable Aerodynamic Decelerator (IAD) Overview
- Mass Estimating Process
- Dimensional Analysis
- Mass Components
  - Inflation Gas Pressure & Mass
  - Toroid Mass
  - Radial Straps and Gores
- Results
- Summary

Inflatable Aerodynamic Decelerators (IAD) Overview

Inflatable Re-Entry and Descent Technology (IRDT)

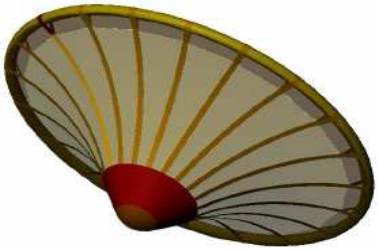
Inflatable Re-entry Vehicle Experiment (IRVE)

Mars Inflatable Aeroshell System (MIAS)

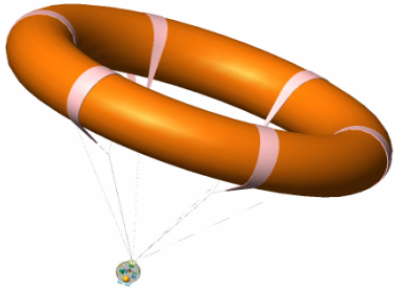


Flare

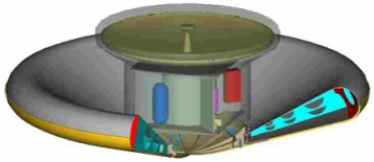
Hypercone



Trailing IAD

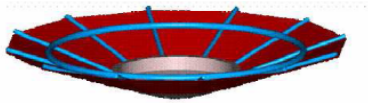


Ribbed Double Surface Inflatable (RDSI)



Spars & Rims

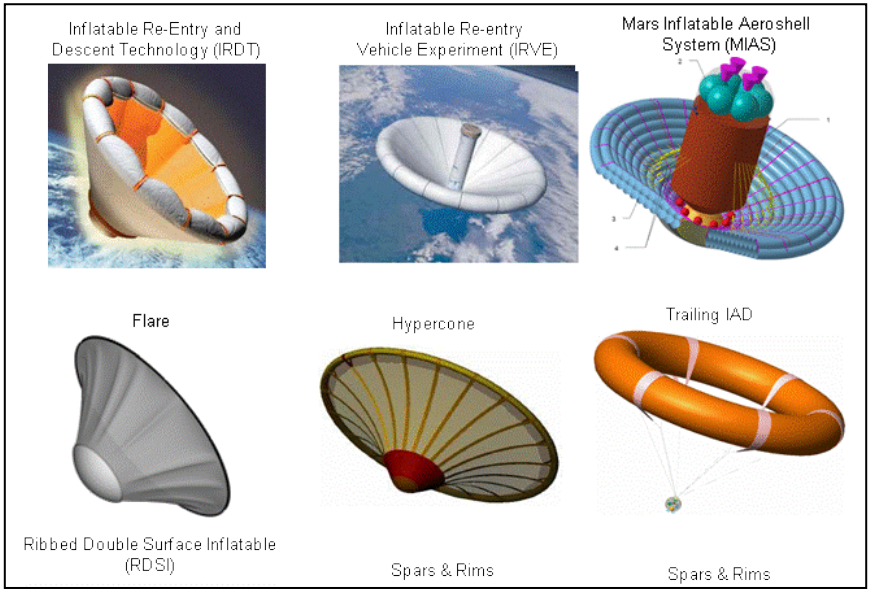
Spars & Rims

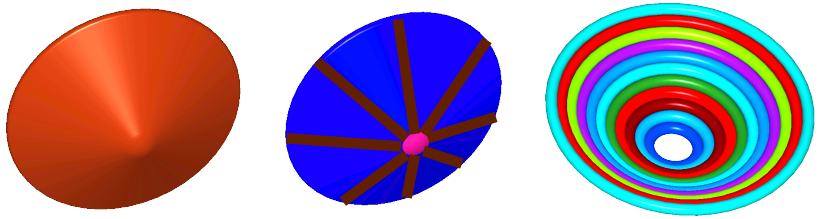


Mass Estimation Process

Steps for Estimating IAD Mass:

- Toroid
  - Inflation gas
  - Toroid concepts
    - Film
    - Coated fabric
    - Fiber reinforced fabric
- Radial Straps
- Gores





TPS & Gores | Radial Straps | Toroids

Dimensional Analysis

- Dimensionless parameters provide insight into mass scaling law (e.g., Mach number & Re).
- IAD mass is primary function of q_{max} and IAD area.
- Dimensionless mass parameter (using Buckingham π theorem)

$$\Pi = \Pi(m, q_{\max}, A_{\mathrm{IAD}}, g_e) = m^{a_1}\, q_{\max}^{a_2}\, A_{\mathrm{IAD}}^{a_3}\, g_e^{a_4} \qquad \Pi = \left(\frac{m\, g_e}{A_{\mathrm{IAD}}\, q_{\max}}\right)$$

$$\bar{m} = \left(\frac{\mathrm{m}\, g_e}{A_{\mathrm{IAD}}\, C_d\, q_{\max}}\right) = \left(\frac{\mathrm{m}}{A_{\mathrm{IAD}}\, C_d}\right)\left(\frac{g_e}{q_{\max}}\right) = \left(\frac{\mathrm{m}}{A_{\mathrm{IAD}}}\right)\left(\frac{g_e}{q_{\max} C_d}\right) = \frac{\mathrm{m}}{m_{\mathrm{factor}}}$$

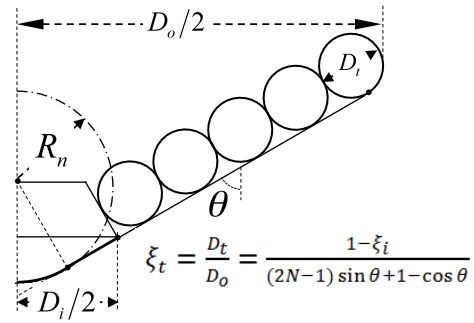
- Material Property $\bar{\sigma} = \frac{\sigma}{\rho g_e L}$
  - For example, the $\bar{\sigma}$ for Kevlar 49 with a yield of 3 GPa and a density of 1440 kg/m^3 is equal to 2.1×10^5. In contrast, the nominal $\bar{\sigma}$ value for aluminum is 2.3×10^4.

- Inflation Gas $\bar{G} = \frac{g_e L}{\frac{\mathrm{R}}{\mathrm{M}}\mathrm{T}}$

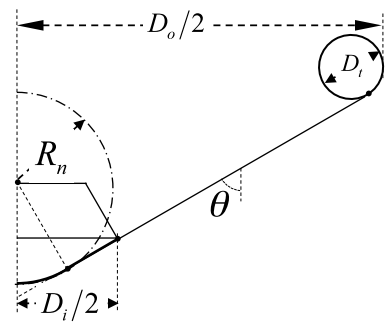
Dimensional Analysis, Cont.

- Rigid aeroshell diameter , $\xi_i = D_i / D_o$
- Toroid diameter, $\xi_t = D_t / D_o$
- Area Ratio, $AR = A_{IAD} / A_{total}$
- Toroid
  - Circumference $\bar{C} = \frac{\sum_{i=1}^{N} C_i}{\pi D_o} = N[1 - \xi_t - \xi_t(N-1)\sin\theta]$
  - Surface area $\bar{S} = \frac{\sum_{i=1}^{N} S_i}{A_{\mathrm{IAD}}} = \frac{4\pi\xi_t}{AR}\bar{C}$
  - Volume $\bar{V} = \frac{\sum_{i=1}^{N} V_i}{D_t A_{\mathrm{IAD}}} = \frac{\bar{S}}{4}$
- Radial straps
- Gore Area $\bar{A}_{\mathrm{gore}} = \frac{A_{\mathrm{gore}}}{A_{\mathrm{IAD}}} = \frac{1}{\sin\theta} + \frac{2\pi\xi_t(1-\xi_t)}{AR}$

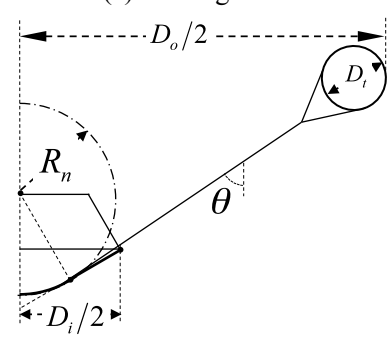
(a) Stacked-Toroid IAD



(b) Tension Cone IAD



(c) Trailing IAD



Inflation Gas Pressure & Mass

Tension Cone, Hypercone, & Trailing IAD

- $p_{\min} = F_a \frac{4 \sin \theta_t}{\pi^2 D_t^2 \cos \theta_h}$
  - Twice Brown's estimate
  - Similar to Yamada et al. (2009)
  - Similar to Kyser (1967)
  - Valid for hypercone ($\theta_t = \pi/2$) and trailing IAD ($\theta_t = \theta_h = \theta_c$)
- Dimensionless Form

$$\bar{p}_{\min} = \frac{p_{\min}}{q_{\max} C_d} = \frac{AR \sin \theta_t}{\pi \xi_t^2 \cos \theta_h} \eta_p$$

  - η_p margin to account for low-fidelity nature of the analysis

Stacked Toroid

- Revised Version of Brown's Form

$$p_{\min} = F_a \frac{4 \tan(\theta) \sin(\theta)}{3 \pi D_o D_t}$$

- Dimensionless Form

$$\bar{p}_{\min} = \frac{p_{\min}}{q C_d} \eta_p = \frac{AR \tan(\theta) \sin(\theta)}{3 \xi_t} \eta_p$$

$\xi_t = D_t / D_o$

$AR = A_{IAD} / A_{total}$

Inflation Gas Pressure & Mass, Cont.

Mass of inflation gas:

- **Perfect gas assumption**
- **Dimensionless form:**

$$\bar{m}_{\text{gas}} = \frac{m_{\text{gas}} g_e}{q A_{\text{IAD}} C_d} \eta_g = \frac{g_e}{RT} \cdot \frac{p}{q C_d} \cdot \frac{V}{A_{\text{IAD}}} \cdot \eta_g \qquad \Delta\bar{p}_{\text{static}} = p_{\text{static}}/(q C_D)$$

$$\bar{m}_{\text{gas}} = \bar{G} \cdot (\bar{p}_{\min} + \Delta\bar{p}_{\text{static}}) \cdot \bar{V} \cdot \xi_t \cdot \bar{D}_o \cdot \eta_g \Rightarrow \bar{m}_{\text{gas}} \propto \bar{D}_o$$

- **Valid for stacked toroid, tension cone, hypercone, trailing IAD, …**

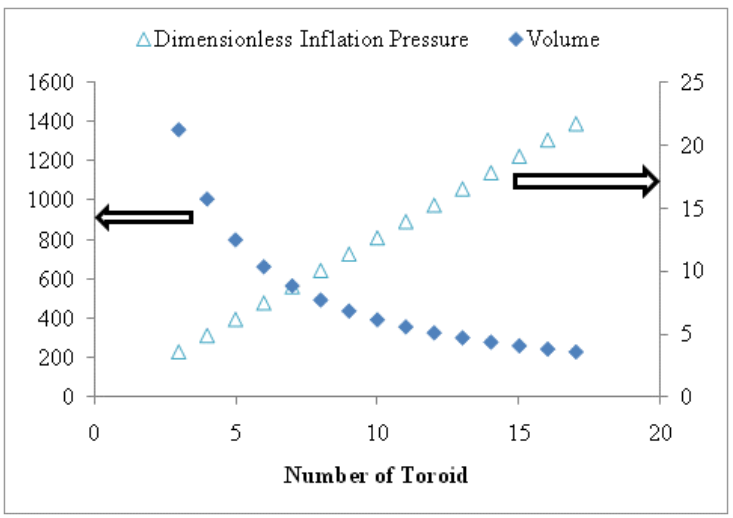
Inflation Gas Pressure & Mass, Cont.

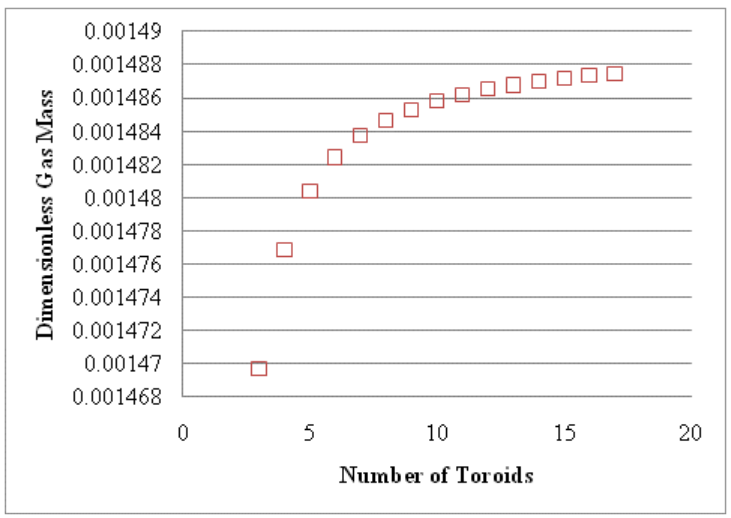
Inflation Gas Mass for Stacked Toroid:

$$\bar{m}_{\text{gas}} = \bar{G} \cdot (\bar{p}_{\text{min}} + \Delta\bar{p}_{\text{static}}) \cdot \bar{V} \cdot \xi_t \cdot \bar{D}_o \cdot \eta_g$$

Stacked Toroid

$$\bar{p}_{\text{min}} = \frac{p_{\text{min}}}{qC_d}\eta_p = \frac{AR\tan(\theta)\sin(\theta)}{3\xi_t}\eta_p$$





Flexible Material Mass

- Toroid Mass $m_{\text{toroid}} = \max\left[S \cdot \rho \cdot t_{\min},\ m_{\text{fully stressed}}\right]$
  - Fiber Reinforced Concept

$$\bar{m}_{\text{fiber}} = \frac{1}{\bar{\sigma}} \cdot \left(1 + \frac{1}{\tan^2\beta}\right) \cdot \bar{p}_{\min} \cdot \bar{S} \cdot \frac{\xi_t}{2} \cdot \bar{D}_o \cdot \eta_{\text{fiber}}$$

$$\bar{m}_{\text{axial}} = \frac{1}{\bar{\sigma}} \cdot \bar{p}_{\min} \cdot \bar{S} \cdot \frac{\xi_t}{4} \cdot \bar{D}_o \cdot \eta_{\text{axial}}$$

$$\bar{m}_{\text{gas barrier}} = \frac{1}{\bar{\sigma}} \cdot \bar{p}_{\min} \cdot \bar{S} \cdot \frac{\xi_t(2-3\xi_t)}{4(\xi_D - 2\xi_t)} \cdot \bar{D}_o \cdot \eta_{\text{gas barrier}}$$

  - Coated Fabric & Film (Must include mass of coating material for coated fabric)

$$\bar{m}_{\text{toroid}} = \frac{1}{\bar{\sigma}} \cdot \bar{p}_{\min} \cdot \bar{S} \cdot \frac{\xi_t(2-3\xi_t)}{4(\xi_D - 2\xi_t)} \cdot \bar{D}_o \cdot \eta_{\text{toroid}}$$

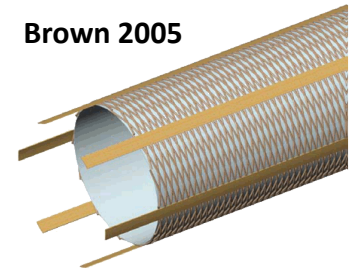
- Gores

$$\bar{m}_{\text{gores}} = \frac{1}{\bar{\sigma}} \cdot \bar{r}_c \cdot \bar{A}_{\text{gores}} \cdot \bar{D}_o \cdot \eta_{\text{gores}}$$

- Radial Straps

$$\bar{m}_{\text{radial}} = \frac{1}{\bar{\sigma}} \cdot \frac{\bar{L}_r}{\cos\theta_h} \cdot \bar{D}_o \cdot \eta_{\text{radial}}$$

Brown 2005



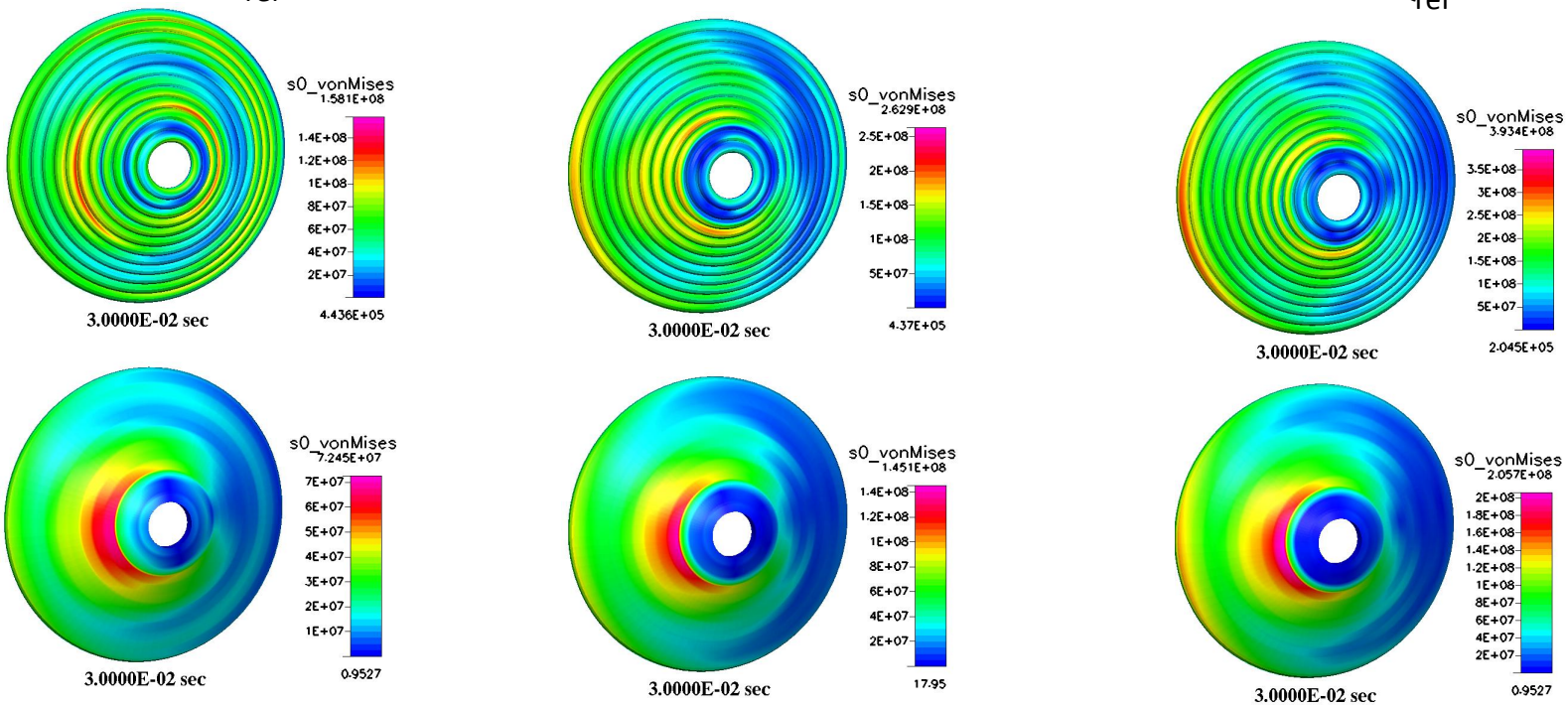
12× advantage in specific strength of fiber compared to film (AIAA-2007-2543)

Results

NASA/CR–2010-216731 (Courtesy of Essam Sheta of CFD Research Corporation)

- EDL-SA IAD Concept
- Coupled Euler & Nonlinear FEA
- 5 deg/s^2 Bank Rotation

0.5 * Q_{ref} | At Q_{ref} | 1.5 * Q_{ref}



- Scales are different to show the maximum values.

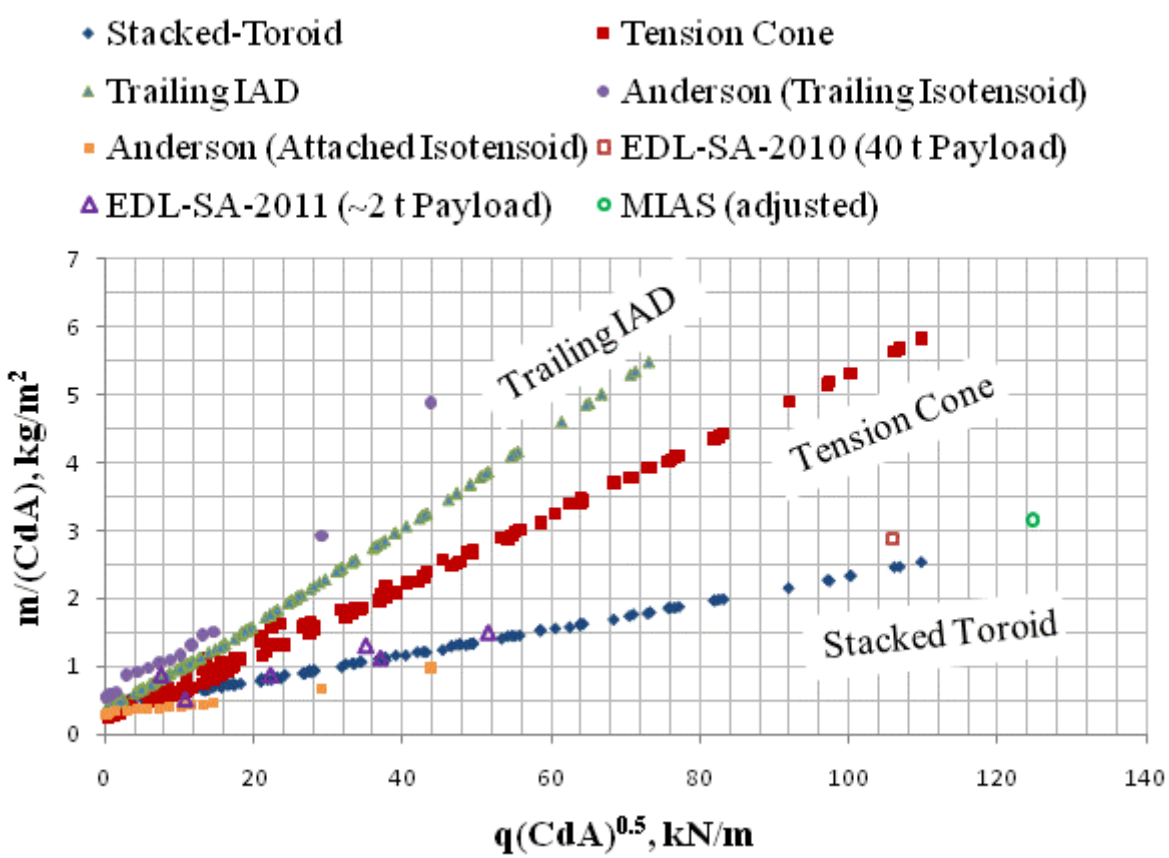
Results, Cont.

Sample Input Parameters (Cases 1-3)

	Common Parameters				
Environment Parameters	2	Hypersonic Regime	Geometry	4.5	Inner Heatshield Diameter, m
	1.5	Drag Coefficient		60	Cone Angle, deg
	100	Static Pressure, Pa		18	Number of Radial Straps
	0	Inflation Gas Temperature, C	Gas	22	Inflation Gas Molecular Weight
	1	Gores Ps / (qCd)		0.3	Inflation System Mass Fraction
Material Properties	3E+09	Radial Straps Yield, Pa	Factor of Safety, Margins, and Knock Down Factors	1.05	Gores Seams Margin
	1440	Radial Straps Material Density, kg/m^3		4	Gores DFS for Loads
	2.54E-05	Toroid Minimum Thickness, m		1	Gores Knock Down
	75	Toroid Fiber Reinforced Bias Angle, deg		4	Toroid Fiber Reinforced DFS
	0.05	Toroid Fiber Gap Ratio (gap over minor diameter)		1	Toroid Fiber Reinforced MGA
	0.5	Toroid Fiber Adhesive or Coating Mass Fraction		1	Toroid Fiber Reinforced Knock Down
	5E+08	Toroid Gas Barrier Material Yield, Pa		4	Toroid Gas Barrier DFS
	1470	Toroid Gas Barrier Material Density, kg/m^3		1	Toroid Gas Barrier knockdown factor
	5.08E-05	Toroid Gas Barrier Minimum Thickness, m		4	Toroid Axial Straps DFS
	1.05	Toroid Gas Barrier Seam Allowance + MGA		1	Toroid Axial Straps MGA
	3E+09	Toroid Axial Straps Material Yield, Pa		1	Toroid Axial Straps Knock Down
	1440	Toroid Axial Straps Material Density, kg/m^3		1.25	Inflation Gas Pressure Margin
	5E+08	Gores Material Yield, Pa		1.25	Inflation Gas MGA
	1470	Gores Material Density, kg/m^3		4	Radial Straps DFS
	10	Gores Material Max Strain, %		1	Radial Straps MGA
	1.4732E-05	Gores Minimum Thickness, m		1	Radial Straps Knock Down

Results, Cont.

- Cases 1-3 with randomly selected diameters (6-40 m) and dynamic pressures (20-3000 Pa) with fiber reinforced fabric concept
- Anderson merit function (NASA-TN-D-5535, 1969)
- Includes flexible materials, inflation gas, & inflation system (30%)
- Excludes TPS, rigid nose, payload adapter, …



Summary

Dimensionless Parameters for IAD Mass:

- **Provide an insight into mass scaling laws**
- **Inflation pressure** **(DGP: dimensionless geometry parameters)**

$$\bar{p}_{\min} = \frac{p_{\min}}{q_{\max} C_d} = f_1(\mathrm{DGP})$$

- **Inflation gas mass**

$$\bar{m}_{\mathrm{gas}} = \left(\frac{\mathrm{m}\, g_e}{A_{\mathrm{IAD}}\ C_d q_{\max}}\right) = \bar{G} \cdot (\bar{p}_{\min} + \Delta \bar{p}_{\mathrm{static}}) \cdot f_2(\mathrm{DGP}) \cdot \bar{D}_o$$

- **Toroid material mass**

$$\bar{m}_{\mathrm{fabric}} = \frac{1}{\bar{\sigma}} \cdot \bar{p}_{\min} \cdot f_3(\mathrm{DGP}) \cdot \bar{D}_o$$

- **Straps and gores**

$$\bar{m}_{\mathrm{radial\ and\ gores}} = \frac{1}{\bar{\sigma}} \cdot f_4(\mathrm{DGP}) \cdot \bar{D}_o$$

Questions