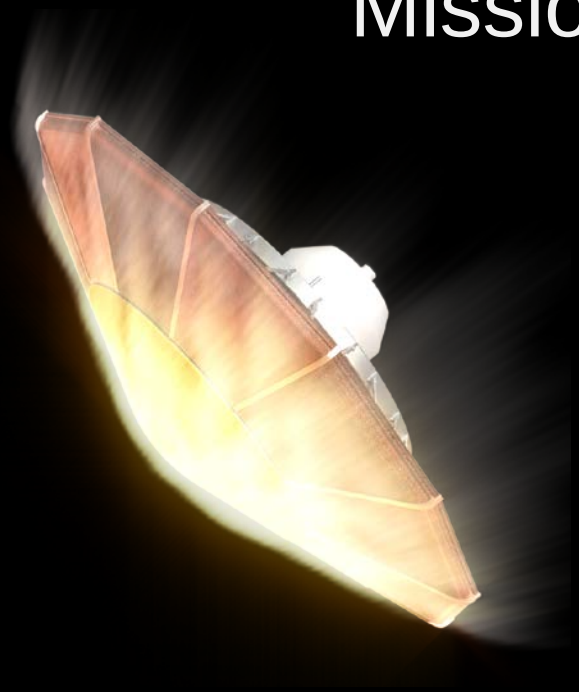
ADEPT

Adaptable Deployable Entry Placement Technology

A Versatile 3D-Woven Carbon Fabric for Broad Mission Application of ADEPT



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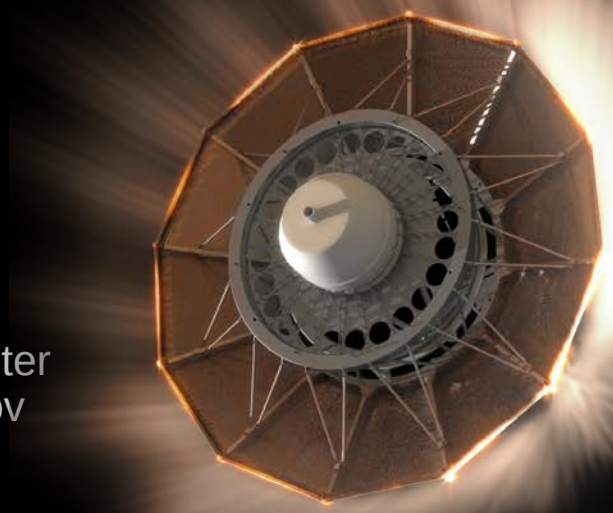

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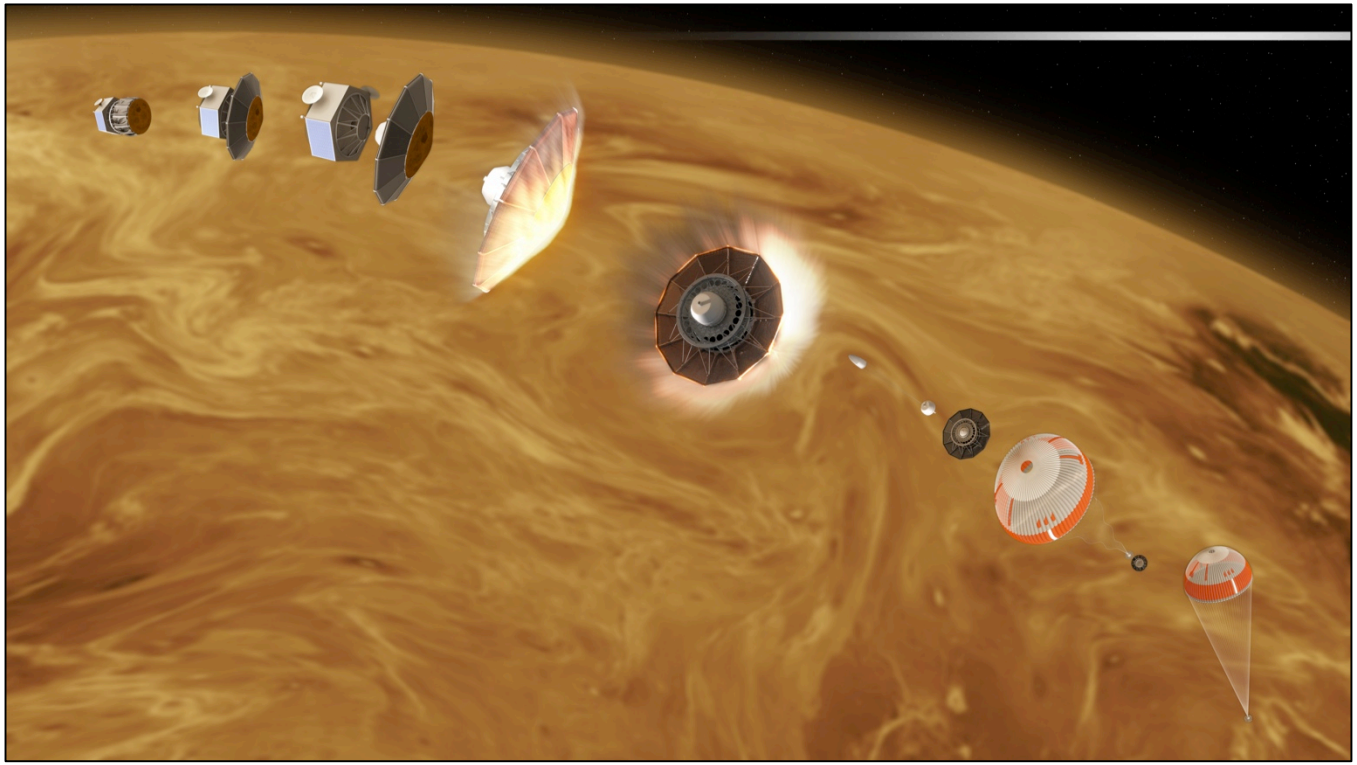
The ADEPT Architecture

- The ADEPT architecture utilizes a mechanically deployable aeroshell for atmospheric entry applications to provide substantial benefits over rigid aeroshells [1]
- Enabling technology is a 3D woven carbon fabric for the skin of the vehicle, acting both as a structural webbing and an ablator to manage entry environments [1,2]



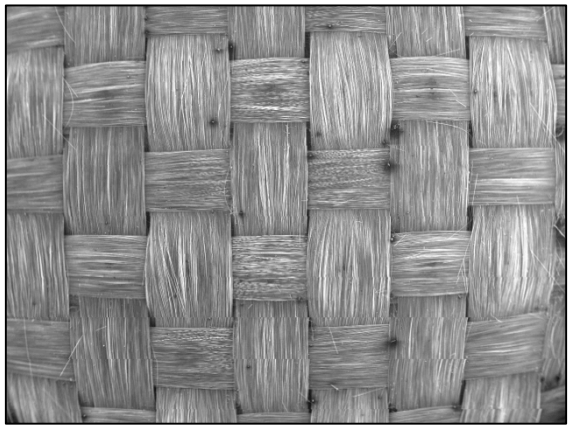
Motivation for A Versatile Fabric

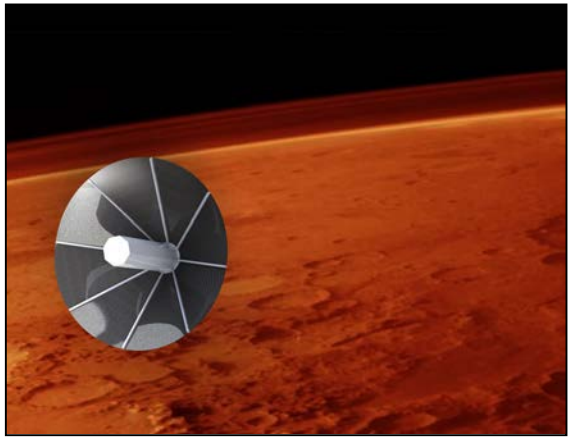
- Carbon fabric development to date has converged on a 12 layer fabric (8 layers for thermal on top of 4 for structural)

- Fabric architecture driven by requirements for Venus entry:
  - Shallow entry (-8.25º EFPA)
  - 6m diameter vehicle (β = 44 kg/m^2)

- **Understanding the carbon fabric is a big investment:**
  - Characterizing the thermal and structural properties of this complex, anisotropic material has been costly
  - Changing the mission application of the ADEPT system requires a change in the fabric thickness

- Many mission concepts being considered for secondary payload scale (diameter < 1m) applications of the ADEPT architecture (see talk by Brandon Smith on Thrursday) [3]





Goal: determine a fabric architecture which has broad mission application at the secondary class scale to accelerate maturation and expand infusion opportunities

Approach

1. Use 3DOF trajectory tool (*Traj*) to perform trajectory analysis to predict entry environments
2. Feed entry environments into FIAT to predict carbon fabric recession using ***equilibrium*** surface chemistry assumptions (Diffusion limited reactions)
   - Note: sizing is driven by recession only and doesn't employ a traditional temperature constraint
3. Using sizing results, perform systems study on various fabric thickness choices
4. Identify a fabric which is best investment for broad mission applicability

- The FIAT material response model is based on ***equilibrium*** recession of pure carbon, with an empirical recession augmentation factor (RA = 1) derived from arc jet test data (in ***equilibrium*** conditions) gathered by the ADEPT Project [4]

Hiccup:

The trajectories being looked at are low ballistic coefficient (and/or low EFPA) and spend much of the heat pulse in the low heat flux heating regime. This results in non-equilibrium (rate limited) chemistry and FIAT overpredicts recession because of its equilibrium assumptions…

ADEPT

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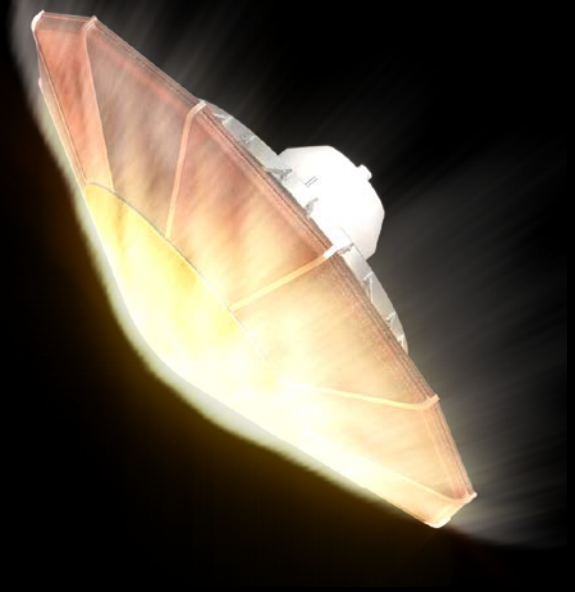
Application of Temperature and Pressure Cutoffs to FIAT Recession Predictions for Low Heat Flux Entry Trajectories



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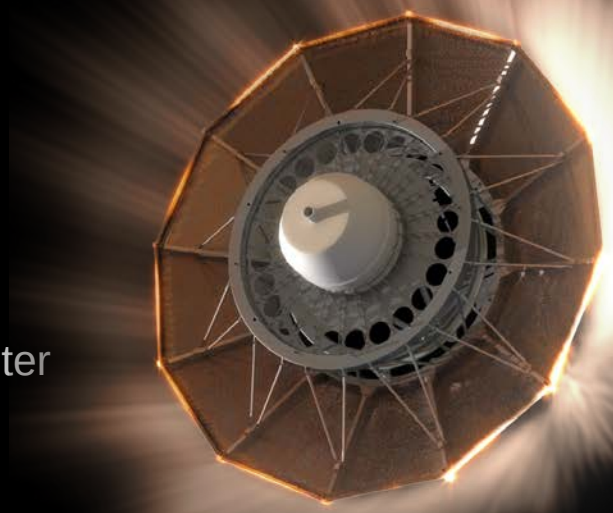

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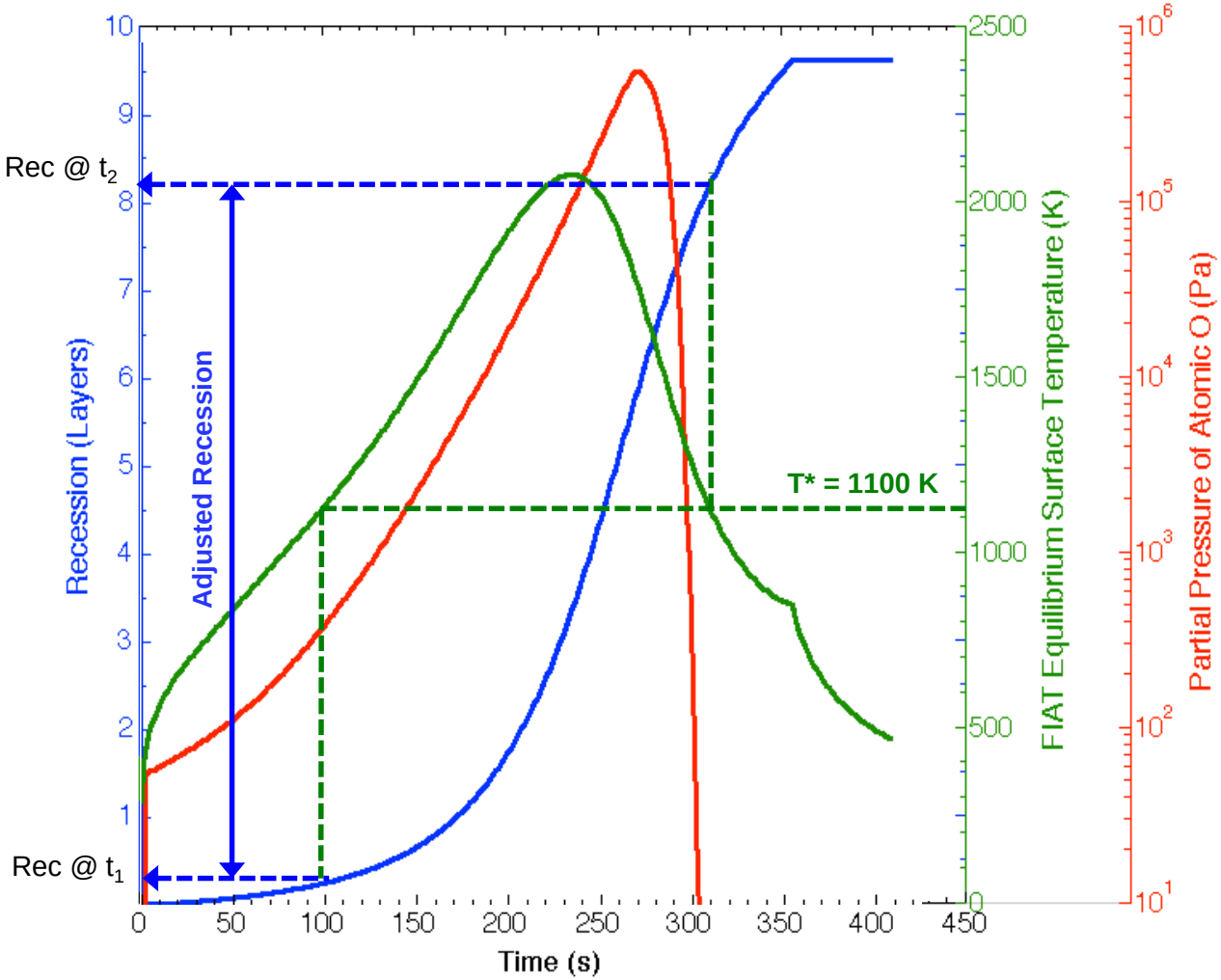
Limiting Recession

- Potential remedy to the recession overprediction in low heat flux environments: employ surface environment constraints which prevent recession below some threshold value
- Carbon recession occurs when the surface temperature is sufficiently high and there is atomic oxygen available at the surface to react with the carbon
- Two options for recession constraints:
  - T* = Surface temperature below which recession will not occur (predicted with FIAT)
  - P_O* = Partial pressure of oxygen at the boundary layer edge below which recession will not occur (predicted with CEA/Traj)

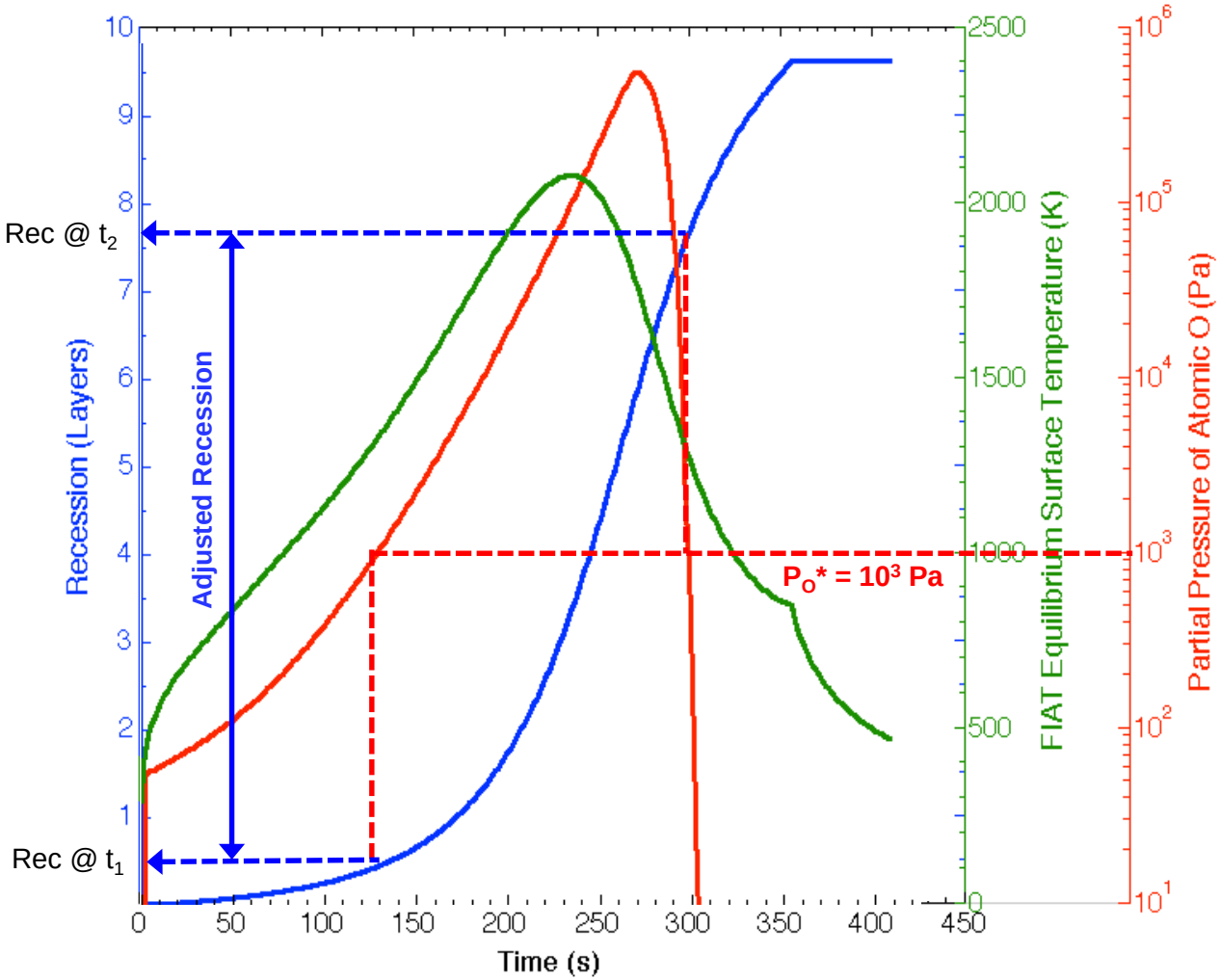
Example of Recession Cutoff

- Adjusted Recession = Recession at threshold temperature value (at time t_2) - Recession at threshold temperature value (at time t_1)



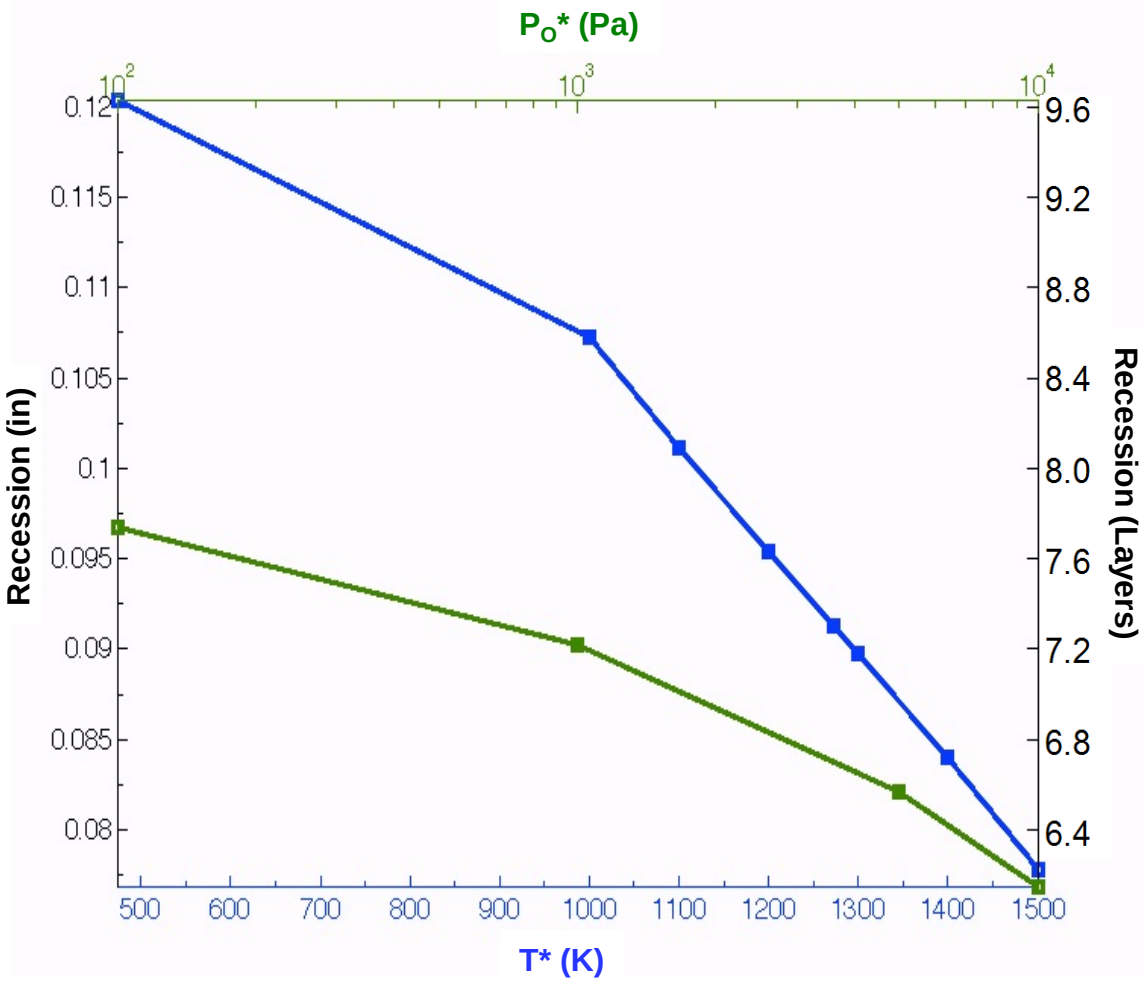
Example of Recession Cutoff

- Adjusted Recession = Recession at threshold P_O value (at time t_2) - Recession at threshold P_O value (at time t_1)



Sensitivity to Different T* and P_O* Values

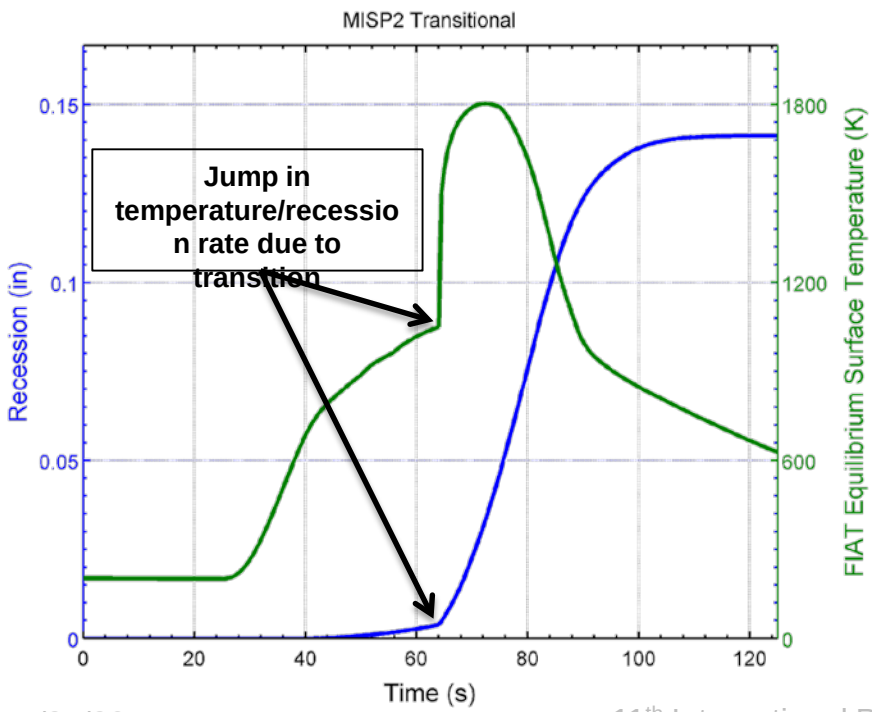
- What T* and P_O* values should be used as the threshold for allowing recession?
- Values for the threshold temperature differ for different carbon based materials and for carbon fabric, that value has not been studied
- Milos showed that for PICA, recession rates are very low below P_O values of 10^3 Pa [5]

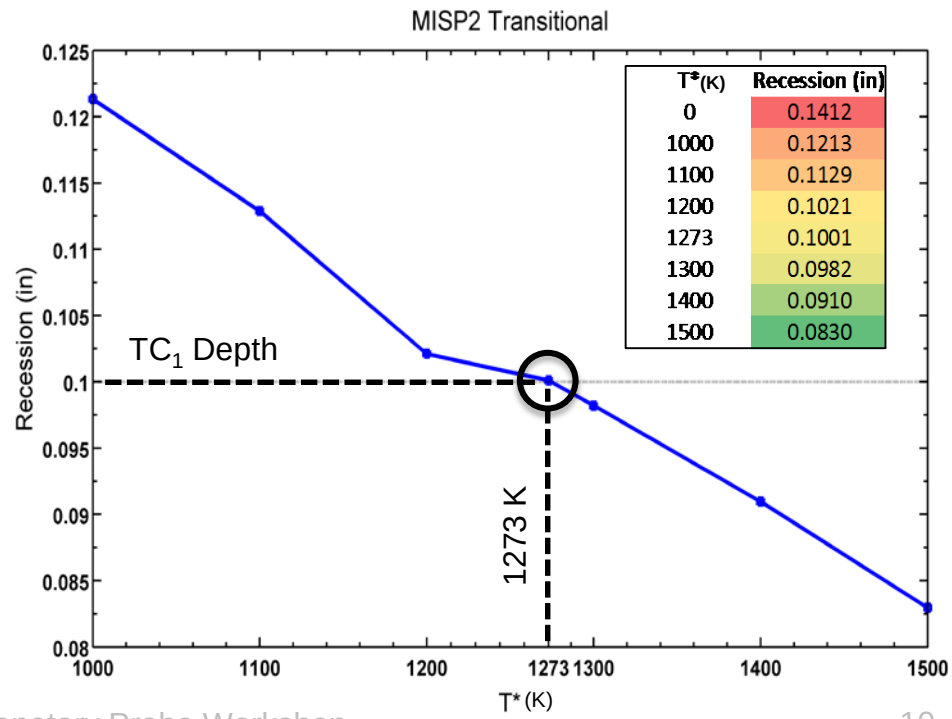


MSL Validation

- As a validation of this idea, we can leverage the fact that FIAT predicts the recession in the MISP2 location of MSL to be 0.14” (using CBE of environments), when we know the upper bound on the actual recession is depth of TC1 (0.1”)
  - Previous studies have cited 1500K as a threshold temperature for PICA recession – using this value, the recession is reduced to 0.083”
  - Using 1273K (1000 ºC) as a threshold temperature below which recession does not occur, the total recession predicted by FIAT is reduced to the depth of TC1 (0.1”)

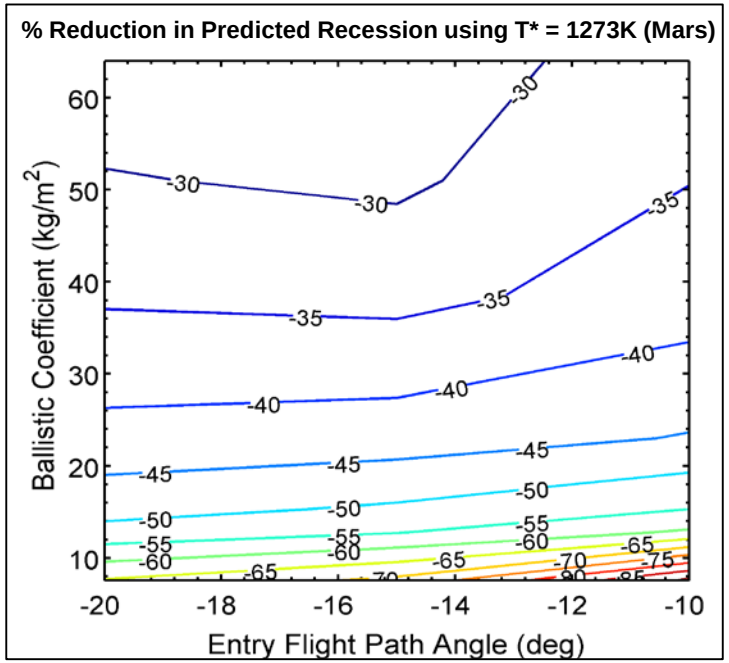
Use of T* = 1273K provides conservative upper bound estimate consistent with flight data for application in case study for carbon fabric

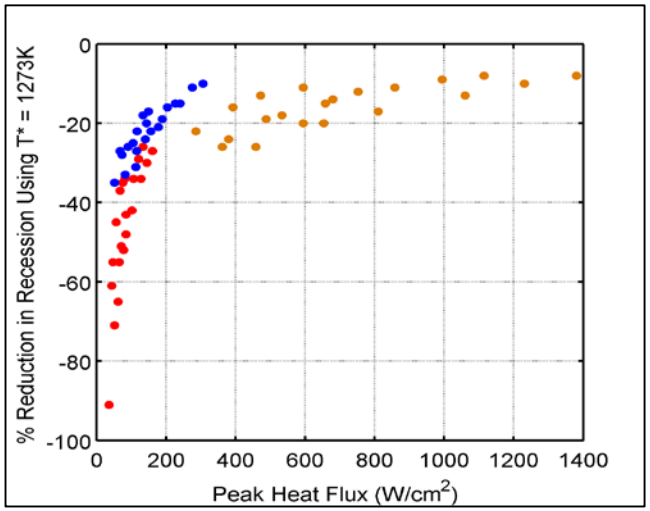




Effect of using T*=1273 K

- Impact of using T* = 1273K assessed for carbon fabric at Mars, Earth, and Venus for entry conditions relevant to the ADEPT architecture at the "Nano scale" (< 1 m)
  - "Mid β = 51 kg/m^2 (D=0.7m, 20 kg, 45º spherecone)
  - "Low β = 7.5 kg/m^2 (D=0.7m, 5 kg, 70º spherecone)
- % Reduction in recession is:
  - greatest at Mars (lowest heat flux trajectories)
  - lowest at Venus (highest heat flux trajectories)
  - sensitive to ballistic coefficient: increases as β decreases
  - less sensitive to changes in EFPA over ranges considered
- % Reduction in recession has an approximate logarithmic dependence with peak heat flux across all mission profiles considered





	Mars Mid β	Mars Low β	Earth Mid β	Earth Low β	Venus *Mid* β	Venus Low β
	(EFPA = -15º)		*(EFPA = -1º)*		*(EFPA = -8.5º)*	
FIAT Recession Prediction (in)	0.076	0.026	0.145	0.059	0.155	0.059
Recession Prediction: T*=1273K (in)	0.054	0.007	0.118	0.038	0.134	0.046
Peak Heat Flux (W/cm^2)	120.7	52.1	133.9	51.9	679.0	285.6
% Reduction in Recession	**29%**	**71%**	**18%**	**35%**	**14%**	**22%**

Trade space for Secondary Class ADEPT Vehicles

- Application of T*=1273K to Nano-ADEPT at various sizes/destinations to identify a versatile fabric
- Total layers required = Ceiling (number of recession layers) + 1 layer of recession margin + 2 structural layers
- For the trade space considered: required number of fabric layers for Earth and Venus similar and are greater than for Mars entries
- Convective heating rates driven by small nose radius associated with small scale and heritage ratio of nose-to-base radius
- Reasonable to expect fabric performance to extend to 500 W/cm^2
  - Many Venus cases exceed this threshold: could increase nose radius and/or diameter to reduce convective heating
- Packaging concerns: folding fabric >8 layers thick into small volume would likely be challenging

Number of Fabric Layers Required

Earth

EFPA (°) \ Ballistic Coefficient (kg/m^2)	64.0	50.0	38.3	23.0	15.3	12.8	7.7
-1	14	13	12	10	8	8	6
-5	12	11	10	8	7	7	6
-10	10	9	9	7	6	6	5

Venus

EFPA (°) \ Ballistic Coefficient (kg/m^2)	64.0	50.0	38.3	23.0	15.3	12.8	7.7
-8.5	16	14	12	10	9	8	7
-10	12	11	10	9	8	7	6
-12	11	10	9	8	7	7	6

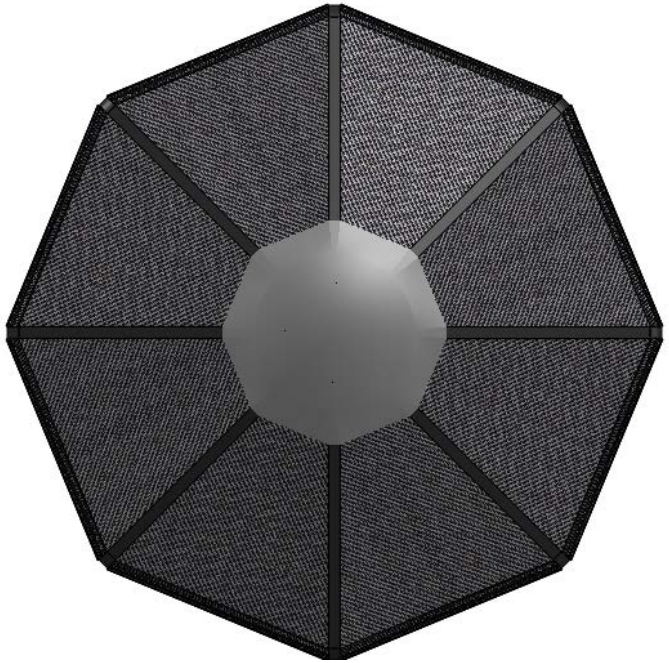
Mars

EFPA (°) \ Ballistic Coefficient (kg/m^2)	64.0	50.0	38.3	23.0	15.3	12.8	7.7
-10	10	9	8	7	6	5	4
-15	9	8	7	6	5	5	4
-20	8	7	6	5	5	5	4

-All sizing based on stagnation point environments
-Convective radiation uses a nose radius = ½ base radius

A Versatile Fabric For Secondary Payload Nano–ADEPT Vehicles

- A 7 layer fabric would be broadly applicable to potential missions using an ADEPT architecture as a secondary payload:
  - **Earth:**
    - up to 15 kg for steep entries with a 70º cone angle @ -10º EFPA
    - 5-10 kg for shallow entries with a 70º cone angle @ -1º EFPA
  - **Venus:**
    - 5-10 kg for a 70º cone angle @ -10º or -12º
    - more possibilities if peak higher peak heat flux capability can be demonstrated or if geometry can be allowed to grow
  - **Mars:**
    - up to 25 kg for steep entries with a 70º cone angle @ -15º EFPA
    - significant available solution space for very reasonable entry masses and entry angles



Conclusions

FIAT Sizing Approach for Low Heat Flux Entries:

- Temperature and/or pressure constraints imposed upon FIAT may improve recession predictions in the low heat flux regimes for carbon based materials
- Application of this idea to the MSL MISP2 environments established that imposing T* = 1273K can remedy the difference between the FIAT predictions and known upper bound of actual recession in flight
- Reduction in recession predictions using T*=1273K shows the largest effect for low β trajectories at Mars
- Testing is required to identify the proposed concept and appropriate values of T* and P_O*

Identification of a Versatile Fabric for ADEPT Missions:

- Investing in a common fabric architecture during the technology development phase can save on material characterization efforts and expand mission infusion opportunities
- A 7 layer fabric would allow for broad mission application for ADEPT concepts as secondary payloads
- A more rigorous margins policy (instead of simply adding one extra layer) would improve fidelity of predictions
- Higher fidelity assessment of the number of structural layers needed is required

References

1. Smith, B. et al., “Venus In Situ Explorer Mission Design using a Mechanically Deployed Aerodynamic Decelerator,” IEEE Aerospace Conference, Big Sky, MT, March 2013.

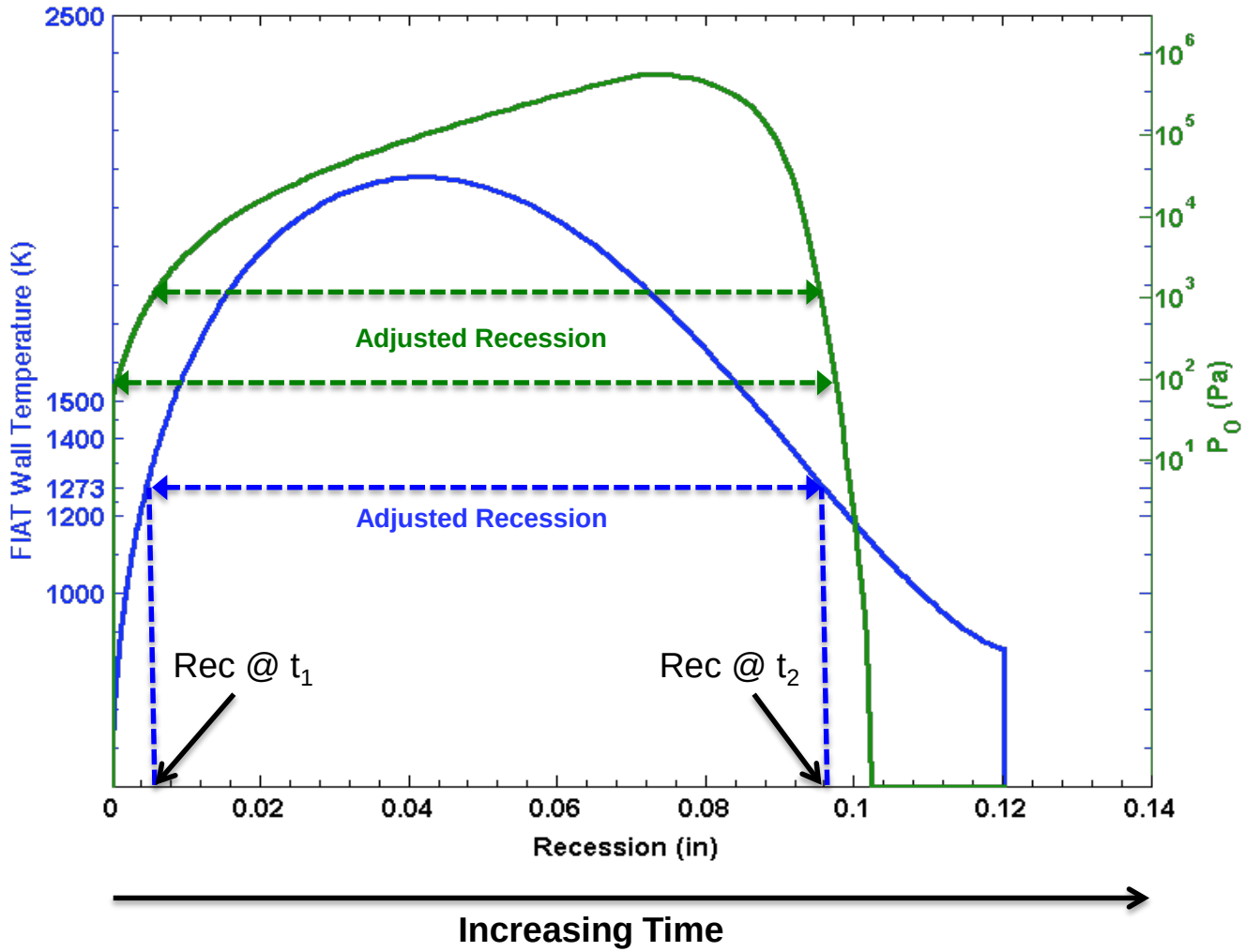
2. Venkatapathy, E. et al., “Mechanically-Deployed Hypersonic Decelerator and Conformal Ablator Technologies for Mars Missions,” Concepts and Approaches for Mars Exploration Workshop, Houston, TX, June 2012.

3. Smith, B., et al., “ADEPT for Secondary Payloads,” International Planetary Probe Workshop 11, Pasadena, CA, June 2014.

4. Arnold J.A. et. al., (2013), “Thermal and Structural Performance of Woven Carbon Cloth for Adaptive Deployable Entry and Placement Technology,” *AIAA Aerodynamic Decelerator Systems Technology Conference*, Daytona Beach, FL.

5. Milos, F. S., Chen, Y. K., and Gokcen, T. “Nonequlibrium Ablation of Phenolic Impregnated Carbon Ablator.” *AIAA Journal of Spacecraft and Rockets*, Vol. 49. No. 5. Sept 2012.

Backup

Example of Recession Cutoff

- Adjusted Recession = Recession at threshold value (t_2) - Recession at threshold value (t_1)