Ballistic Entries at Venus

A study sponsored by the NASA ISPT/EVT Program

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Prologue

- **Current Venus mission concepts have:**
  - **Entry masses much larger (>3-5x) compared to Pioneer-Venus Large Probe**
  - **Plans to land as much as 1000 kg on the surface of the planet**
  - **An instrument suite (inside the lander) for atmospheric and surface science**
- **We would like to explore the Venus entry (ballistic) trajectory space:**
  - **With a 45° sphere-cone rigid aeroshell**
    - **Legacy shape from Pioneer Venus**
    - **Used in proposed mission concepts**
  - **For a range of entry velocities, entry flight path angles, and mass-diameter combinations**
- **The experience base for Venus entries:**
  - **Pioneer Venus Multiprobe Mission (USA)**
  - **Numerous Venera missions (Russia)**

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**
- **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**
- **Heading angle (ψ_E): Not particularly relevant at Venus**
- **Entry velocity (V_E) – 10.8, 11.2, and 11.6 km/s (inertial)**
  - **Interplanetary trajectories assumed available**
- **Ballistic coefficient (β_E) – Mass and Diameter combinations**
  - **Attempt to cover VME, VCM, VITaL-class 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**

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

Entry Trajectory Space
Ballistic Coefficient (β_E)

Ballistic coefficients, kg/m^2

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

	Diameter, m		
Mass, kg	**2.5**	**3.5**	**4.5**
1500	291	148	*90*
1750	340	173	105
2000	388	**198**	120
2250	*437*	223	135
2500	*485*	247	150
2750	*534*	272	165

Pioneer-Venus Large Probe

- **Entry mass = 316.5 kg**
- **Entry velocity = 11.54 km/s**
- **Entry flight path angle = -32.4°**
- **Probe type = 45° sphere-cone**
- **Probe diameter = 1.42 m**
- **Entry BC = 190 kg/m^2**
- **Heatshield material = FDCP**

2000 kg case is the basis of discussion
β_E of 198 kg/m^2 similar to Pioneer Venus probes & current mission concepts
Some mass and diameter combinations are perhaps not physically realizable

Process

- **VenusGRAM 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?**

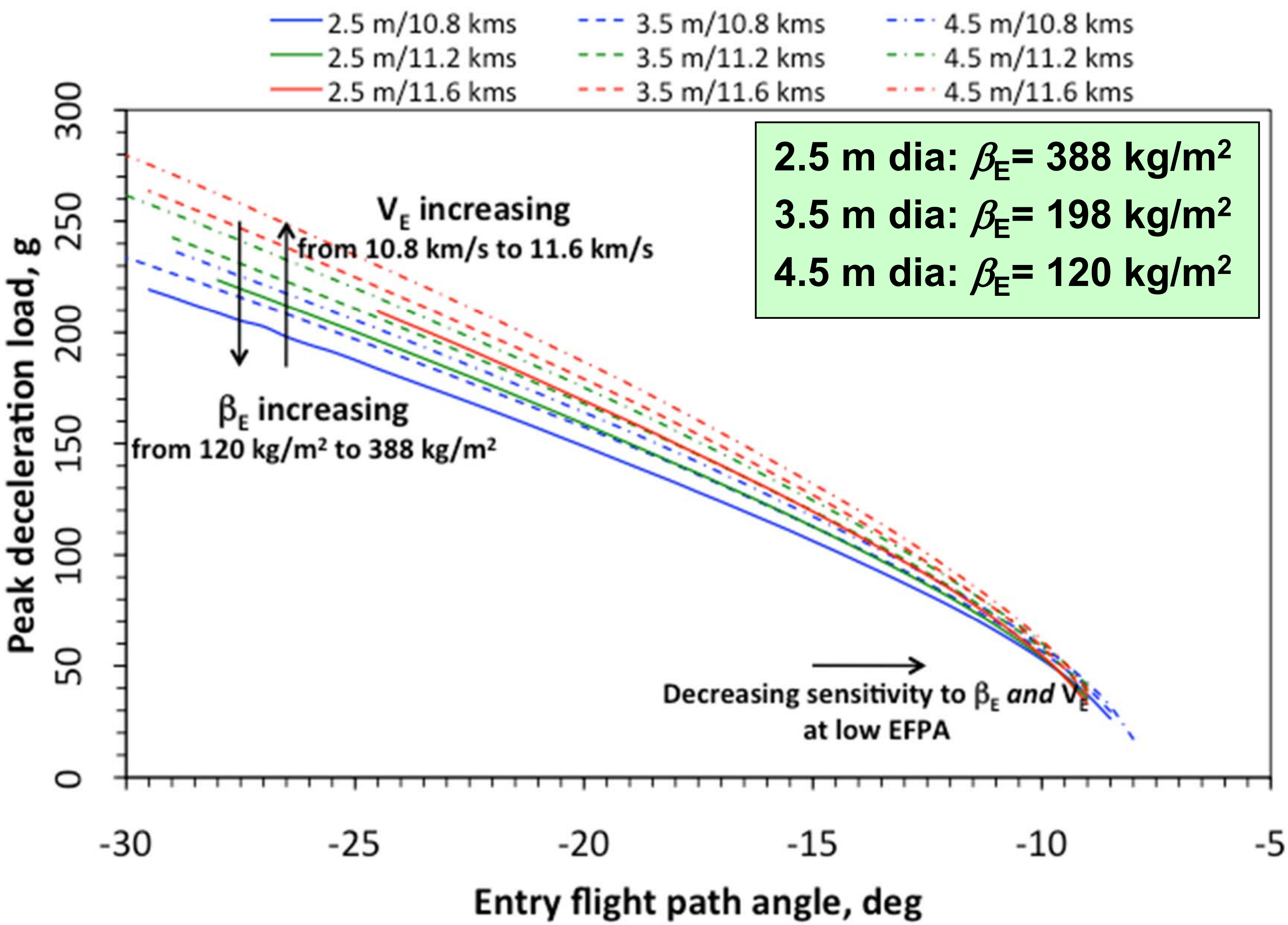
Total heat load: Determine "knee in the curve"

- **"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 Pioneer Venus Large & Day Probes
There is subjectivity in choice of constraints and limit values

Deceleration Loads

2000 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**

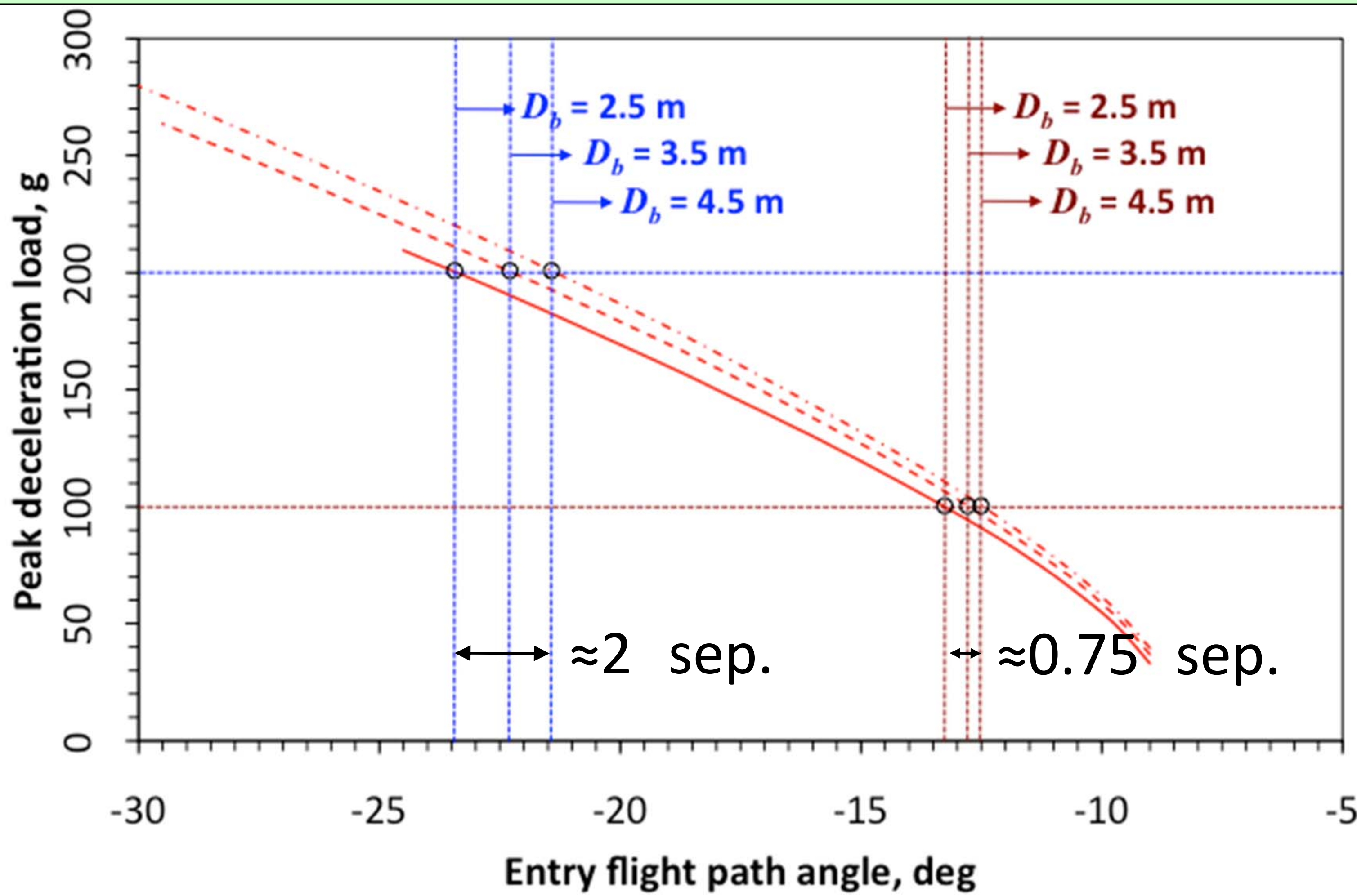
The highest V_E bounds peak deceleration loads for each β_E
Sufficient to look at V_E = 11.6 km/s case

Deceleration Loads – 100 & 200 g Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

Entry Systems and Technology Division

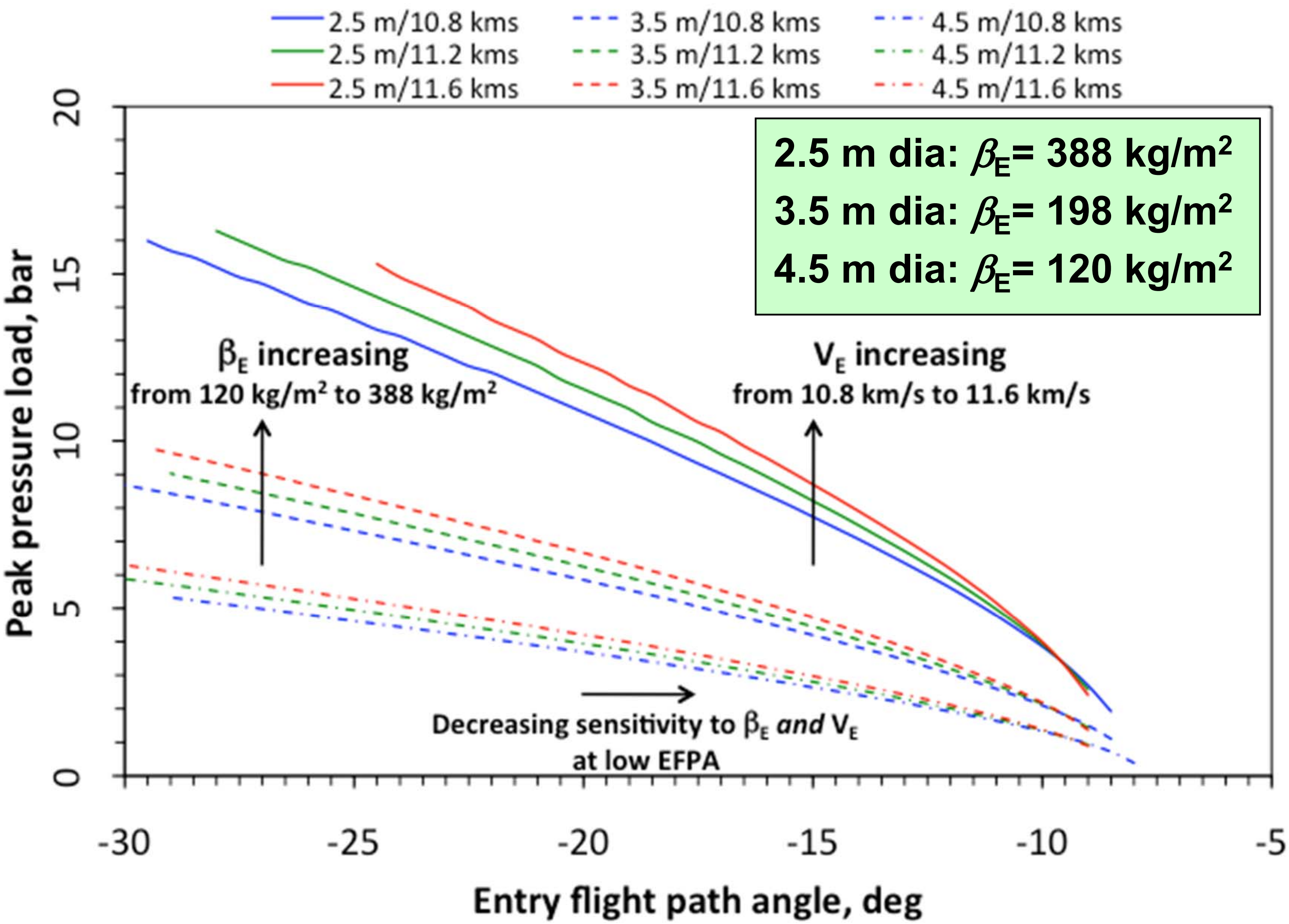
2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2



Separation between ballistic coefficients increases with increasing g load limit

Pressure Loads

2000 kg Entry Mass – β_E varying, V_E varying



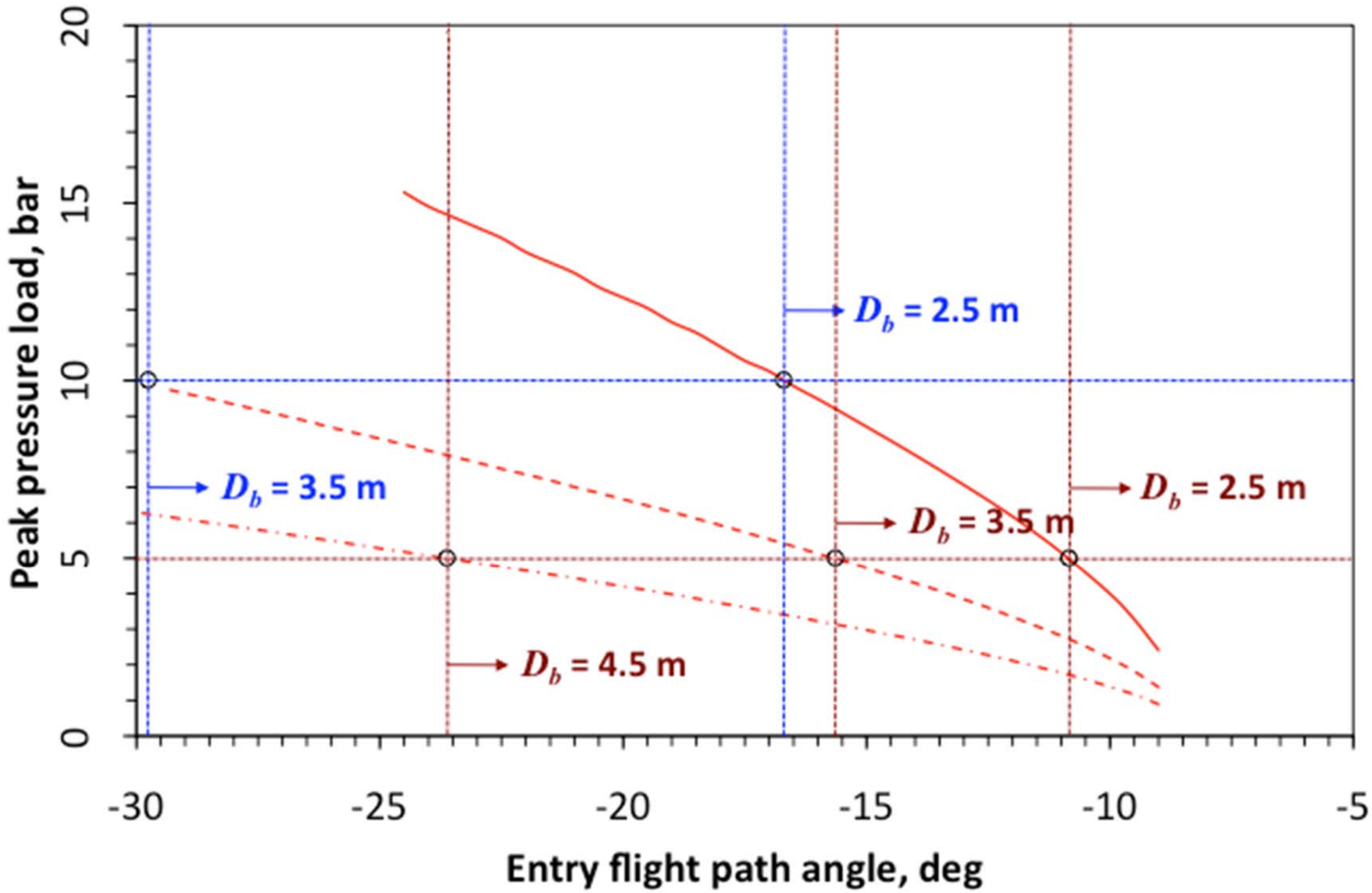
- **Each point on a curve is a 3-DoF trajectory**
- **For fixed V_E, pk. pres. load *increases* with *increasing* β_E**
- **For fixed β_E, pk. pres. load *increases* with *increasing* V_E**
- **For $\gamma_E > -10°$, pk. pres. load *insensitive* to V_E & β_E**

The highest V_E bounds peak pressure loads for each β_E
Sufficient to look at V_E = 11.6 km/s case

Pressure Loads – 5 & 10 bar limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

2.5 m dia: β_E= 388 kg/m², 3.5 m dia: β_E= 198 kg/m², 4.5 m dia: β_E= 120 kg/m²

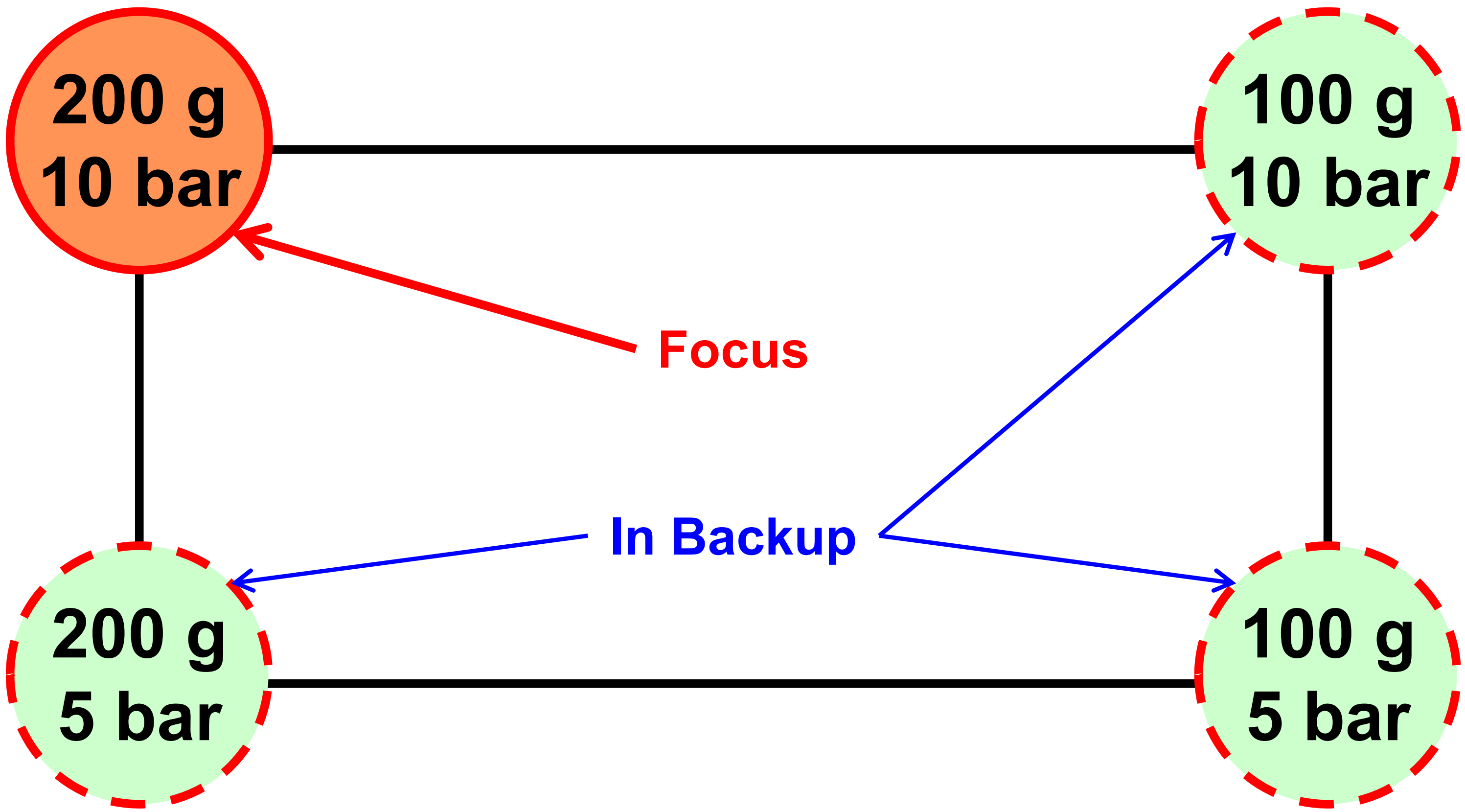


Are the deceleration load and pressure load constraints mutually exclusive?
The answer is, "Yes. For some ballistic coefficients, pressure is the key"

Pressure Load Limit vs Deceleration Load Limit

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

4 Cases to examine

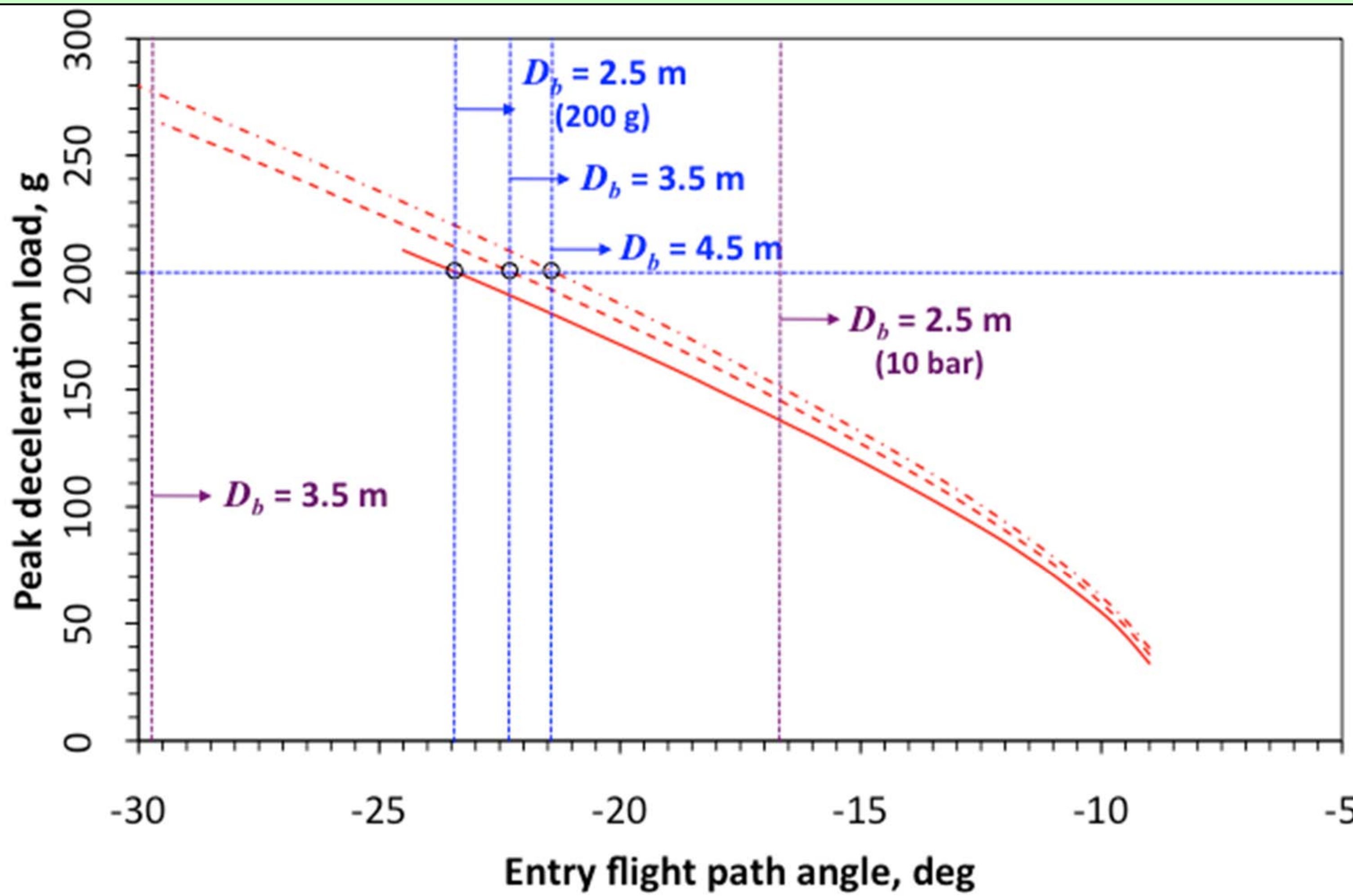


The possibilities represent "what if" scenarios with combinations of *assumed* peak deceleration and pressure load limits

Case 1: 200 g and 10 bar Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2



Case 1: 200 g and 10 bar Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

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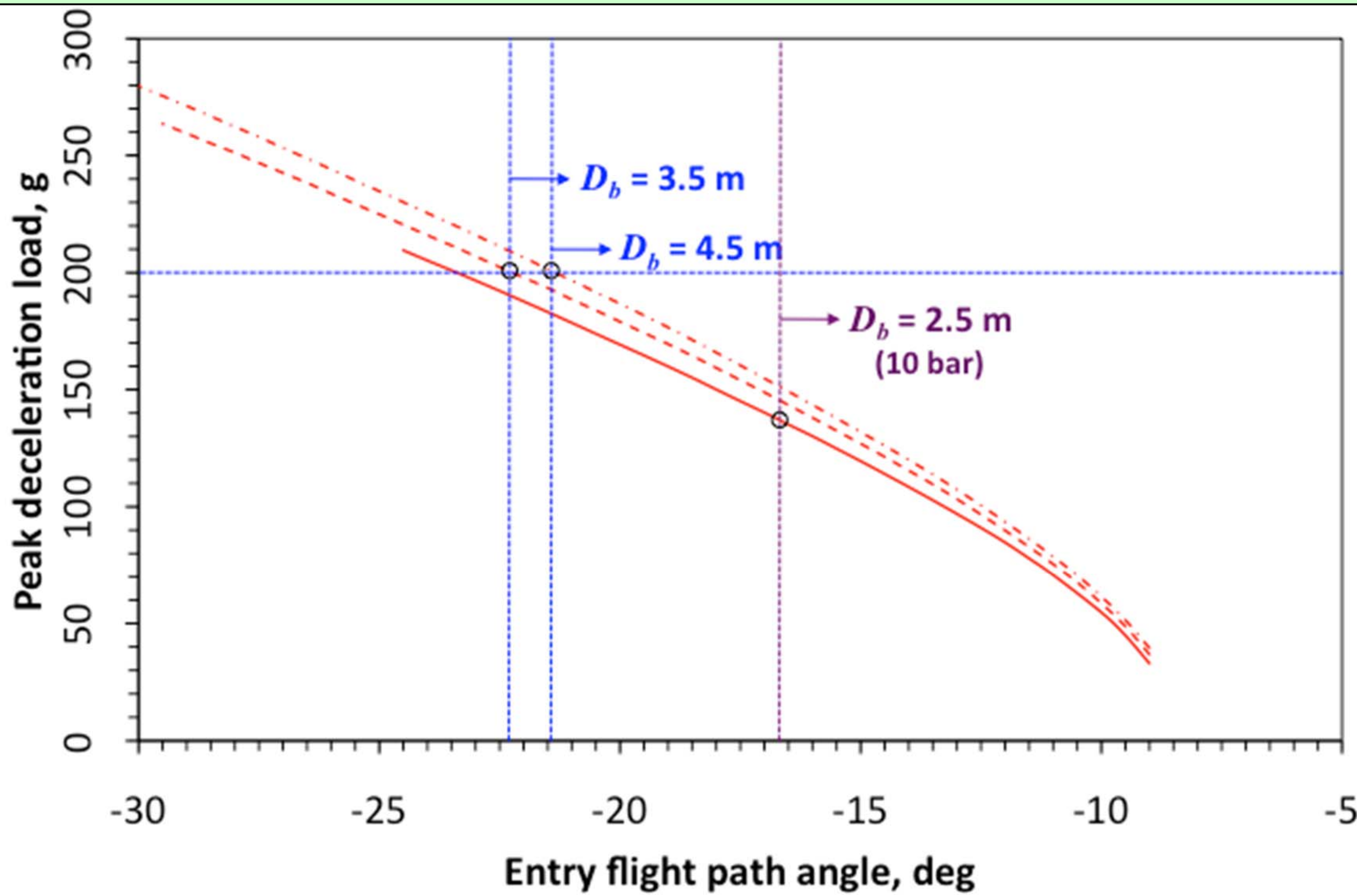
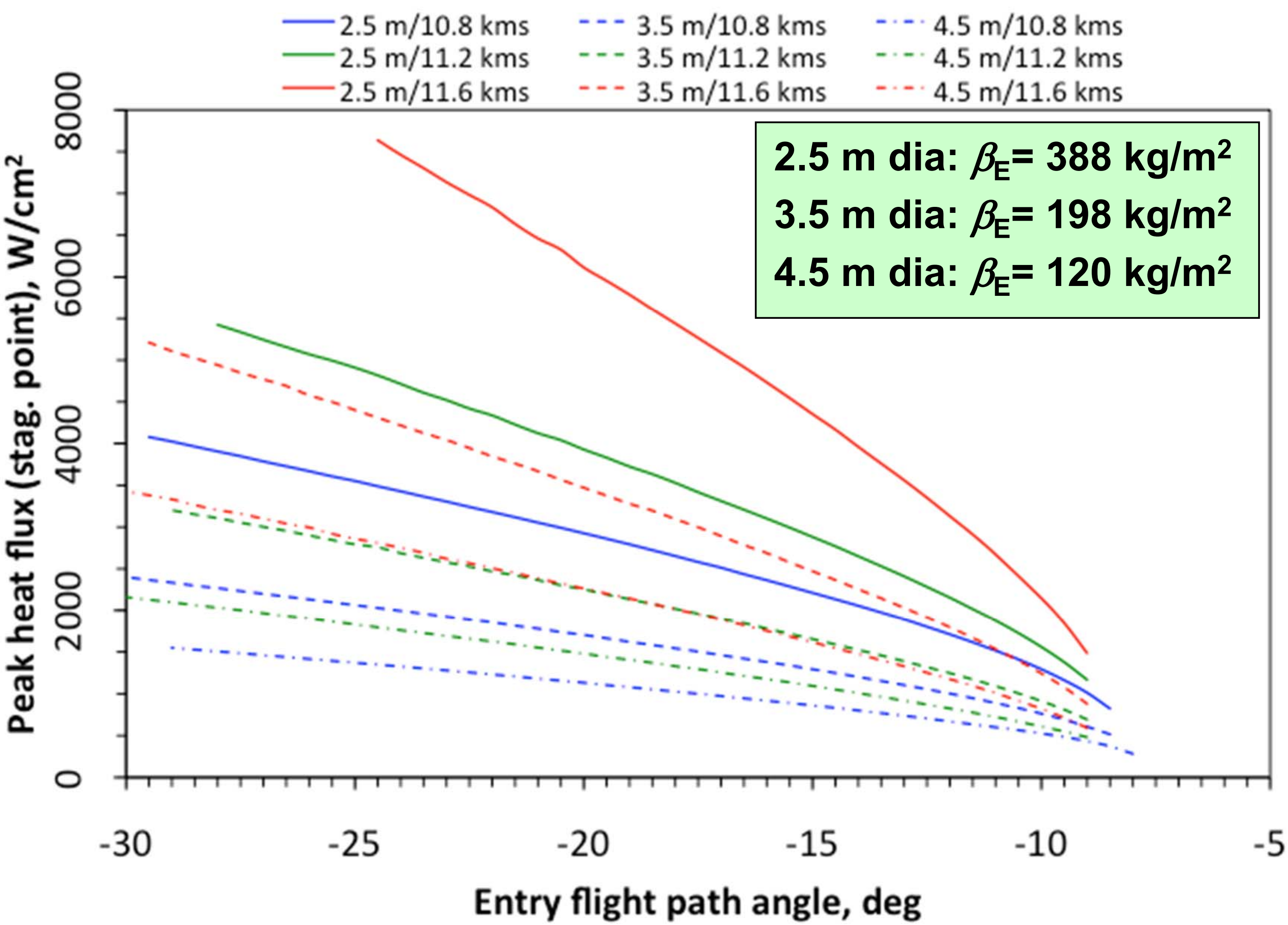


For 2.5 m dia., steepest entry is determined by the pressure limit (10 bar)
For 3.5 m and 4.5 dia, steepest entry is determined by g load limit

Peak Heat Flux

2000 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**

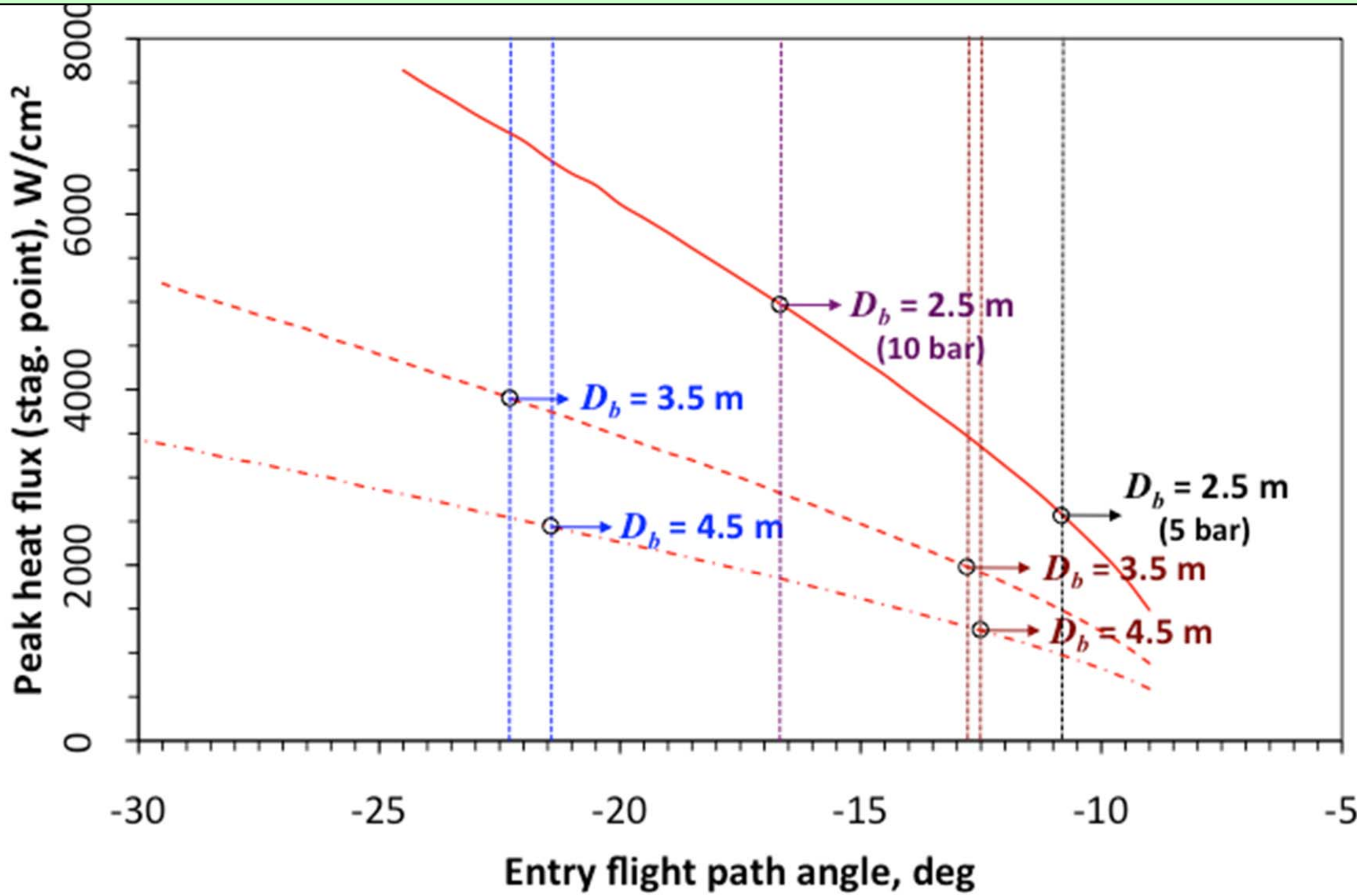
The highest V_E bounds peak heat fluxes for each β_E
Sufficient to look at V_E = 11.6 km/s case

Peak Heat Flux

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

Entry Systems and Technology Division

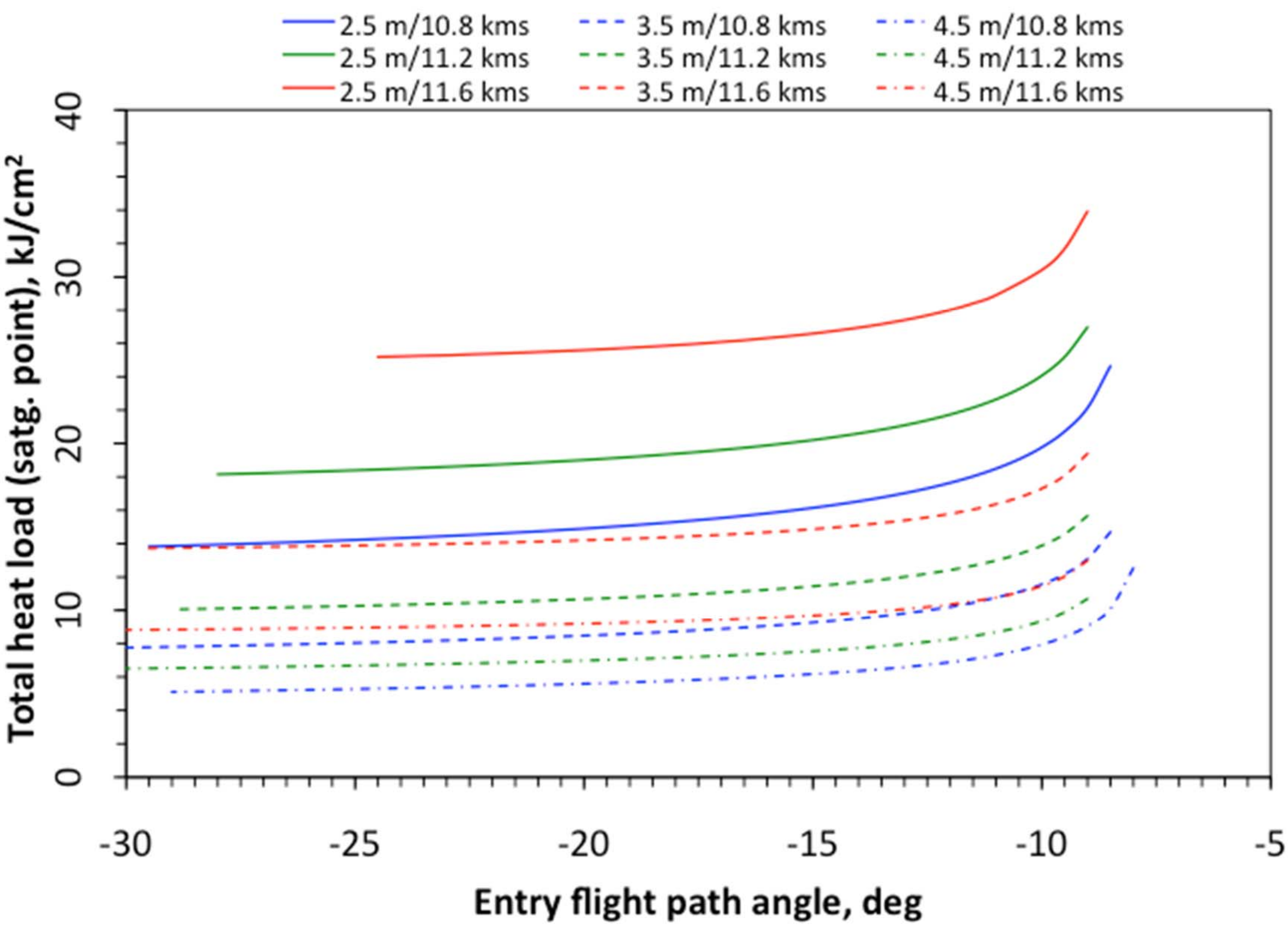
2.5 m dia: β_E= 388 kg/m², 3.5 m dia: β_E= 198 kg/m², 4.5 m dia: β_E= 120 kg/m²



2.5 m dia. case has high peak heat flux *and* pressure at steepest entry
Heat fluxes greater than 2.5 kW/cm² are hard to achieve in current arc jets

Total Heat Loads

2000 kg Entry Mass – β_E varying, V_E varying



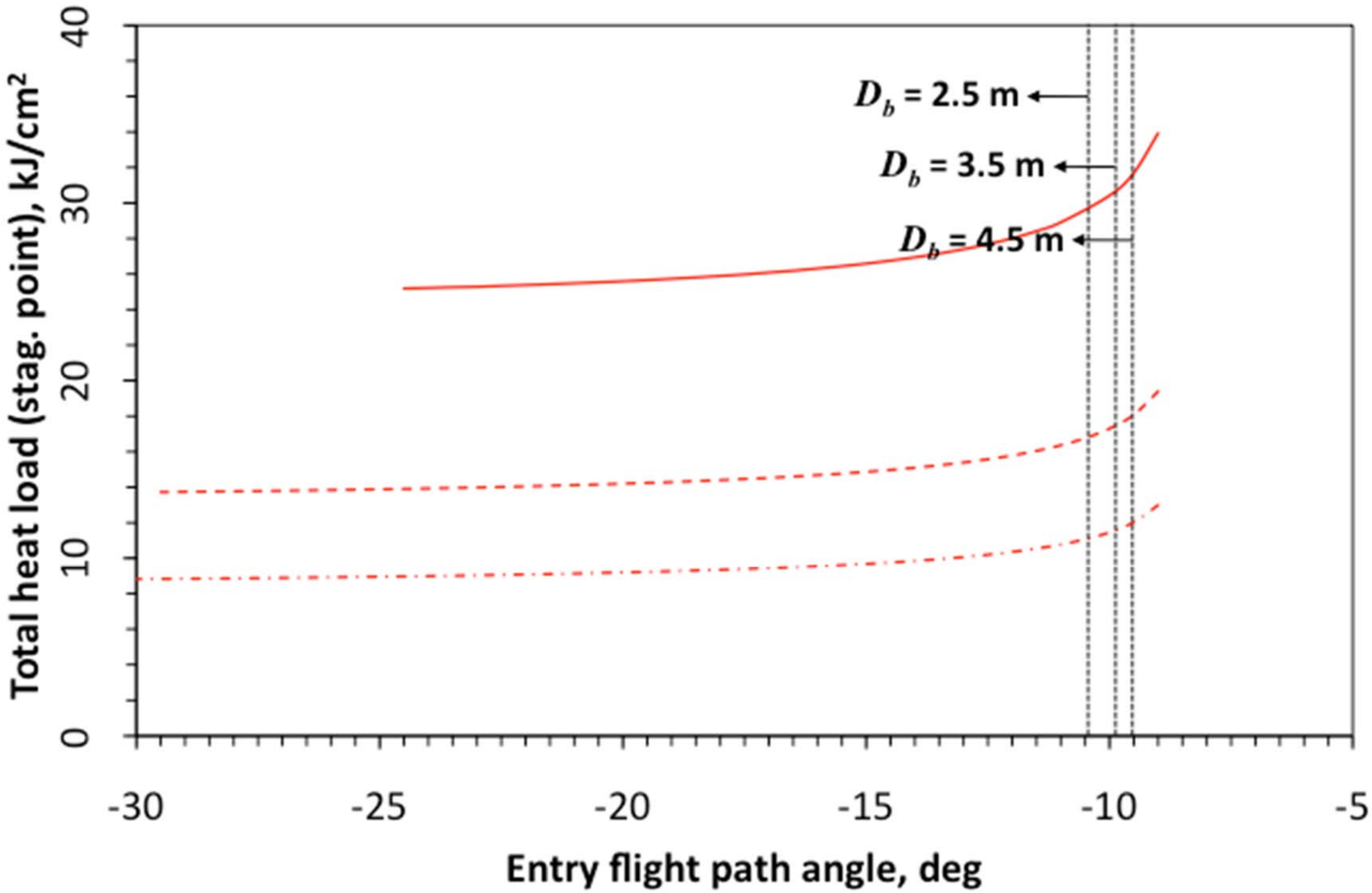
- **Each point on a curve is a 3-DoF trajectory**
- **For fixed V_E, total heat load *increases* with *increasing* β_E**
- **For fixed β_E, total heat load *increases* with *increasing* V_E**

The highest V_E bounds peak heat fluxes for each β_E
Sufficient to look at V_E = 11.6 km/s case
Determine "max. curvature" of total heat load distributions

Total Heat Loads

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2

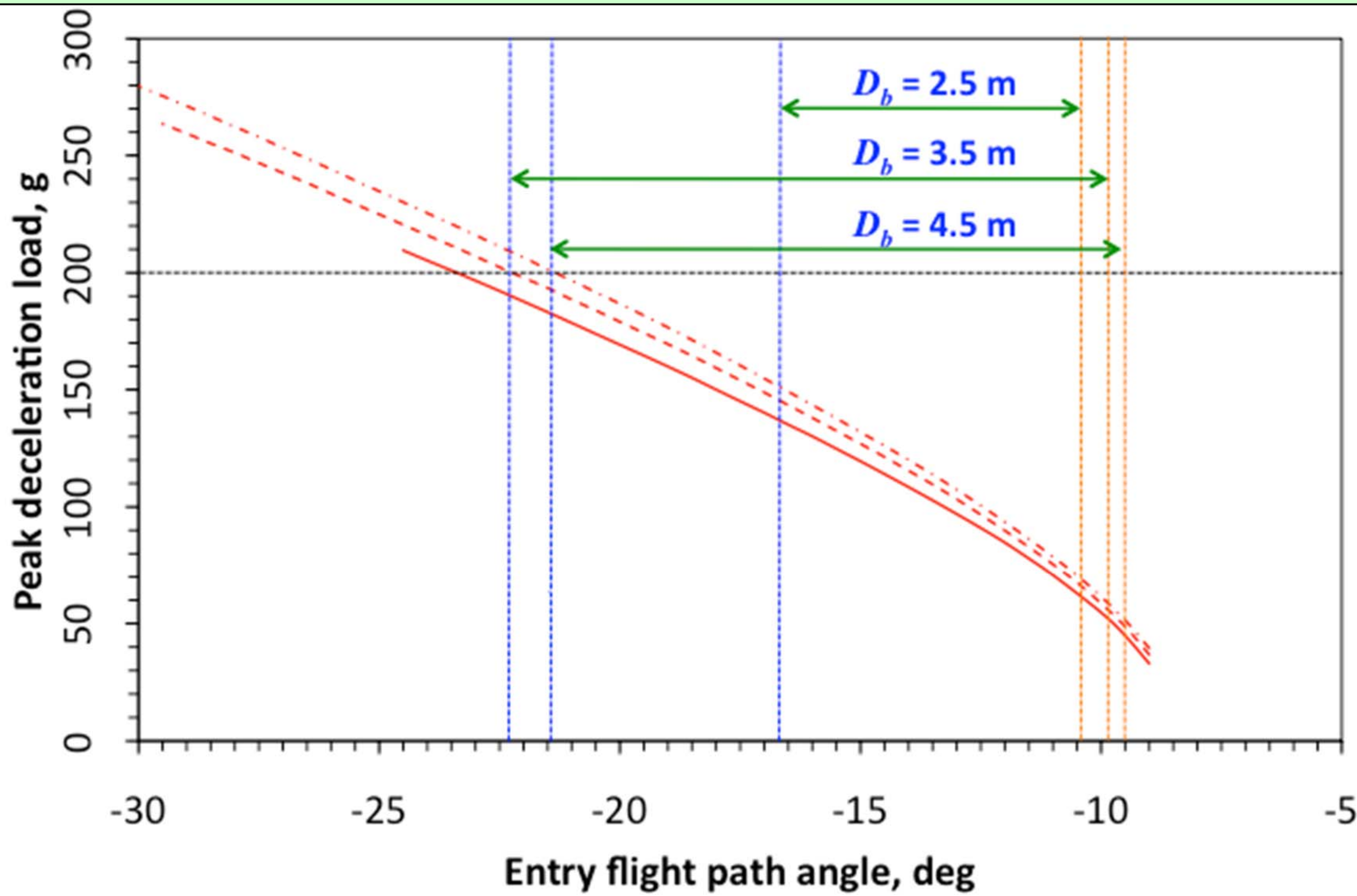


Entry angles correspond to max. curvature in heat load curves for highest β_E
These entry angles close the entry flight path angle interval at the shallow end

Putting it All Together

2000 kg Entry Mass, V_E = 11.6 km/s, 200g, 10 bar

2.5 m dia: β_E= 388 kg/m², 3.5 m dia: β_E= 198 kg/m², 4.5 m dia: β_E= 120 kg/m²



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

- **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 (388 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**

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**
- **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**
- **Move away from rigid aeroshell idea and use deployable decelerator**

Last two ideas are currently funded by the NASA Space Technology Program

Acknowledgments

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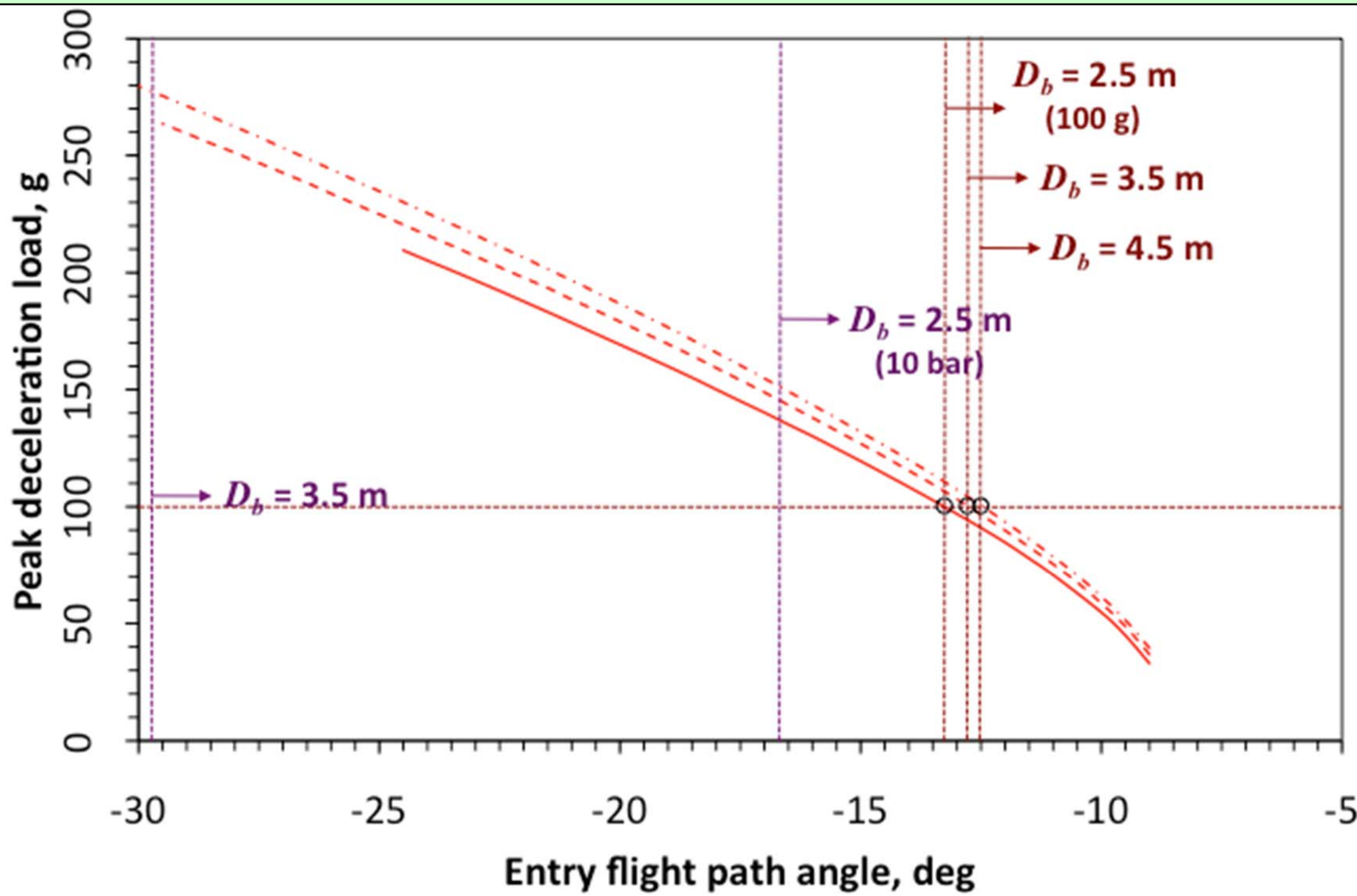
Backup

Case 2: 100 g and 10 bar Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2



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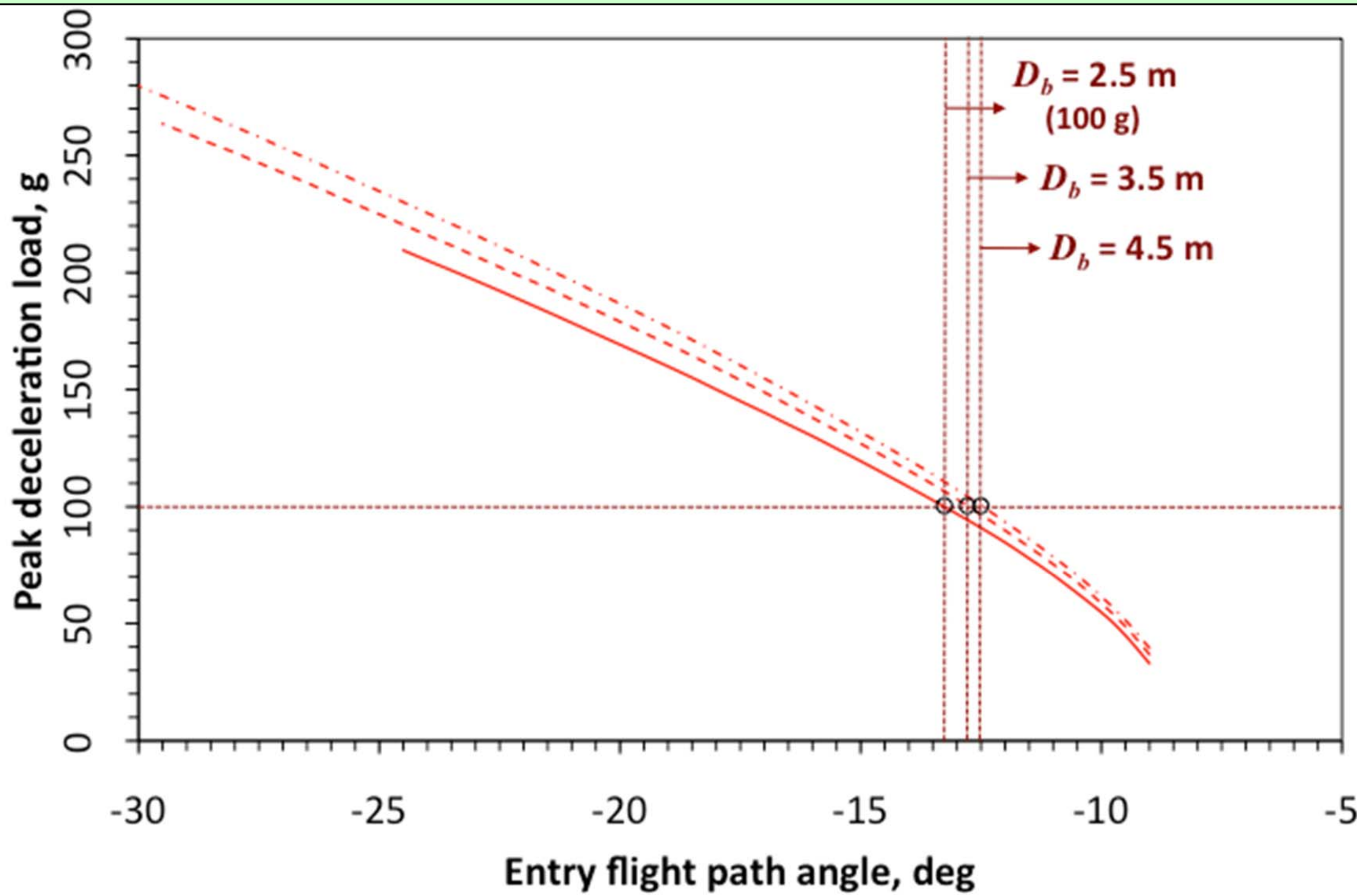


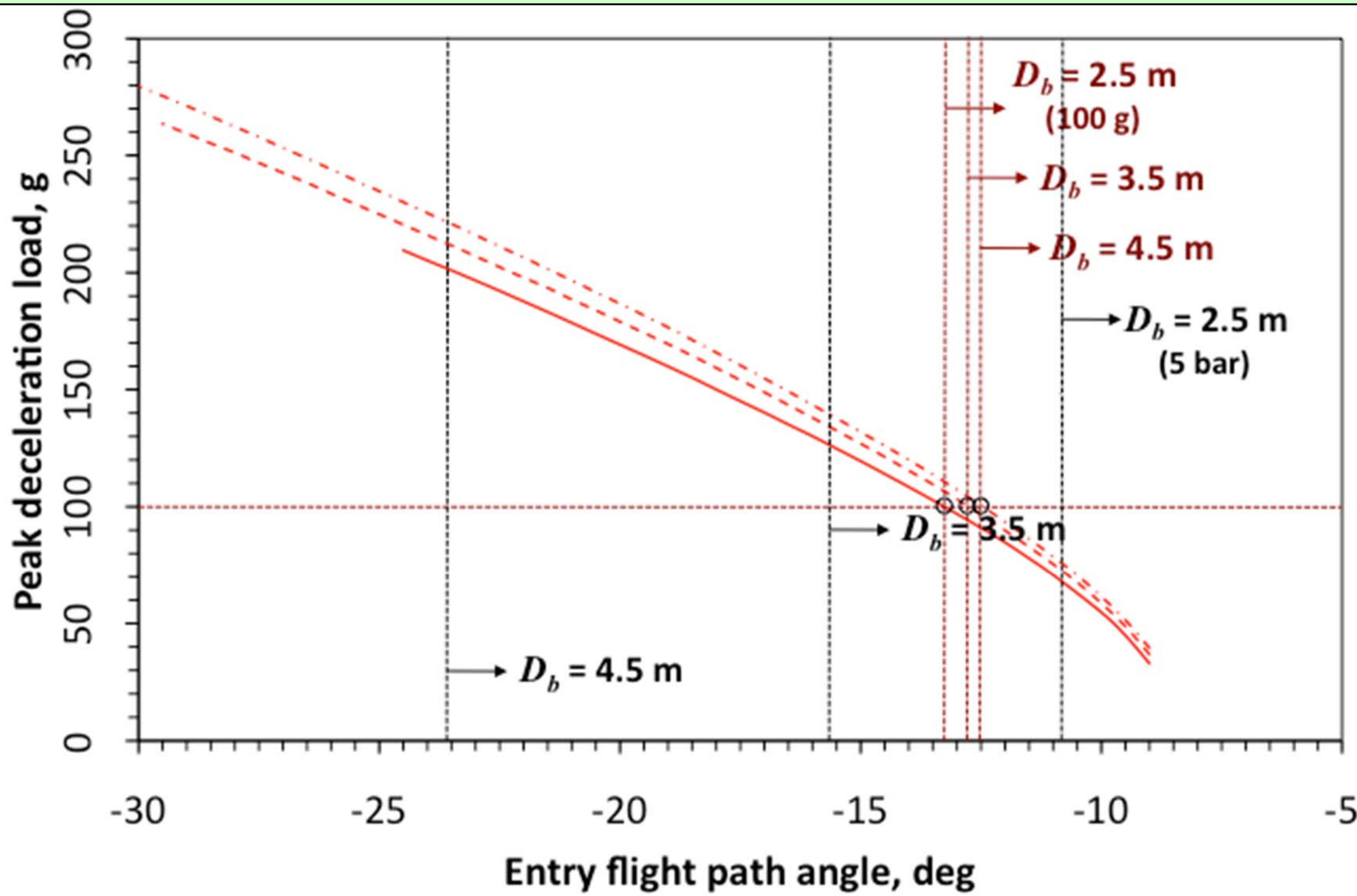
Steepest entry angle is determined solely by g load limit

Along the lines of "standard" analysis, where pressure load limit is not factored in

Case 3: 100 g and 5 bar

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

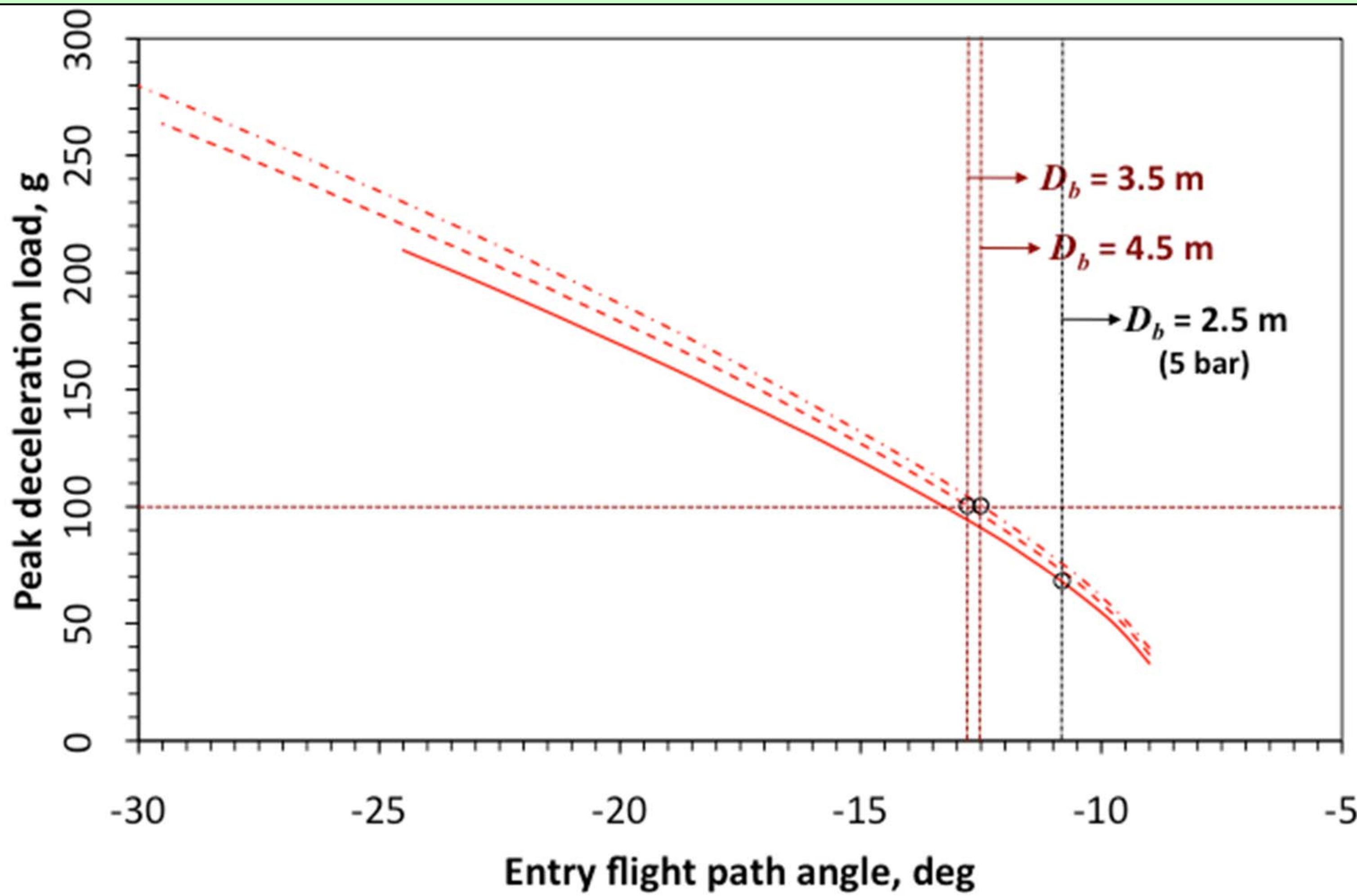
2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2



Case 3: 100 g and 5 bar Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2

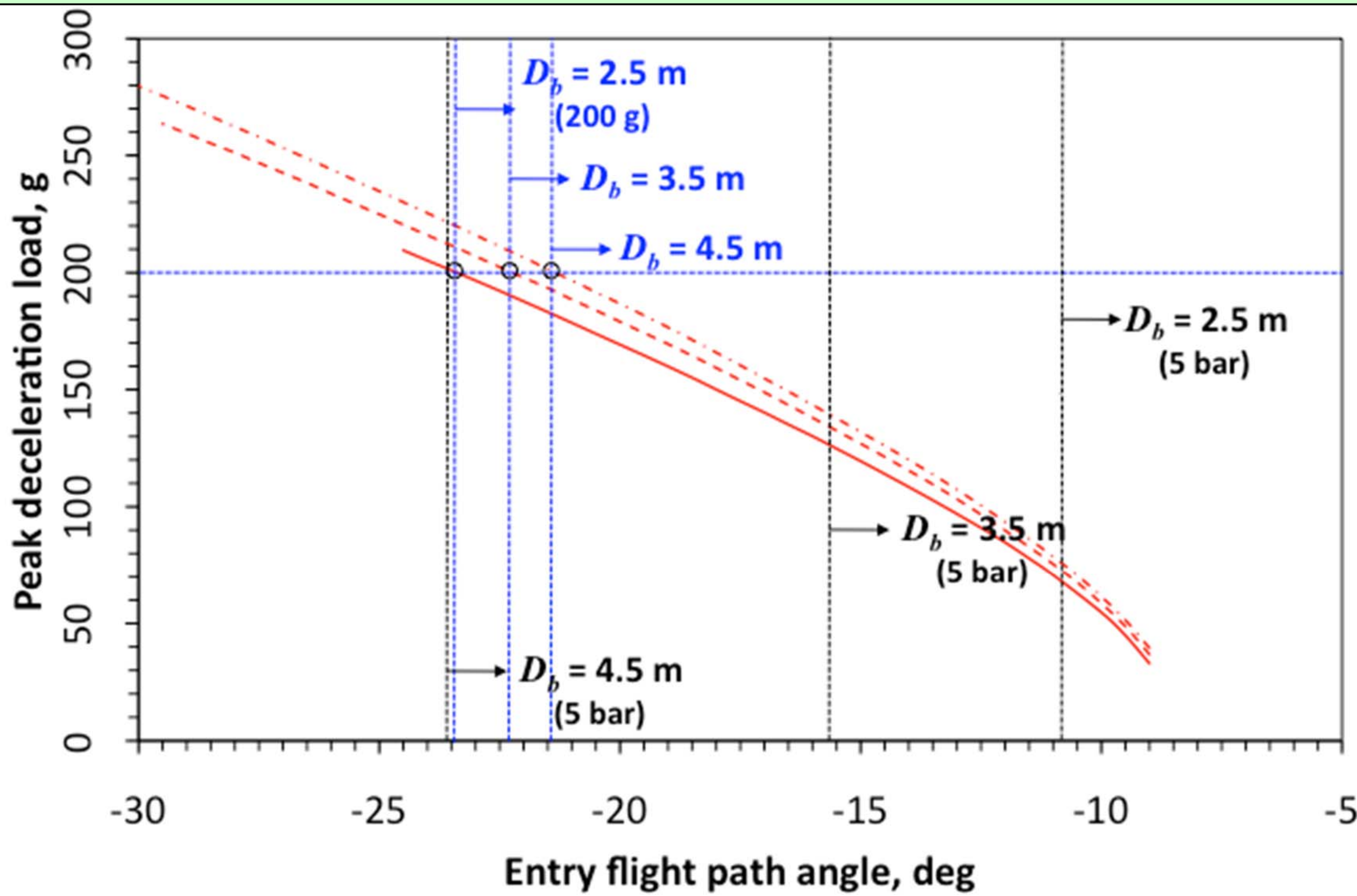


Results are similar to those of Case 1
For 2.5 m dia., steepest entry is determined by the pressure limit (5 bar)
For 3.5 m and 4.5 dia, steepest entry is determined by g load limit

Case 4: 200 g and 5 bar Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

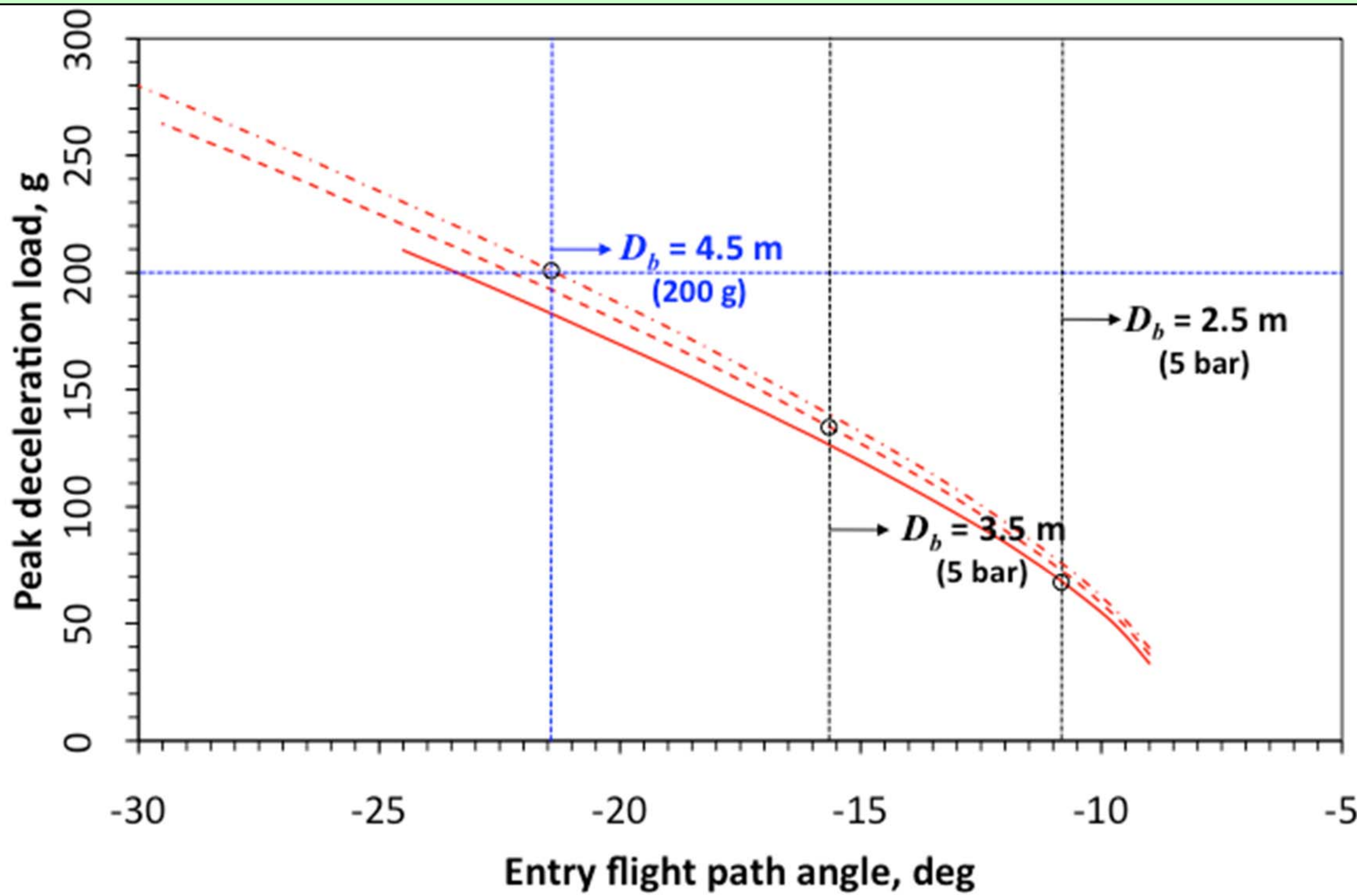
2.5 m dia: β_E= 388 kg/m², 3.5 m dia: β_E= 198 kg/m², 4.5 m dia: β_E= 120 kg/m²



Case 4: 200 g and 5 bar Limits

2000 kg Entry Mass, V_E = 11.6 km/s (bounding case)

2.5 m dia: β_E= 388 kg/m², 3.5 m dia: β_E= 198 kg/m², 4.5 m dia: β_E= 120 kg/m²

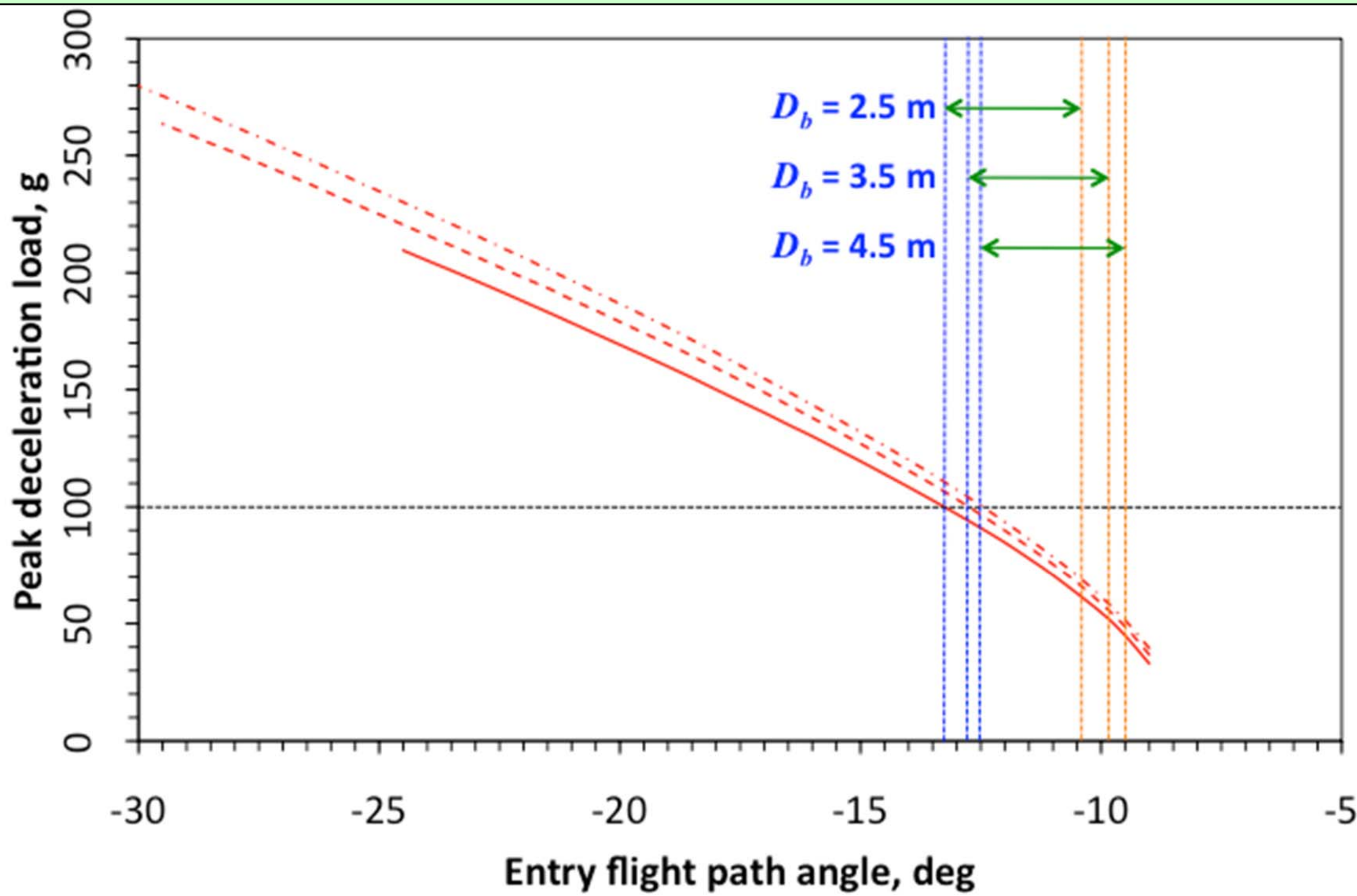


For 2.5 m and 3.5 dia., steepest entry is determined by the pressure limit (10 bar)
For 4.5 m dia, steepest entry is still determined by g load limit

Putting it All Together, II

2000 kg Entry Mass, V_E = 11.6 km/s, 100 g, 10 bar

2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2



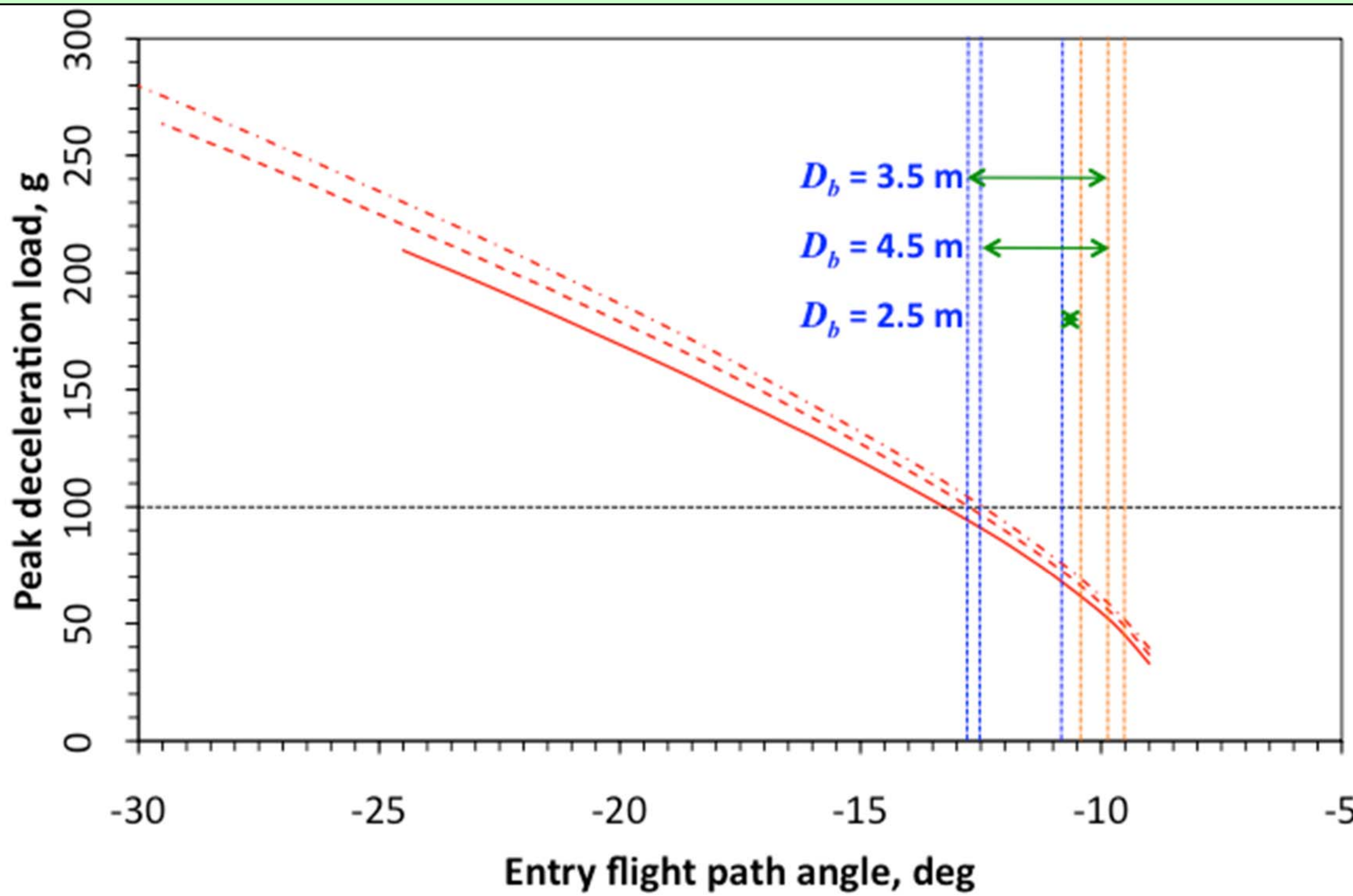
Slightly narrower entry flight path angle window

Window determined only by g load limit and heat load curvature

Putting it All Together, III

2000 kg Entry Mass, V_E = 11.6 km/s, 100 g, 5 bar

2.5 m dia: β_E= 388 kg/m^2, 3.5 m dia: β_E= 198 kg/m^2, 4.5 m dia: β_E= 120 kg/m^2



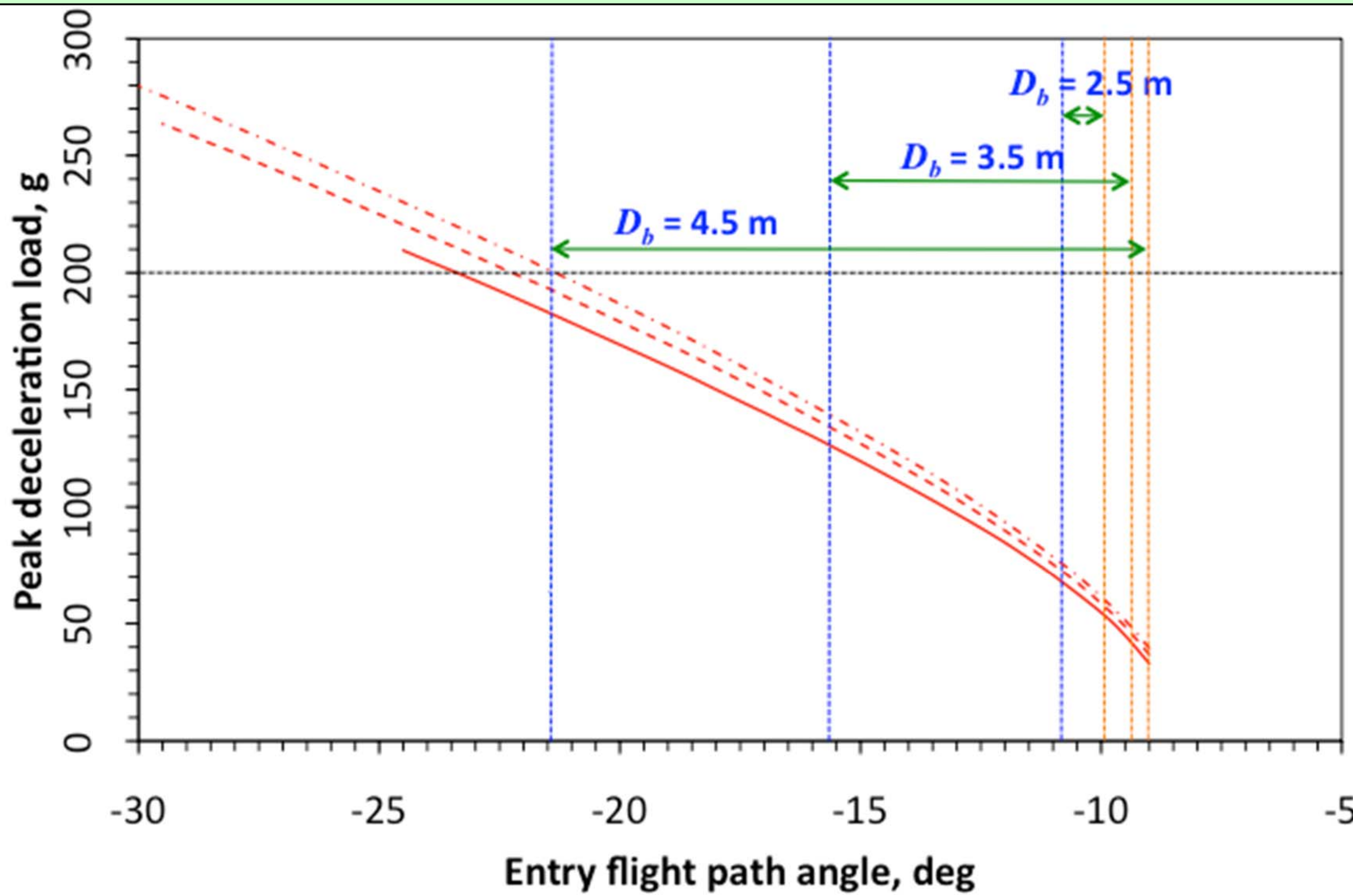
Very narrow (< 0.5°) entry flight path angle window for highest ballistic coeff.

Narrowing of window is due to pressure load limit

Putting it All Together, IV

2000 kg Entry Mass, V_E = 11.6 km/s, 200 g, 5 bar

2.5 m dia: β_E= 388 kg/m², 3.5 m dia: β_E= 198 kg/m², 4.5 m dia: β_E= 120 kg/m²



Pressure load limit still limits entry flight path angle window for highest ballistic coefficient