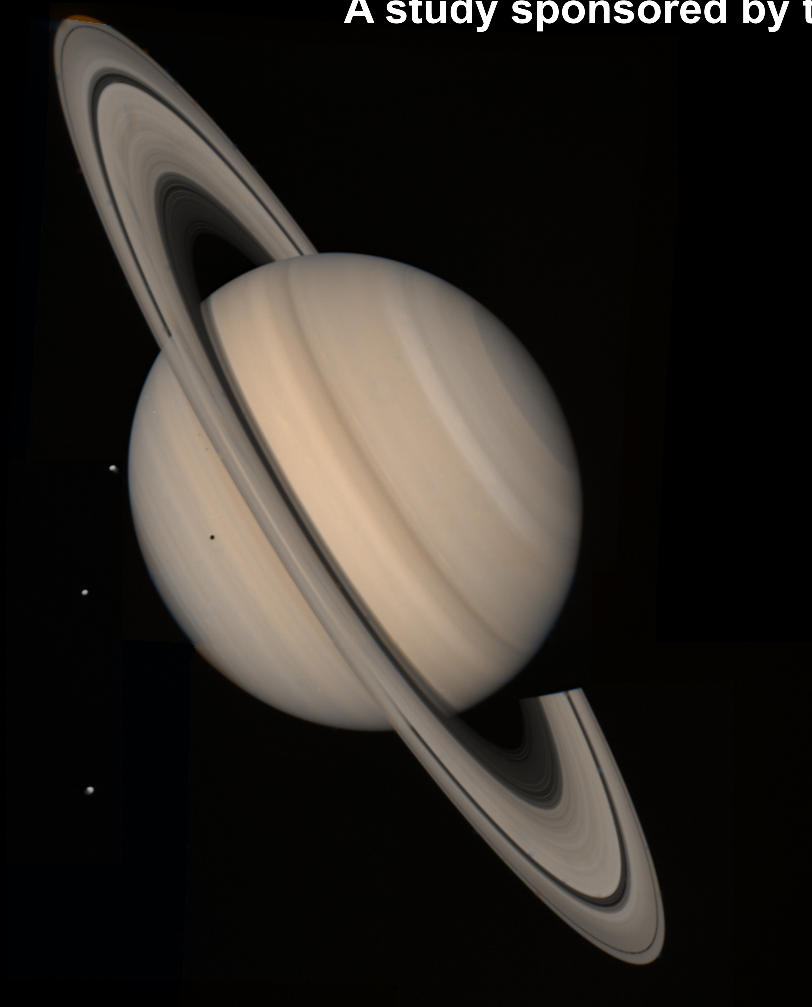
Atmospheric Entry Studies for Saturn Missions: 45° Sphere-Cone Rigid Aeroshells and Ballistic Entries

A study sponsored by the NASA ISPT/EVT Program



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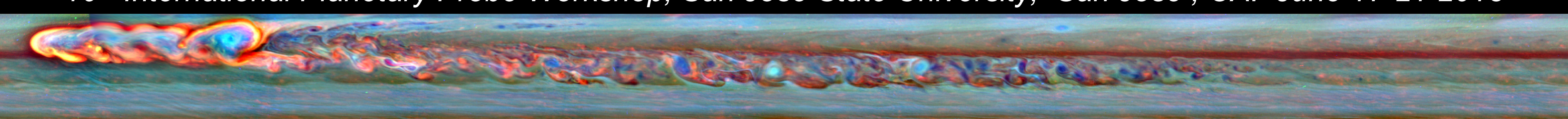

Prologue

- **The experience base for Gas Giant (Jupiter & Saturn) entries:**
  - **Galileo Mission (USA) to Jupiter**

- **We would like to explore the Saturn entry (ballistic) trajectory space:**
  - **With a 45° sphere-cone rigid aeroshell**
    - **Legacy shape from Galileo Mission**
  - **For two heading angles, a range of entry velocities, entry flight path angles, and mass-diameter combinations**

- **Two-tier approach to Saturn science objectives*:**
  - **Tier I (high priority) focused on atmospheric structure & elemental composition**
    - **Desired depth of 5-10 bar (1 bar @ Saturn = 0 km altitude)**
    - **Small number of instruments => Small probe => New Frontiers Class?**
  - **Tier II (lower priority) larger number of science objectives**
    - **Galileo-like instrument suite**

***Ref: Spilker, T, and Atkinson, D H, "Saturn Entry Probe Potential," 9th IPPW, Toulouse, France, June 2012**

Our entry trajectory space exploration is from a thermal protection perspective
We include a science instrument qualification perspective in the exploration

Thermal Protection 101

- **We know**
  - **Peak heat flux helps select appropriate thermal protection material**
  - **Total heat load & bondline temperature constraint sizes the select material**
- **Total heat load depends on how steep or shallow the entry is**
  - **Steep entries: high heat fluxes, pressure & deceleration loads, but low heat loads**
  - **Shallow entries: low heat fluxes, pressure & deceleration loads, but higher heat load than steep entries**
    - **Heat flux might be lower but the heat pulse is wider (in time)**
- **High heat loads require thicker thermal protection (mass inefficiency) to keep the bondline temperature below assumed constraint value**
  - **Material's ablative efficiency is low at low heat flux**

Exploration of entry trajectory space is:
To find how steep one can enter without violating a deceleration load constraint (Science imposed)
and
To find how shallow one can enter without compromising ablative efficiency (Material imposed)

Approaches & Inquiry

- **The "standard" approach with "trades"**
  - **3-DoF trajectory analysis for a given entry mass and capsule size**
  - **Entry flight path angle is the primary variable of interest**
  - **Equatorial and High-Latitude entries are considered**

- **This "standard" approach assumes thermal protection materials**
  - **Are readily available (or can be manufactured)**
  - **Can be tested and qualified for flight**

- **Materials development is somewhat disconnected from early trade studies**

- **Can we add notional materials performance parameters of pressure (and heat flux) to the "standard" approach ?**
  - **Operational pressure limits (not always known) vary from material to material**
  - **Materials are usually not subject to comprehensive tests to establish "failure" boundaries and/or mechanisms**

We take a "what if" approach with notional limits of material performance
Determine how these notional limits impact the entry trajectory space

45° Sphere-cone Rigid Aeroshell – A Legacy Config.

Basis for Present Study

- **Entry type: Prograde only (Retrograde entries are Galileo-like)**
- **Heading angles (ψ_E): 90° (equatorial) and 30° (high latitude)**
- **Entry velocity (V_E) – 26, 27, and 28 km/s (relative)***
  - **Interplanetary trajectories assumed available**
- **Ballistic coefficient (β_E) – Mass and Diameter combinations**
  - **Attempt to cover Tier-I and Tier-II size entry capsules**
- **Entry flight path angle (γ_E) – Between skip out and -30°**
  - **Steep entries**
    - **Best for extracting performance from ablating materials**
  - **Shallow entries**
    - **Ablative materials are less mass efficient**
    - **Increased sensitivity of heat shield mass to entry flight path angle**

***Ref: Spilker, T, and Atkinson, D H, "Saturn Entry Probe Potential," 9th IPPW, Toulouse, France, June 2012**

The goal is find steep & shallow entry limits for various V_E–β_E combinations

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Entry Trajectory Space
Ballistic Coefficient (β_E)

$$\beta_E = \frac{4m_E}{C_D \pi D_b^2}$$

Ballistic coefficients, kg/m²

Table entries assume C_D = 1.05 for a 45° sphere-cone

	Diameter, m		
Mass, kg	**0.8**	**1.0**	**1.3**
200	379	**243**	143
250	474	303	179

Galileo Probe

- Entry mass = 335 kg
- Entry velocity = 59.9 km/s
- Entry flight path angle = -6.64°
- Probe type = 45° sphere-cone
- Probe diameter = 1.26 m
- Entry BC = 256 kg/m²
- Heatshield material = FDCP

Focus on Tier-I science only – only 2 to 3 instruments
200 kg case is the basis of discussion
β_E of 243 kg/m² similar to Galileo probe
Some mass and diameter combinations are perhaps not physically realizable

Process

- Orton model for atmosphere with entry interface at 200 km
- 3-DoF trajectories constructed using *TRAJ* (in-house tool)
  - Simulations terminated at Mach 0.8 (parachute deployment)
- For each V_E–β_E combination generate flight trajectories for range of γ_E
- For each flight trajectory, record:
  - Peak deceleration load
  - Peak pressure load (stag. point, correlation)
  - Peak heat flux (stag. point, correlations for conv. & rad. heating)
  - Total heat load (time-integrated stag. point total heat flux)
- No margins for uncertainties in environments
- The process is <u>independent</u> of thermal protection material
  - We can *choose* a material with a calibrated thermal response model and size it for the estimated total heat loads

From the databank of trajectories, determine steep & shallow entry flight path angle limits based on performance constraints

Constraints

Deceleration load: Examine sensitivity to 100 g and 200 g

- **Deceleration load limit determines steepest entry angle for a V_E–β_E combination**

Pressure load: Examine sensitivity to 5 bar and 10 bar

- **Pressure load limit *also* determines steepest entry angle for a V_E–β_E combination**

- **Are g load and pressure load limits mutually exclusive?**

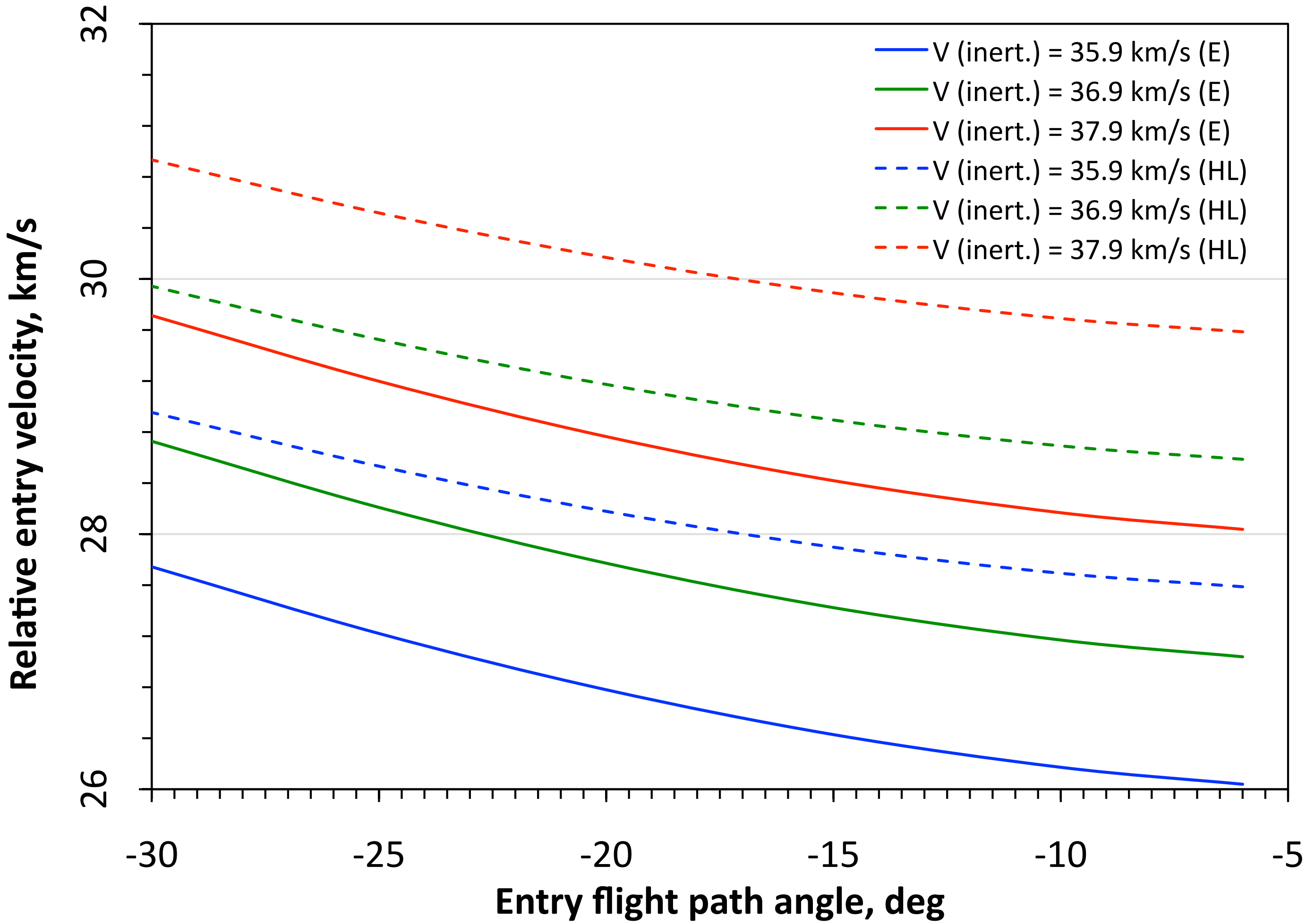
Total heat load: Determine "knee in the curve"

- **"Knee in the curve" of the heat load distribution is point of *max.* curvature**
- **Tie "knee in the curve" idea to "mass inefficiency" of TPS**
- **Heat load limit determines shallowest entry angle for a V_E–β_E combination**

The 200 g deceleration load limit assumes centrifuges are available
The 10 bar pressure limit is from Galileo probe
There is subjectivity in choice of constraints and limit values

Inertial vs Relative Velocity

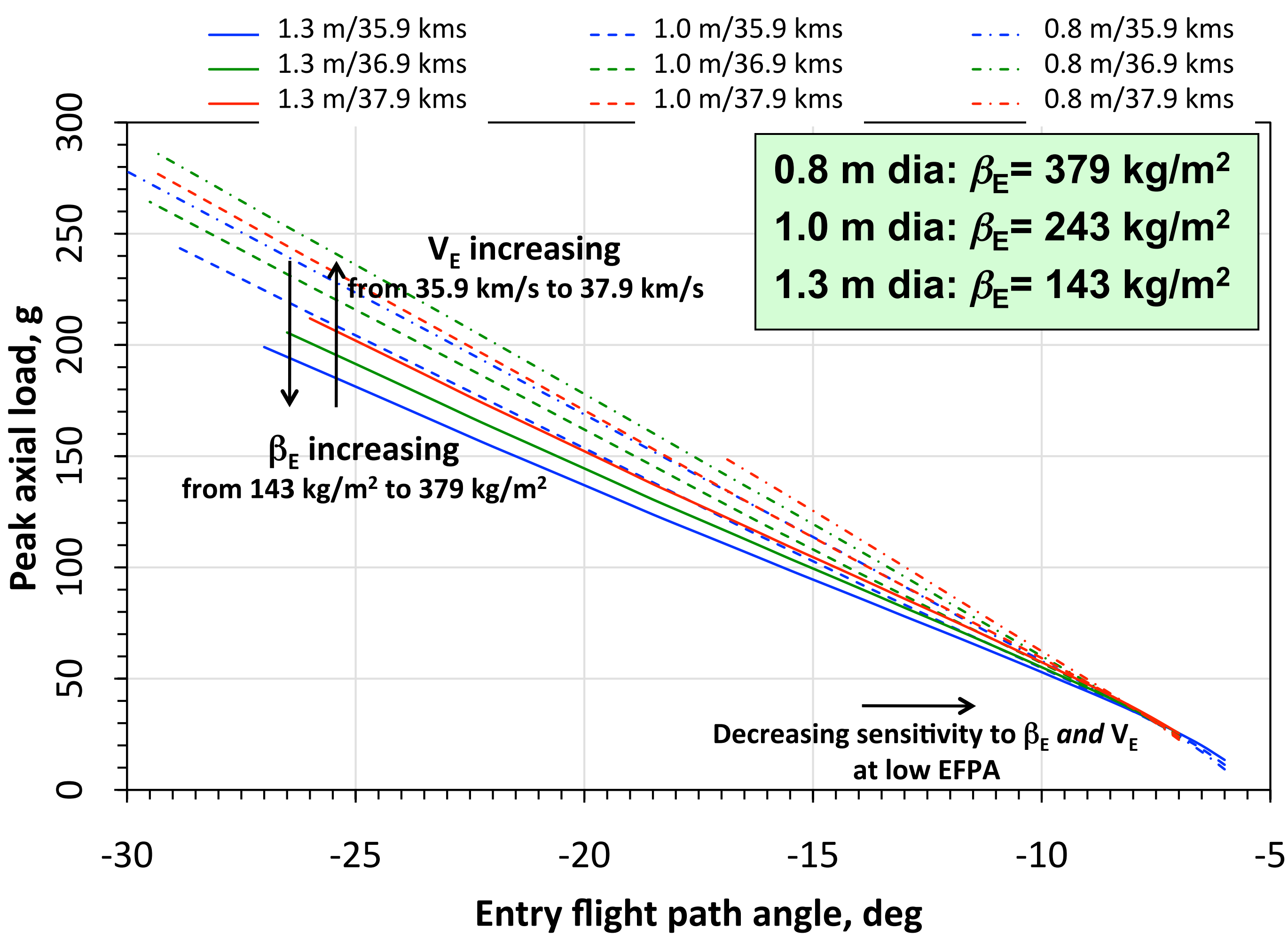
Need to account for rotating planet



Saturn has a sidereal rotation period of 10.57 hours
Inertial velocity kept fixed for all entry & heading angles for a given β_E

Deceleration Loads (High Latitude)

200 kg Entry Mass – β_E varying, V_E varying



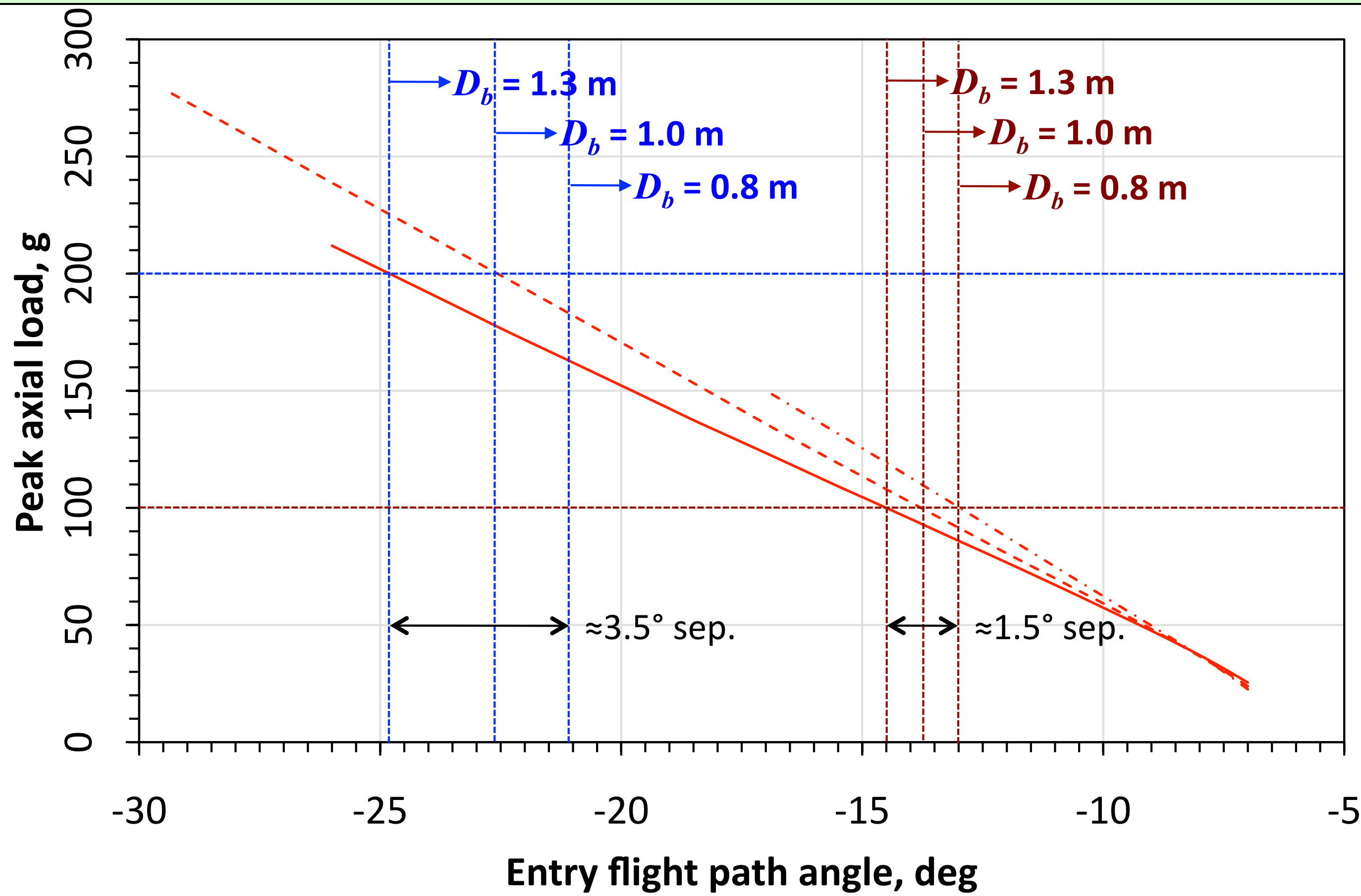
- **Each point on a curve is a 3-DoF trajectory**
- **For fixed V_E, pk. dec. load *decreases* with *increasing* β_E**
- **For fixed β_E, pk. dec. load *increases* with *increasing* V_E**
- **For $\gamma_E > -10°$, pk. dec. load *insensitive* to V_E and β_E**

The highest V_E bounds peak deceleration loads for each β_E
Sufficient to look at V_E = 37.9 km/s case

Deceleration Loads (High Lat.) – 100 & 200 g Limits

200 kg Entry Mass, V_E = 37.9 km/s (bounding case)

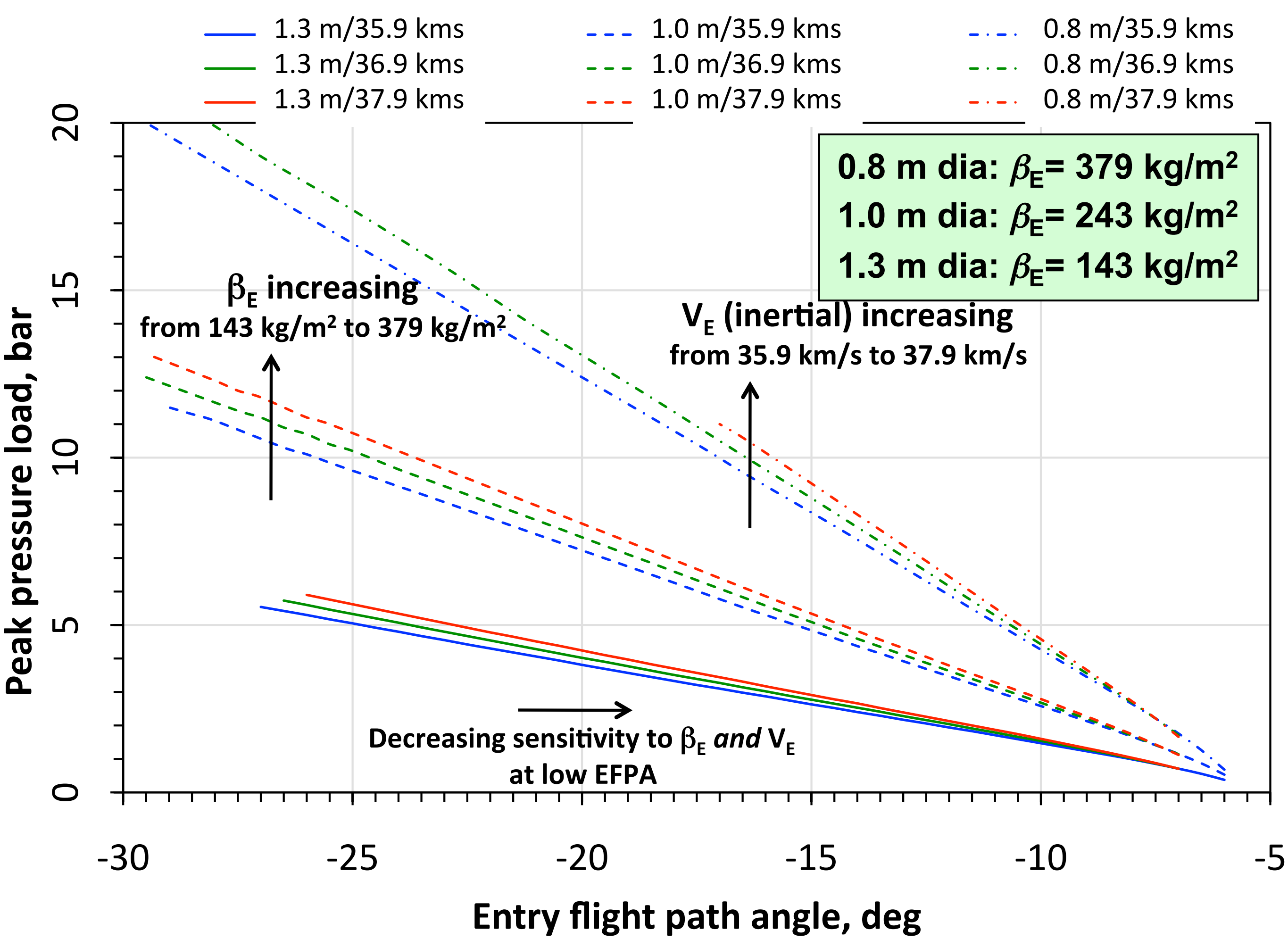
0.8 m dia: β_E= 379 kg/m², 1.0 m dia: β_E= 243 kg/m², 1.3 m dia: β_E= 143 kg/m²



Separation between ballistic coefficients increases with increasing g load limit

Pressure Loads (High Latitude)

200 kg Entry Mass – β_E varying, V_E varying



- Each point on a curve is a 3-DoF trajectory
- For fixed V_E, pk. pres. load *increases* with *increasing* β_E
- For fixed β_E, pk. pres. load *increases* with *increasing* V_E
- For $\gamma_E > -10°$, pk. pres. load *insensitive* to V_E & β_E

The highest V_E bounds peak pressure loads for each β_E
Sufficient to look at V_E = 37.9 km/s case

Pressure Loads (High Lat.) – 5 & 10 bar limits

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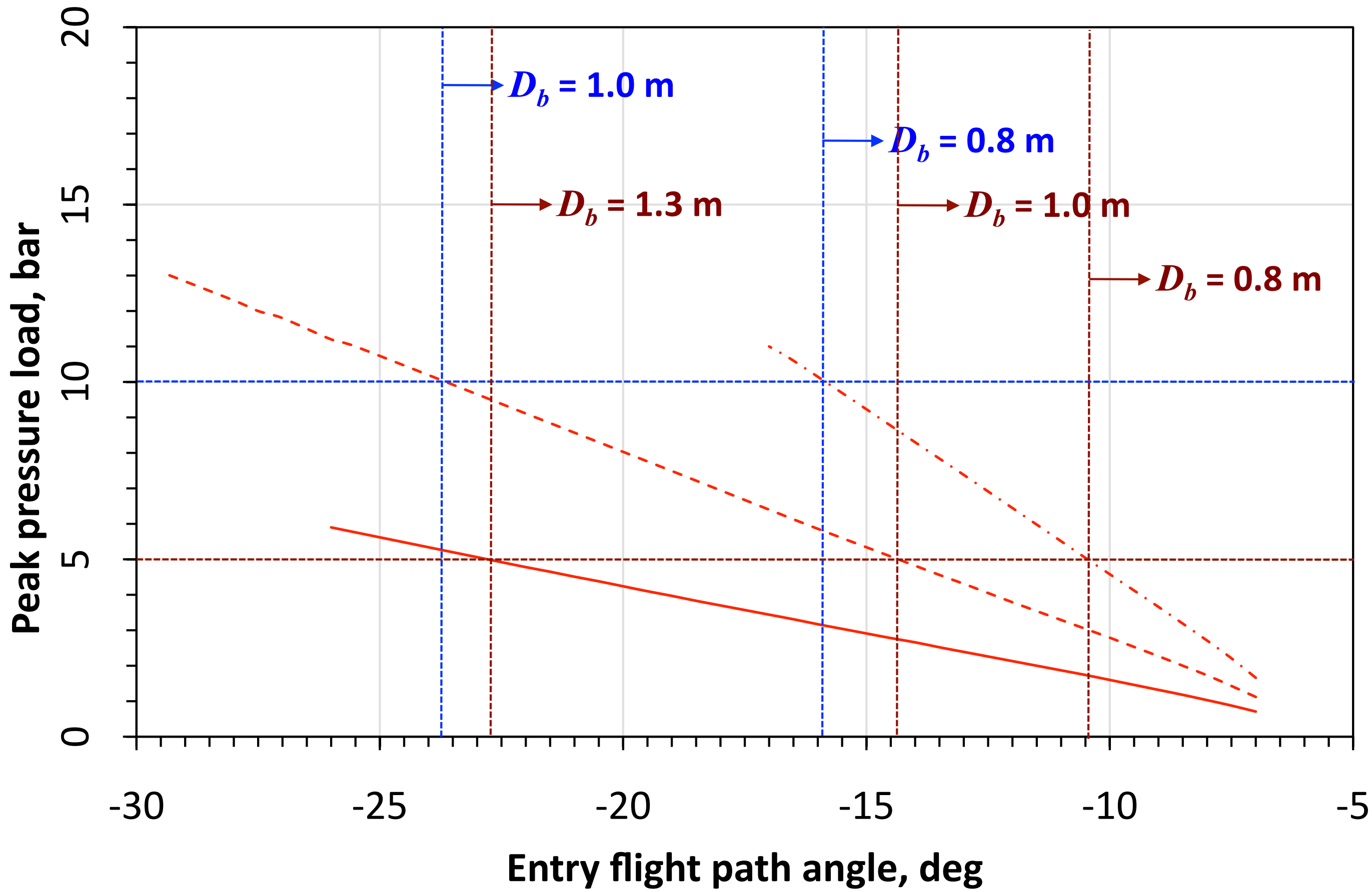
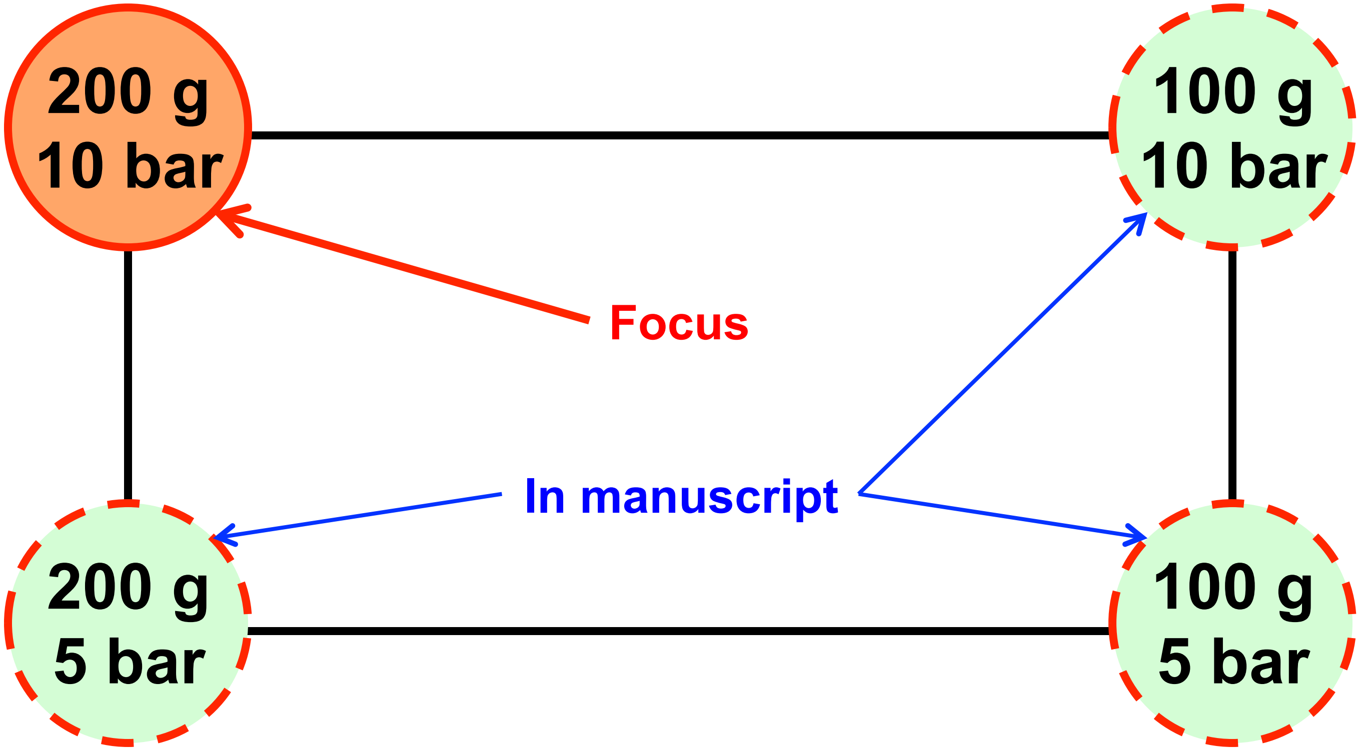


Are the deceleration load and pressure load constraints mutually exclusive? The answer is, "Yes. For some ballistic coefficients, pressure is the key"

Pressure Load Limit vs Deceleration Load Limit

200 kg Entry Mass, V_E = 37.9 km/s (bounding case)

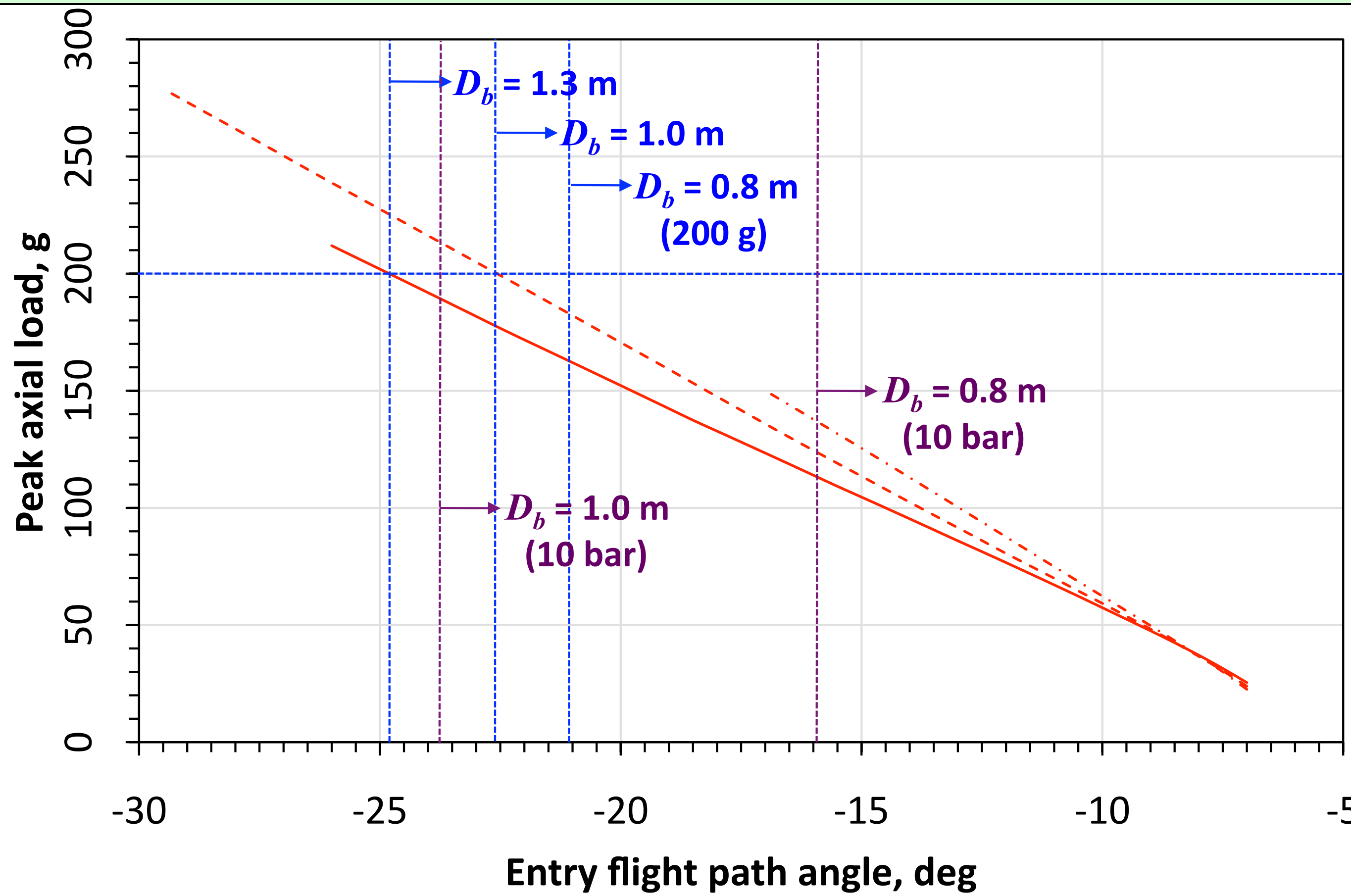
4 Cases to examine



The possibilities represent "what if" scenarios with combinations of *assumed* peak deceleration and pressure load limits

High Latitude, Case 1: 200 g and 10 bar Limits
200 kg Entry Mass, V_E = 37.9 km/s (bounding case)

0.8 m dia: β_E= 379 kg/m^2, 1.0 m dia: β_E= 243 kg/m^2, 1.3 m dia: β_E= 143 kg/m^2



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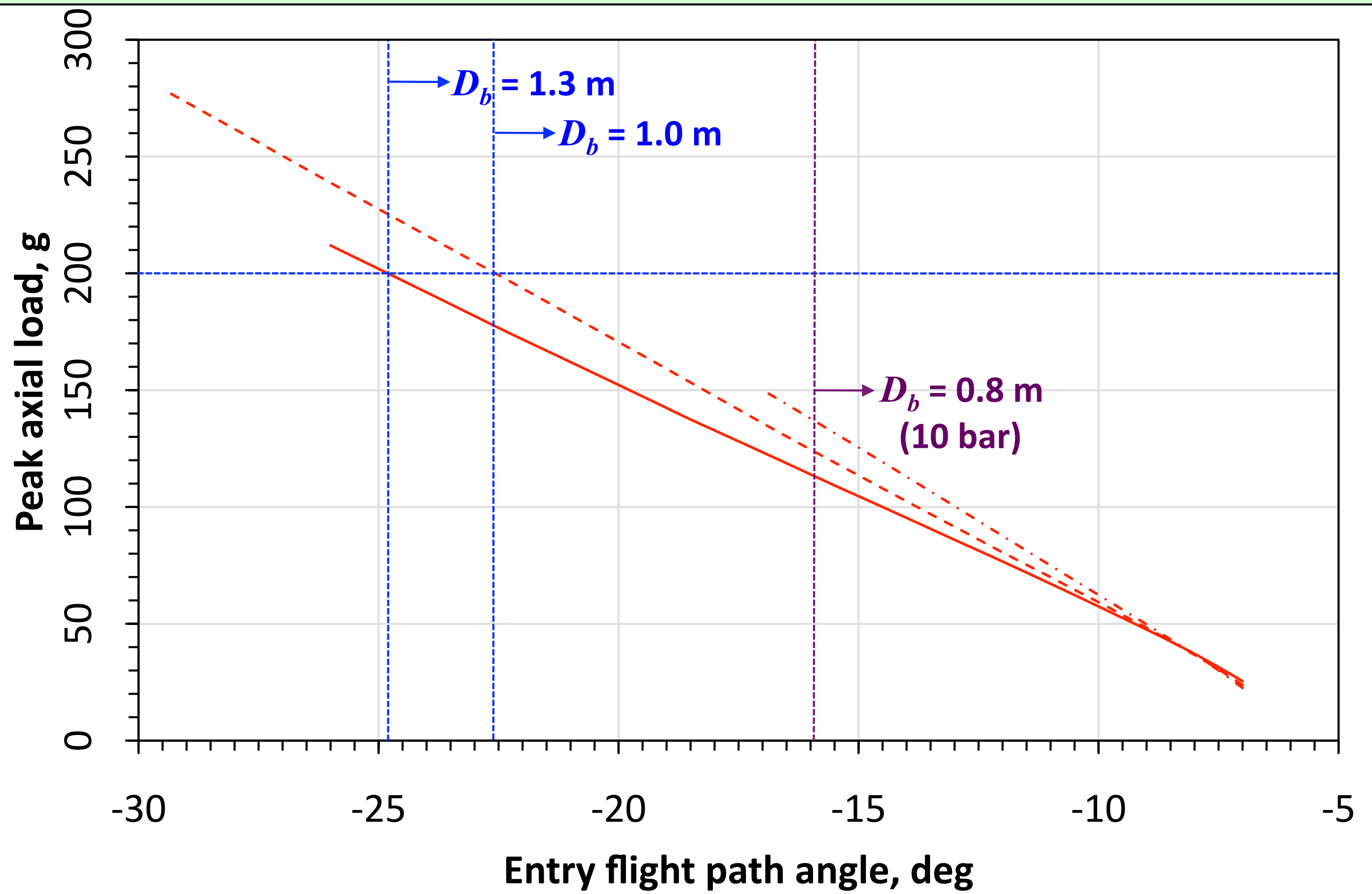
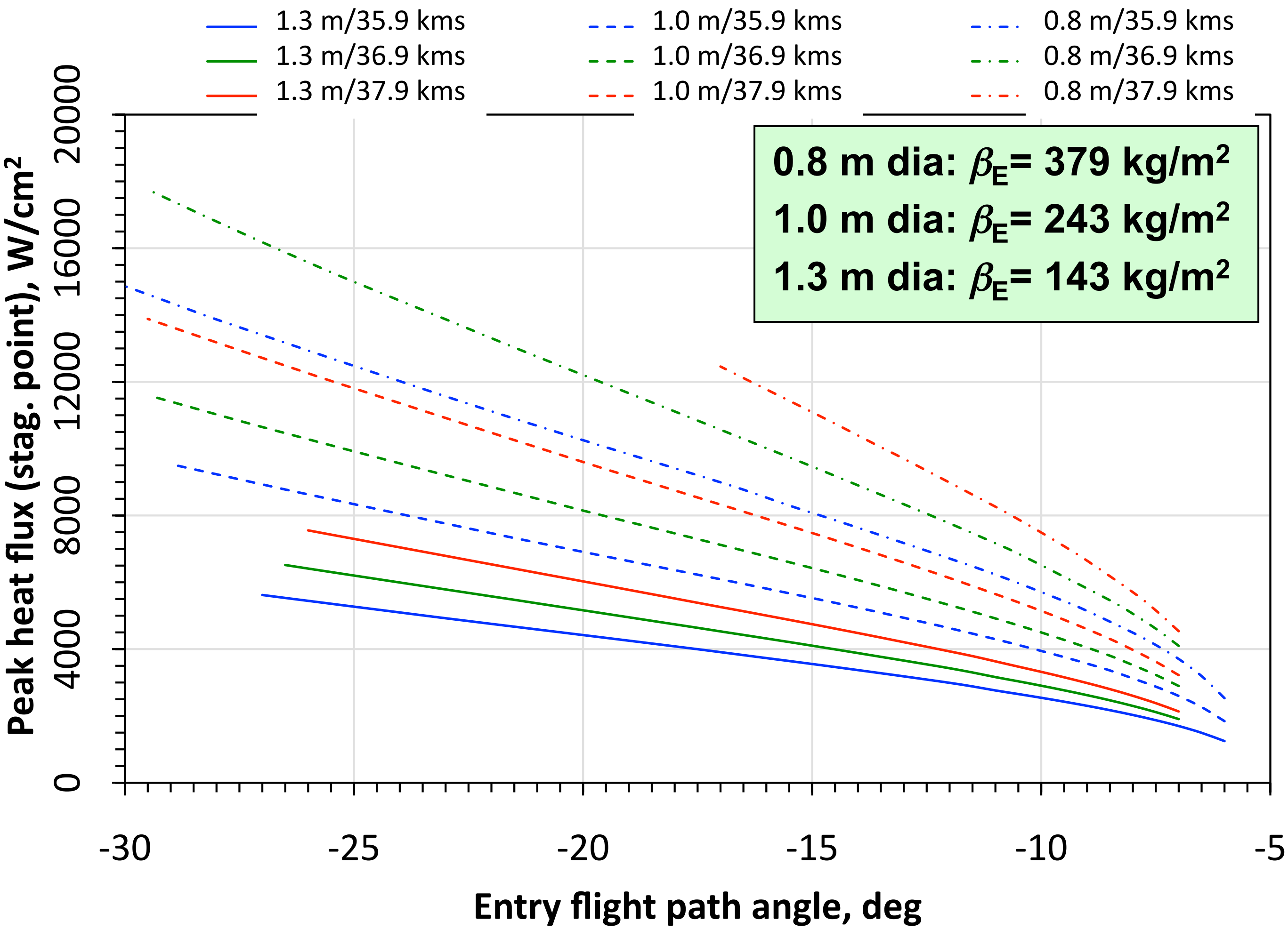


For 0.8 m dia., steepest entry is determined by the pressure limit (10 bar)
For 1.0 m and 1.3 dia, steepest entry is determined by g load limit

Peak Heat Flux (High Latitude)

200 kg Entry Mass – β_E varying, V_E varying



- Each point on a curve is a 3-DoF trajectory
- For fixed V_E, pk. heat flux *increases* with *increasing* β_E
- For fixed β_E, pk. heat flux *increases* with *increasing* V_E

Heating environments for high latitude entries are severe!!
The highest V_E bounds peak heat fluxes for each β_E
Sufficient to look at V_E = 37.9 km/s case

Peak Heat Flux (High Latitude)

200 kg Entry Mass, V_E = 37.9 km/s (bounding case)

Entry Systems and Technology Division

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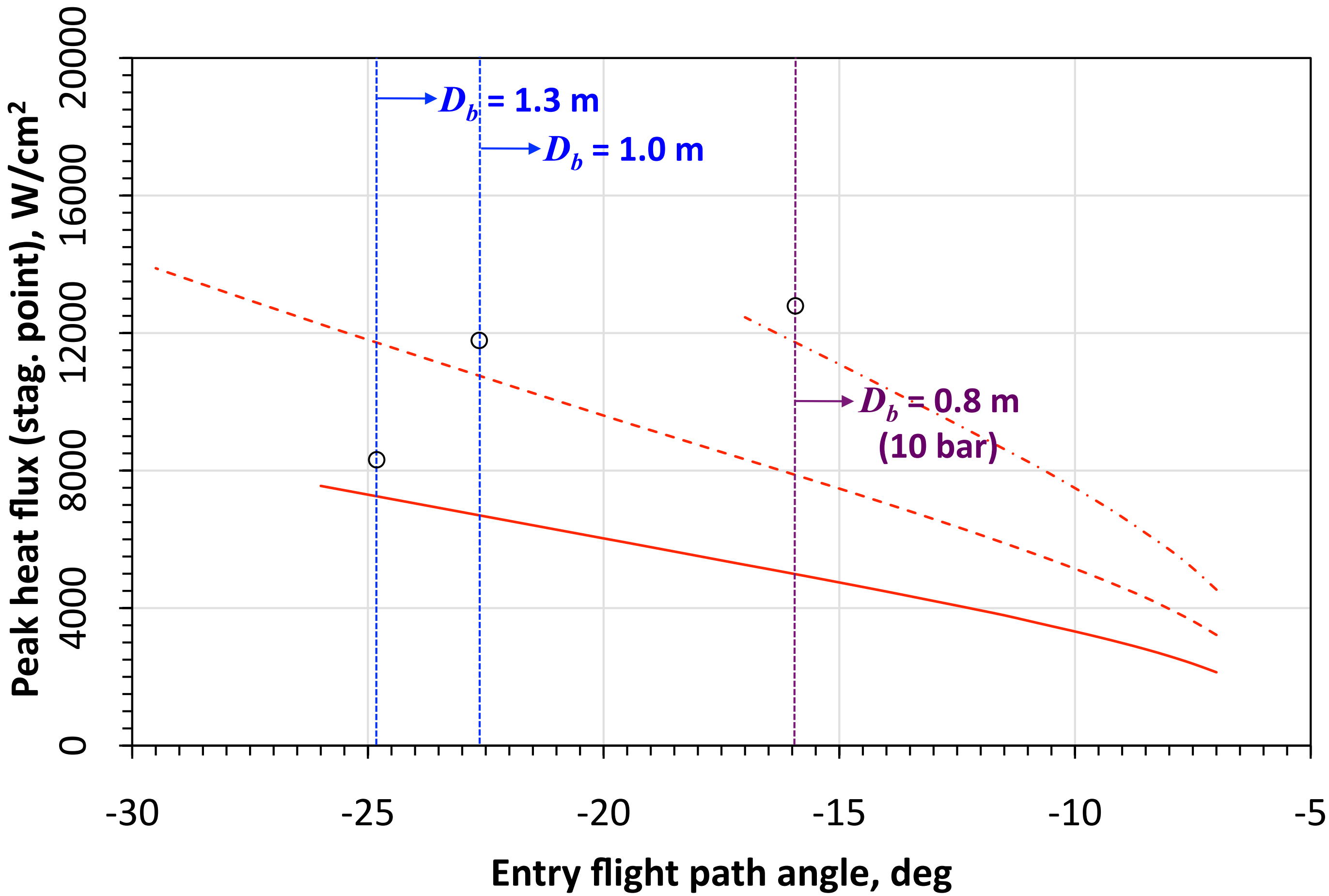
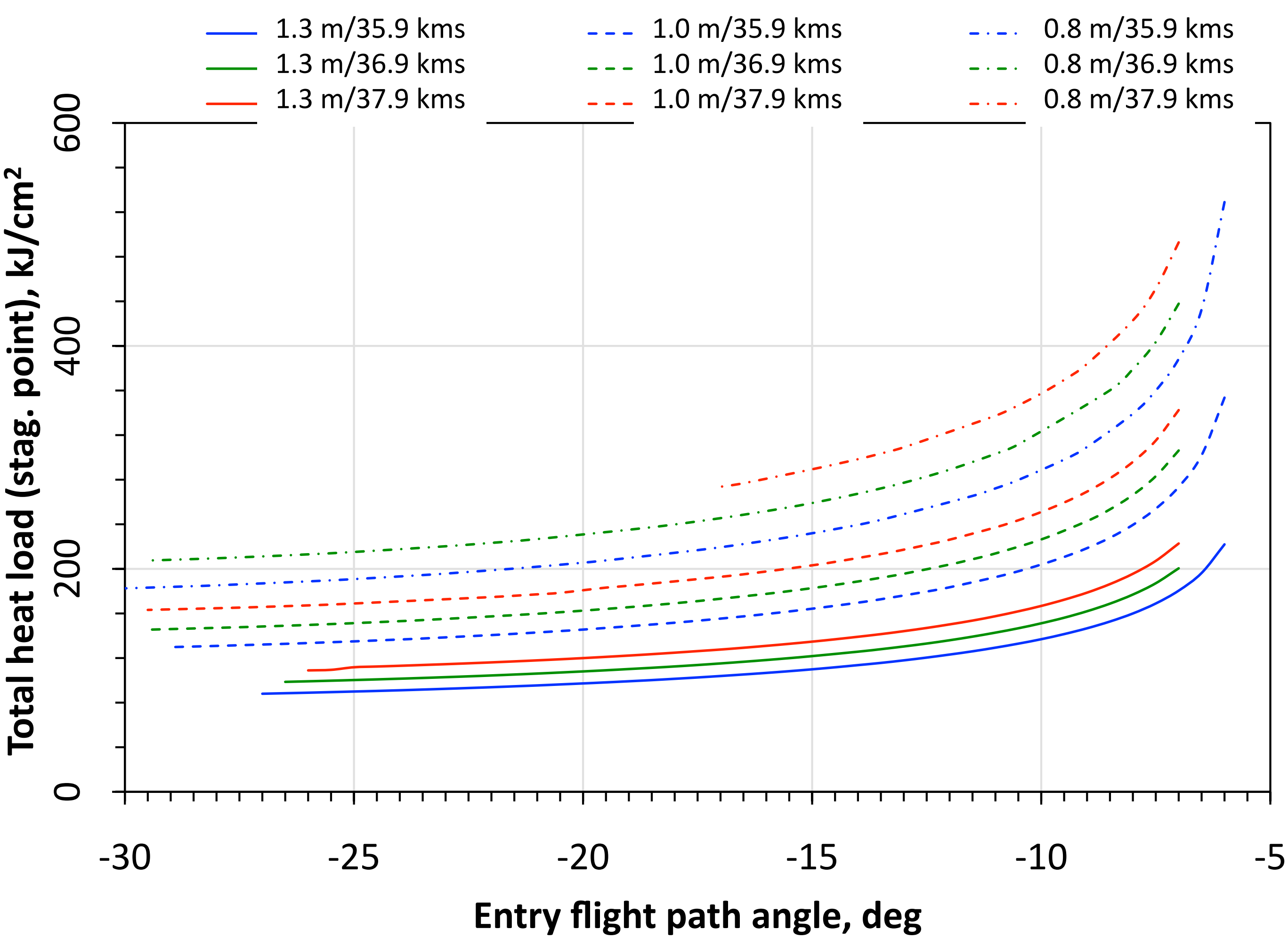


0.8 m dia. case has high peak heat flux *and* pressure at steepest entry
Heat fluxes greater than 2.5 kW/cm^2 are hard to achieve in current arc jets

Total Heat Loads (High Latitude)

200 kg Entry Mass – β_E varying, V_E varying



- **Each point on a curve is a 3-DoF trajectory**
- **For fixed V_E, total heat load *increases* with *increasing* β_E**
- **For fixed β_E, total heat load *increases* with *increasing* V_E**

The highest V_E bounds peak heat fluxes for each β_E
Sufficient to look at V_E = 37.9 km/s case
Determine "max. curvature" of total heat load distributions

Total Heat Loads (High Latitude)

200 kg Entry Mass, V_E = 37.9 km/s (bounding case)

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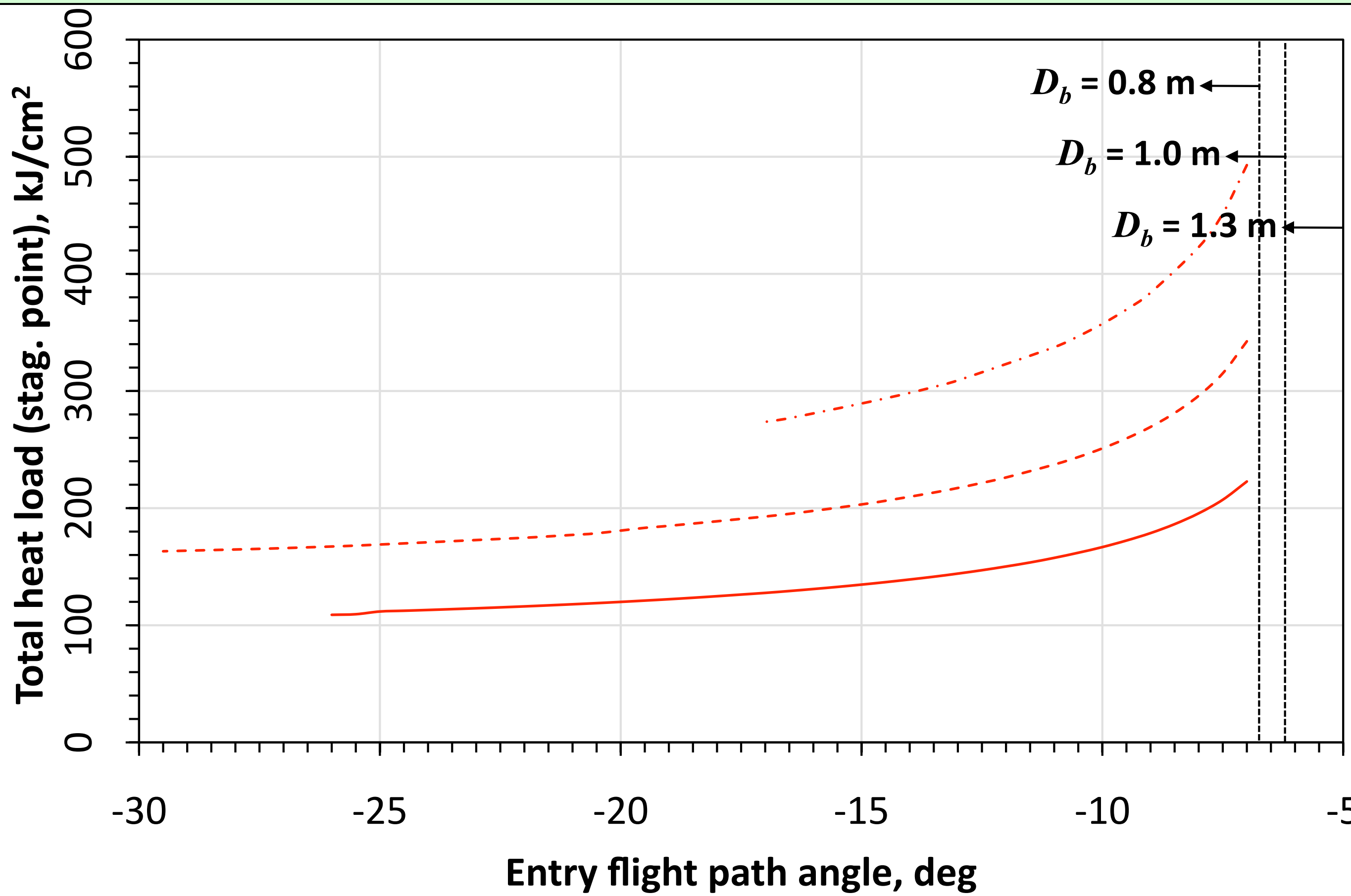
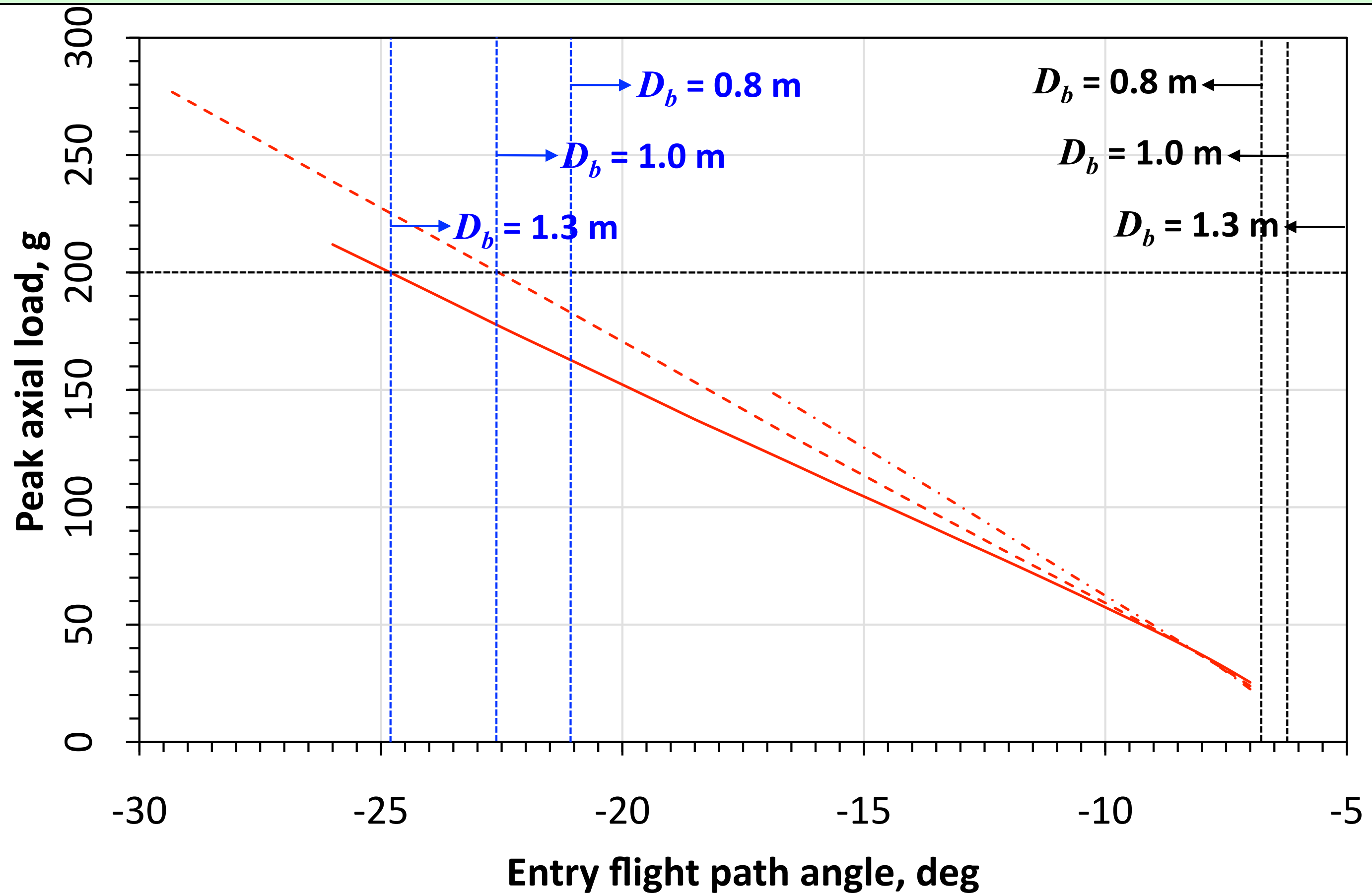


Entry angles correspond to max. curvature in heat load curves for highest β_E
These entry angles close the entry flight path angle interval at the shallow end

Putting it All Together (High Latitude)

200 kg Entry Mass, V_E = 37.9 km/s, 200g, 10 bar

0.8 m dia: β_E= 379 kg/m^2, 1.0 m dia: β_E= 243 kg/m^2, 1.3 m dia: β_E= 143 kg/m^2



Large entry flight path angle window across all three ballistic coefficients

Summary and Some Findings

Observations are strictly for a 45° sphere-cone Rigid Aeroshell

Entry Systems and Technology Division

- **Sufficient to examine just ballistic coefficient–entry angle space (β_E-γ_E space) for the highest entry velocity**
- **Hypothesized that pressure load can be constraining**
  - **The actual limit value varies from material to material**
  - **Two values – 5 bar and 10 bar – used to determine impact on steep entries**
- **Entry flight path angle windows established for 4 combinations of deceleration load and pressure load limits**
- **Highest ballistic coefficient (379 kg/m^2) clearly limited by pressure load limit**
  - **Suggests existence of a critical ballistic coefficient above which pressure becomes the driver in the steep entry limit**
- **Aerothermal environments for high latitude entries are severe**
  - **Fortunately not Galileo-like, even if material response is factored in**
  - **Material will have to be very robust mechanically in severe thermal environments**
  - **Ground-test facilities to replicate environments??**

Other Lines of Inquiry

- **Is there a heatflux threshold that could be used as constraint?**
  - **Below the threshold the material's ablative "efficiency" drops**
  - **Could use this constraint to determine shallowest entry angle?**

- **How about arc jet test envelopes?**
  - **No single arc jet can provide complete coverage of heating along a trajectory**
  - **Might have to resort to piecewise testing of material in different facilities**
  - **Max. test pressure could be used to determine steepest entry angle?**

- **Despite systematization, the procedure misses**
  - **Acreage environments – required for shear (an important component)**
  - **Structural material and sizing instead of a one-size-fits-all approach used**

- **High fidelity flow field analyses will be necessary to address these issues**

Epilogue

- **Retain rigid aeroshell idea, but change L/D (angle of attack or geometry)**
  - This includes Aerocapture
  - Aerocapture well studied for Neptune under ISPT program
- **Retain rigid aeroshell idea, but change thermal protection material**
  - Can the results of this study help guide the development of new materials?
  - Improved mass efficiency through tailoring of material thermal properties

Last idea is currently funded by the NASA Space Technology Program

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