

DSMC Simulations of Mars Science Laboratory Entry from Rarefied to Continuum Conditions

31st International Symposium on Rarefied Gas Dynamics

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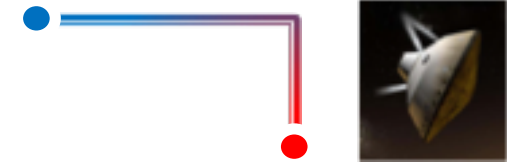
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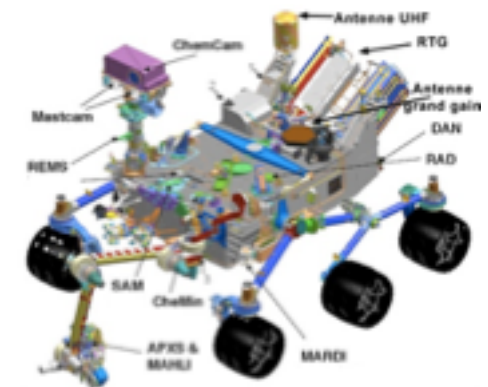


Mars Science Laboratory Mission



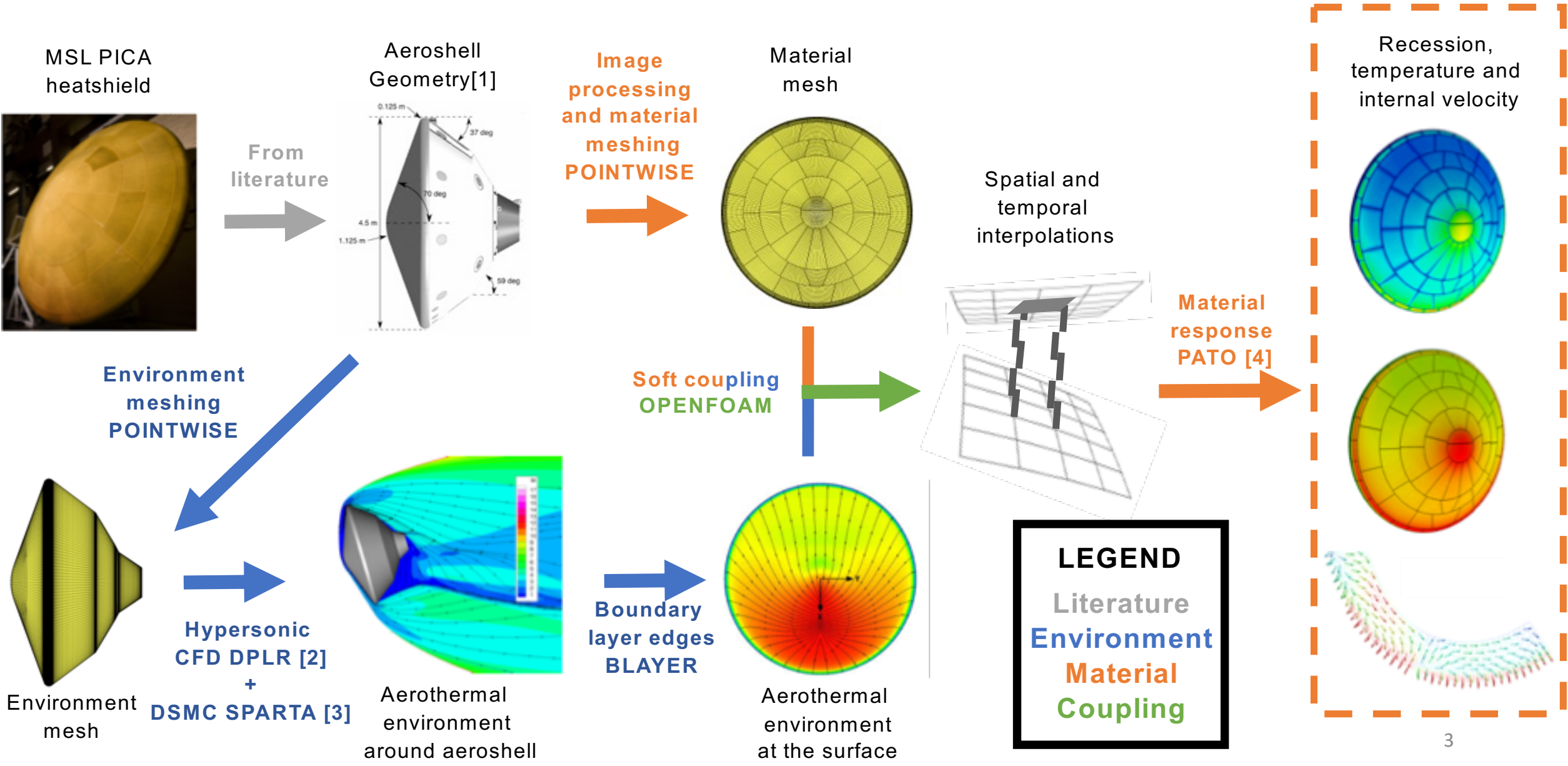
MSL mission

Mission Type	Mars Rover
Operator	NASA
Launch Date	11/26/11
Launch Mass	3839 kg
Rocket	Atlas V
Launch Date	08/06/12
Launch Site	Gale Crater

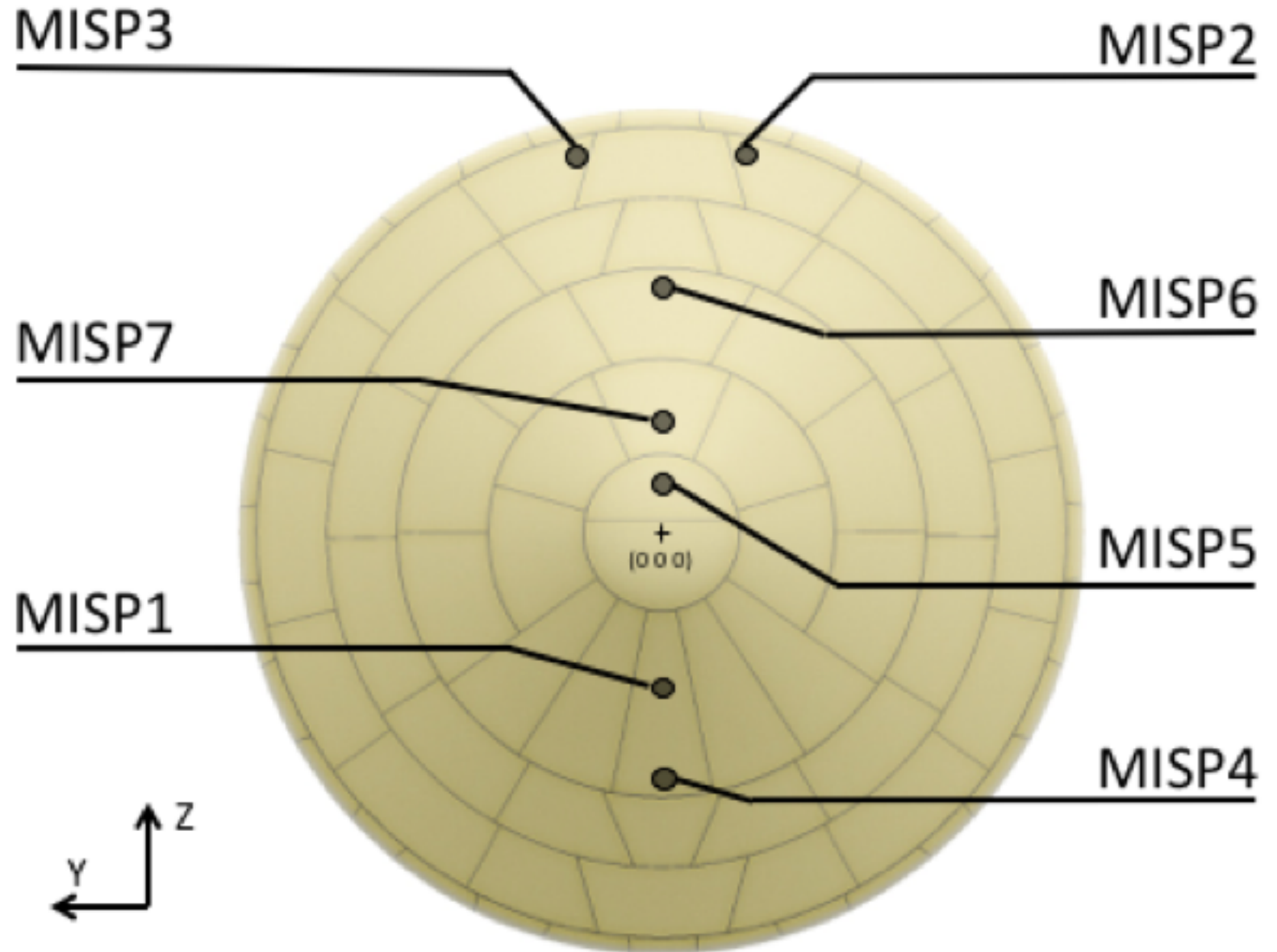
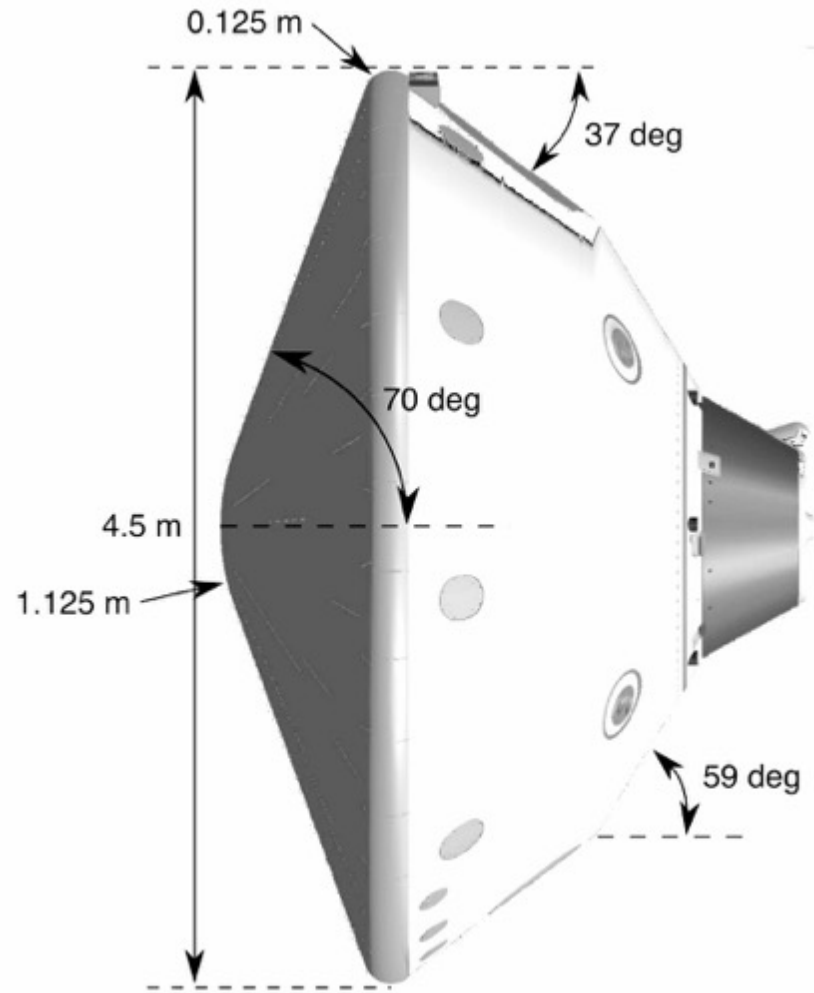


credit: NASA JPL

Overview – Coupling aerothermal environment and material response



MISPs instrument locations

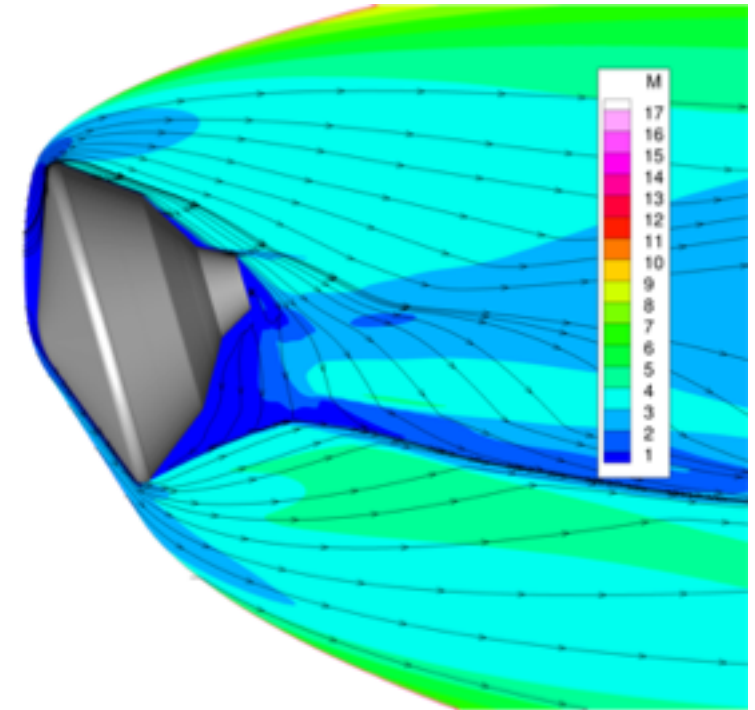


Aerothermal environment computed from DPLR



DPLR assumptions

- **Laminar** boundary layer
- **Non-blowing** & smooth wall
- Chemical and thermal non-equilibrium
- 2 temperatures model
- Radiative equilibrium wall with $\varepsilon = 0.85$
- Super-catalytic wall: recombination to freestream mole fraction
- Mars atmosphere: $y_{\text{CO}_2} = 0.97$, $y_{\text{N}_2} = 0.03$
- 8 species and 24 reactions(12 forward + 12 backward): Mitcheltree model [5]
- Park hypersonics correction to vibrational relaxation [6]
- Used from 48.4s to 100.5s of entry



credit: C. Tang, NASA Ames

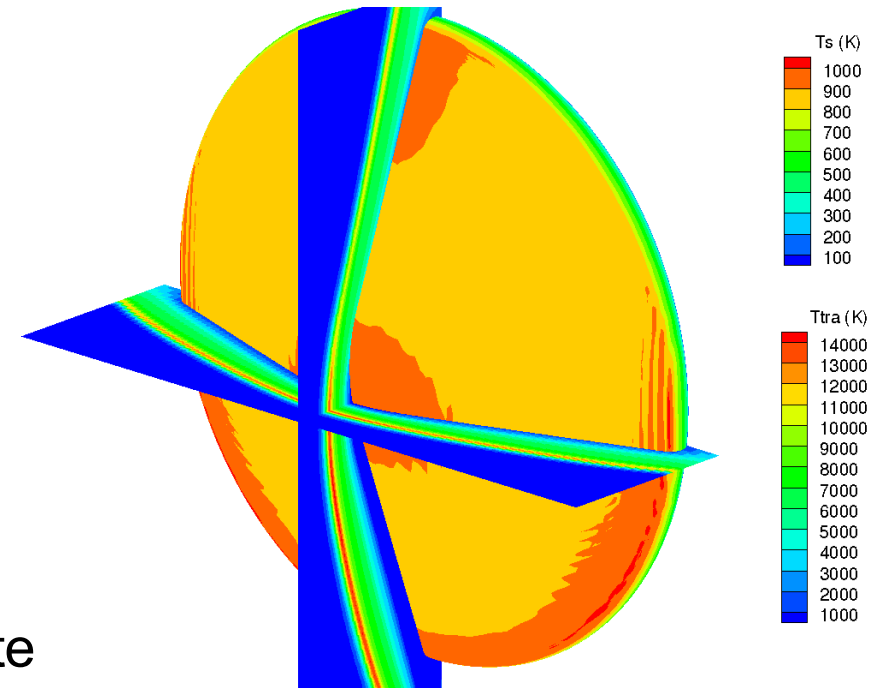
BLAYER calculates the **boundary layer edges** using a curvature-based method

Surface pressure p_w , **heat transfer coefficient** C_H and **enthalpy** h_e at the **boundary layer edges** are used as inputs in the **material response** code: **PATO**

Aerothermal environment computed from SPARTA

SPARTA assumptions

- 3 temperatures model
- Radiative equilibrium wall with $\varepsilon = 0.85$
- Super-catalytic wall: recombination to freestream mole fraction
- Mars atmosphere: $y_{CO_2} = 0.97$, $y_{N_2} = 0.03$
- 8 species and 24 reactions(12 forward + 12 backward): Mitcheltree model [5]
- VSS model with high temperature transport calibration [6]
- Parker equation for rotational relaxation and Millikan-White equation + Park correction for vibrational relaxation [7]
- Discrete vibrational temperature
- Used from 0s to 48.4s of entry



Boundary layer edges calculated using an edge-based method

Surface pressure p_w , heat transfer coefficient C_H and enthalpy h_e at the boundary layer edges are used as inputs in the **material response code: PATO**



High temperature transport model

	VSS: $T_{\text{ref}} = 273 \text{ K}$			Parker		Millikan White		Park [7]
	$d \text{ (\AA)}$	ω	α	Z_{rot}^{∞}	$T^* \text{ (K)}$	$C_1 \text{ (K)}$	$C_2 \text{ (K}^{0.33}\text{)}$	$\sigma_v^{\text{Park}} \text{ (\AA}^2\text{)}$
O ₂	3.896	0.7	1.463	14.4	90	100.7	138	0.3
N ₂	4.04	0.686	1.424	15.7	80	19.87	221	0.3
O	3.692	0.803	1.582					
N	3.697	0.79	1.486					
NO	4.218	0.737	1.542	5	117	49.5	1029	0.3
CO	4.684	0.787	1.494	11.4	92	18.36	198	0.03
CO ₂	4.147	0.632	1.259	15	195	51004	36.5	1
C	4.983	0.883	1.523					



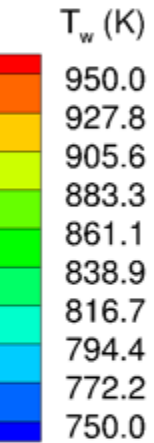
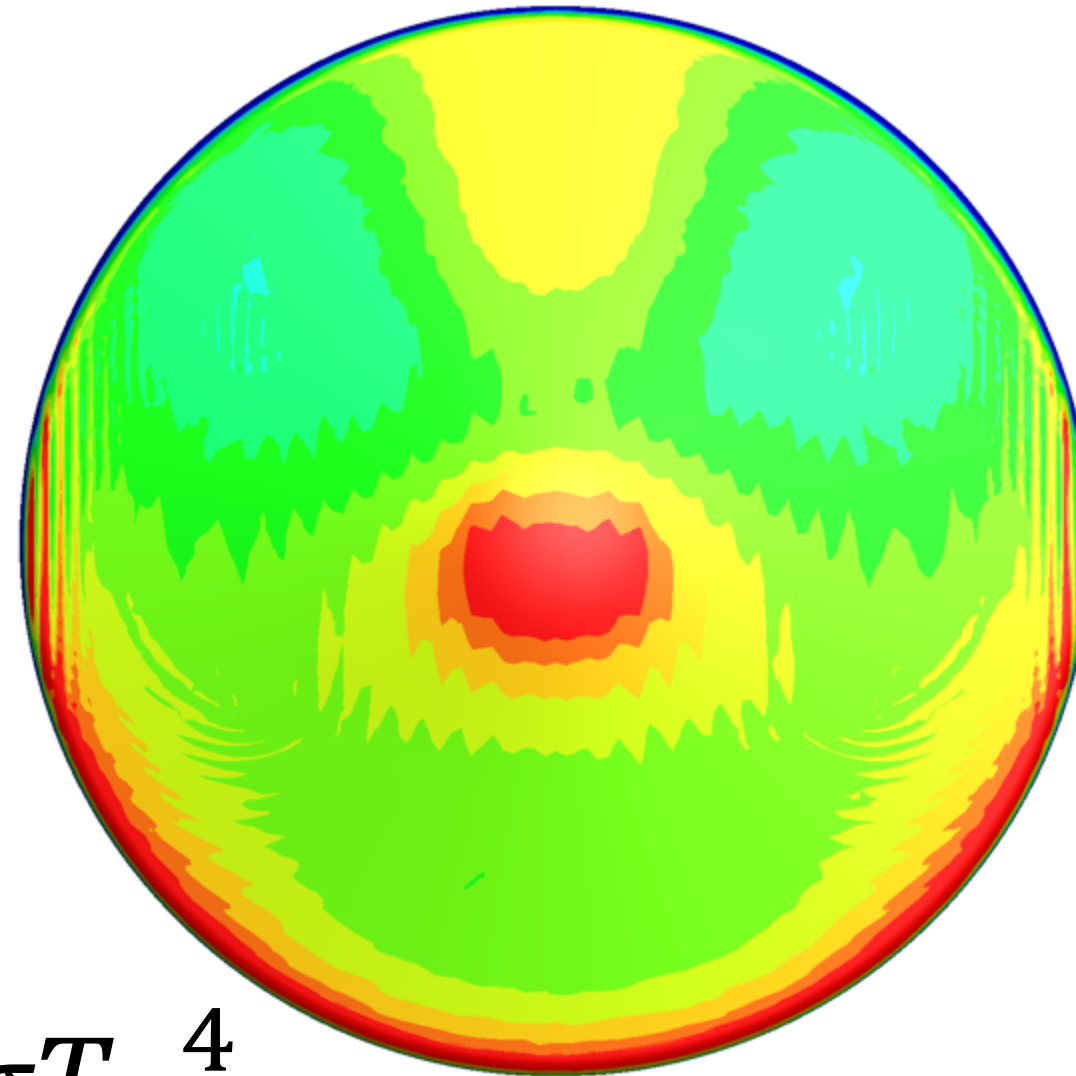
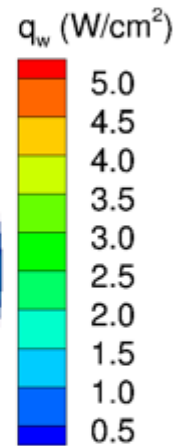
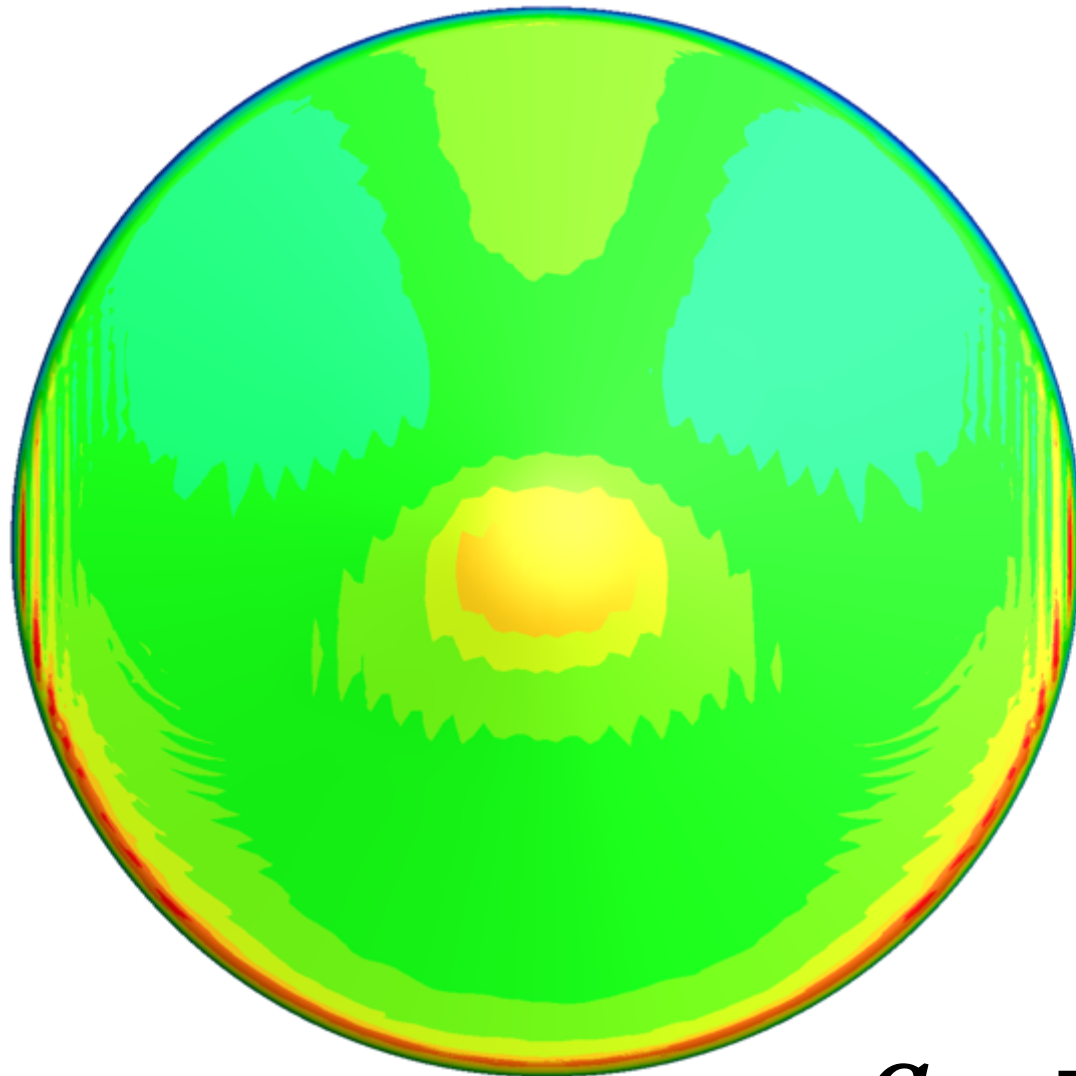
Chemistry model

Reaction parameters for the Micheltree and Gnoffo reaction model [5]

No.	Reaction	A (cm ³ /mol/s)	B	C (K)
1	CO + M \leftrightarrow C + O + M (M = atom)	3.4×10^{20}	-1.00	129,000
2	CO + M \leftrightarrow C + O + M (M = mol.)	2.3×10^{20}	-1.00	129,000
3	CO ₂ + M \leftrightarrow CO + O + M (M = atom)	1.4×10^{22}	-1.50	63,275
4	CO ₂ + M \leftrightarrow CO + O + M (M = mol.)	6.9×10^{21}	-1.50	63,275
5	O ₂ + M \leftrightarrow O + O + M (M = atom)	1.0×10^{22}	-1.50	59,750
6	O ₂ + M \leftrightarrow O + O + M (M = mol.)	2.0×10^{21}	-1.50	59,750
7	N ₂ + M \leftrightarrow N + N + M (M = atom)	3.0×10^{22}	-1.60	113,200
8	N ₂ + M \leftrightarrow N + N + M (M = mol.)	7.0×10^{21}	-1.60	113,200
9	NO + M \leftrightarrow N + O + M (M = C, N, O, NO, CO ₂)	1.1×10^{17}	0.00	75,500
10	NO + M \leftrightarrow N + O + M (M = N ₂ , O ₂ , CO)	5.0×10^{15}	0.00	75,500
11	NO + O \leftrightarrow O ₂ + N	8.4×10^{12}	0.00	19,450
12	N ₂ + O \leftrightarrow NO + N	6.4×10^{17}	-1.00	38,370
13	CO + O \leftrightarrow O ₂ + C	3.9×10^{13}	-0.18	69,200
14	CO ₂ + O \leftrightarrow O ₂ + CO	2.1×10^{13}	0.00	27,800
15	CO + N \leftrightarrow NO + C	2.86×10^{11}	0.50	53,630
16	CO + CO \leftrightarrow CO ₂ + C	2.33×10^9	0.50	65,710
17	NO + CO \leftrightarrow CO ₂ + N	4.59×10^8	0.50	12,070

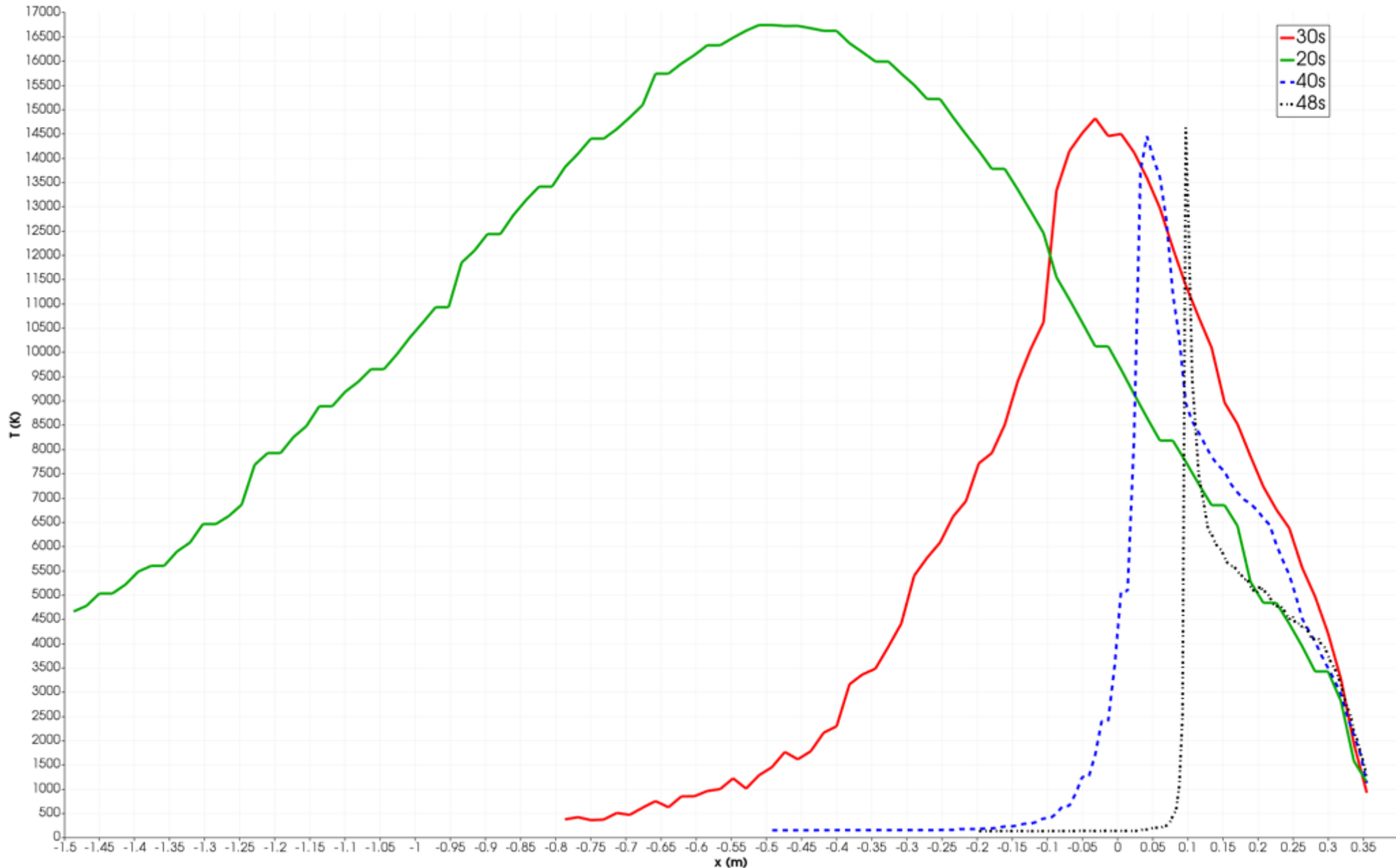
- **Backward rates computed using forward rates and equilibrium constants.**
- **Equilibrium constants computed using van't Hoff equation (Gibbs free energy).**
- **Backward rates fit to modified Arrhenius form between 5,000 and 20,000 K.**

Radiative equilibrium boundary condition

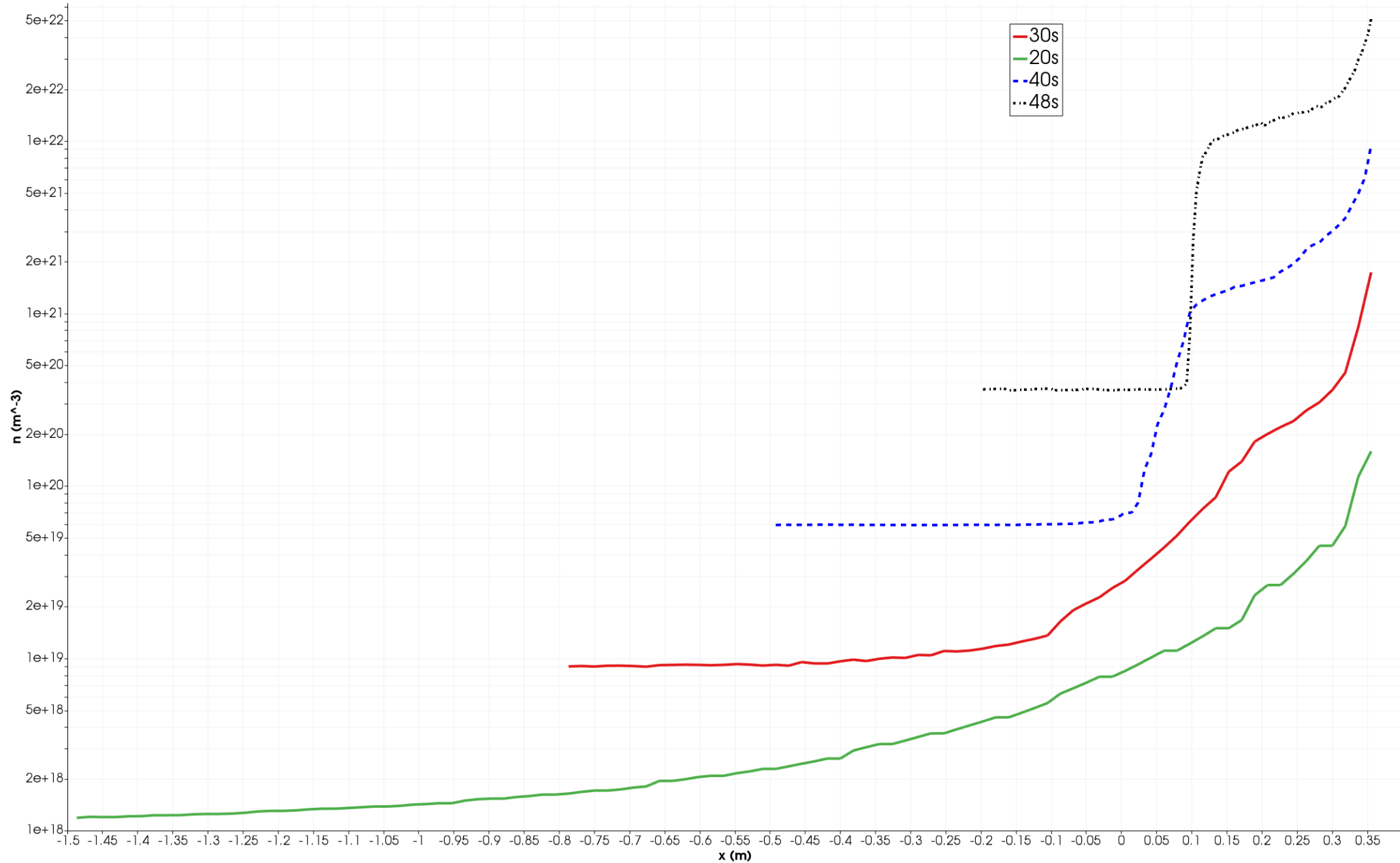


$$q_w = \varepsilon \sigma T_w^4$$

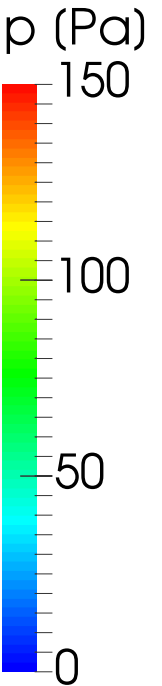
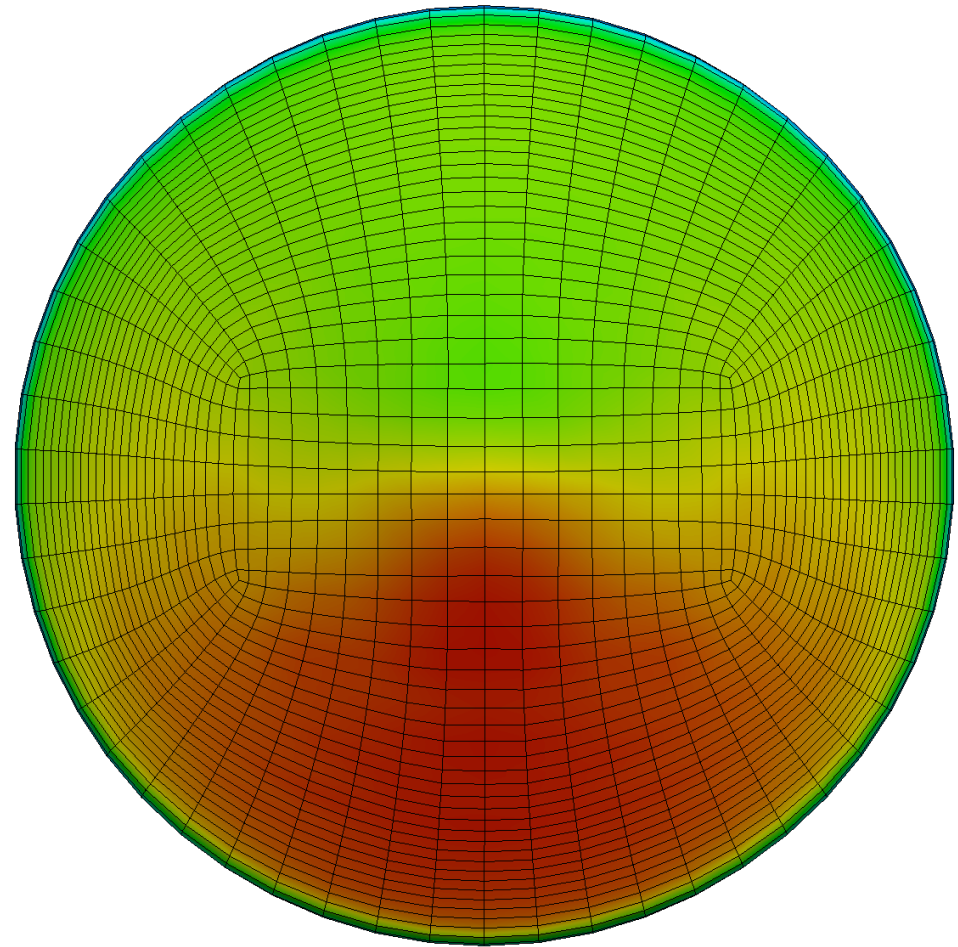
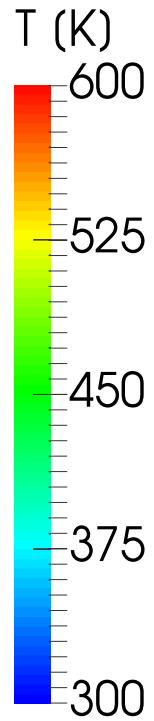
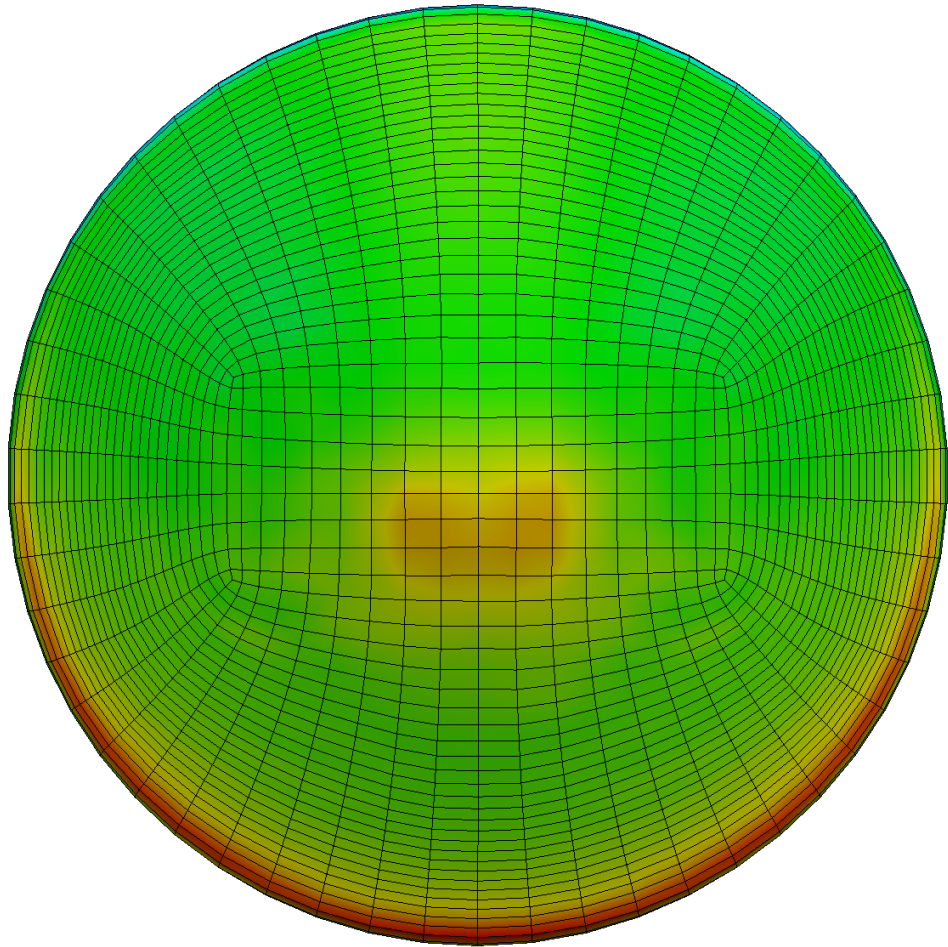
Translational temperature at different altitudes



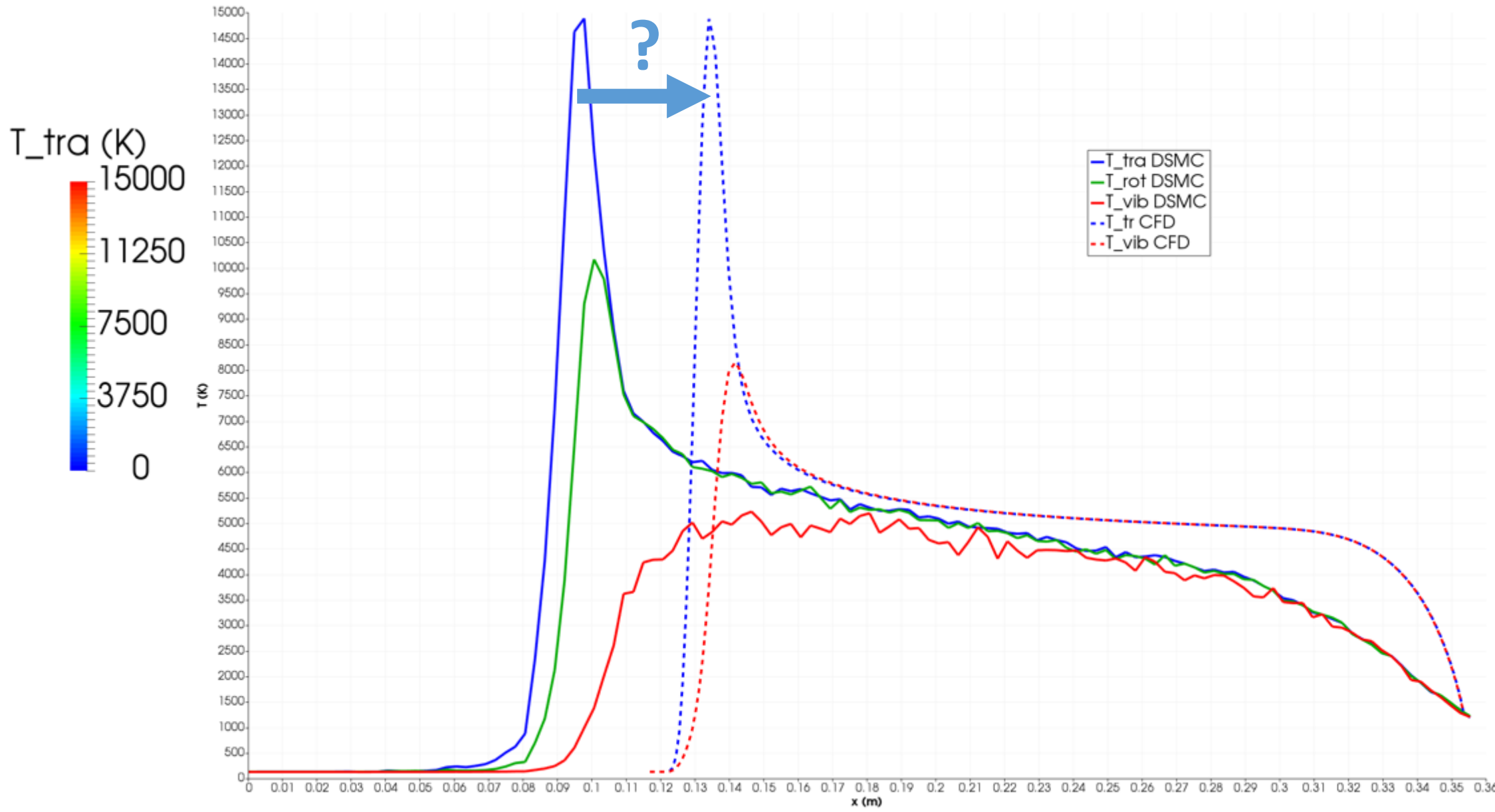
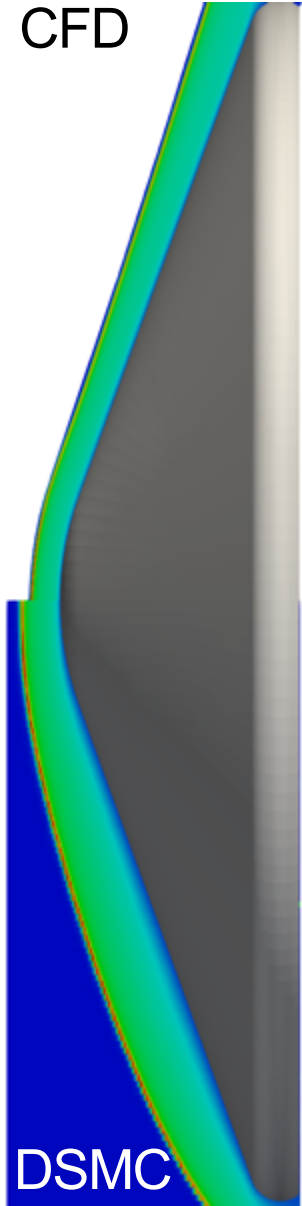
Number density at different altitudes



Surface temperature and pressure from DSMC at 40s

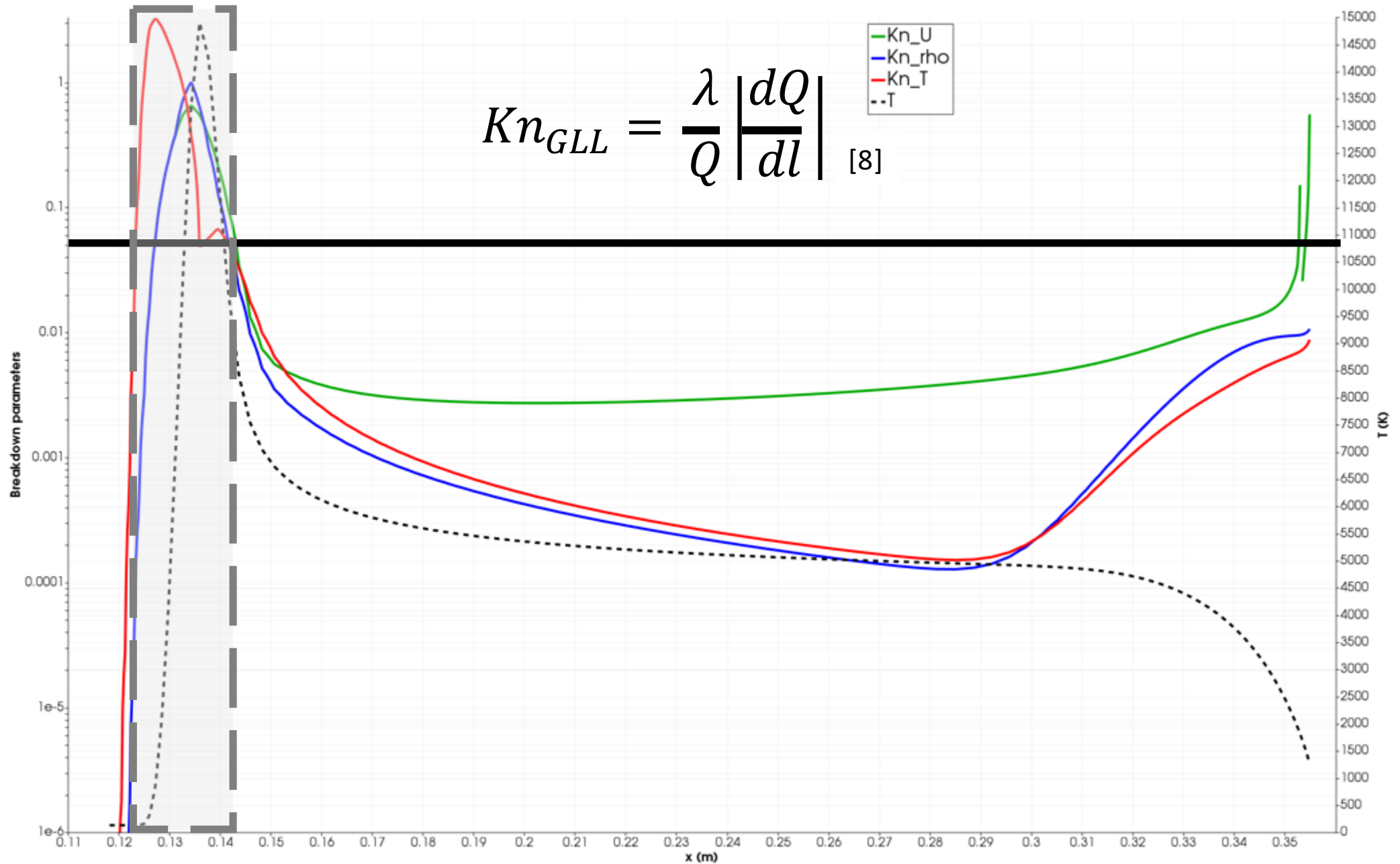


The 48.4s of entry point: DSMC vs CFD

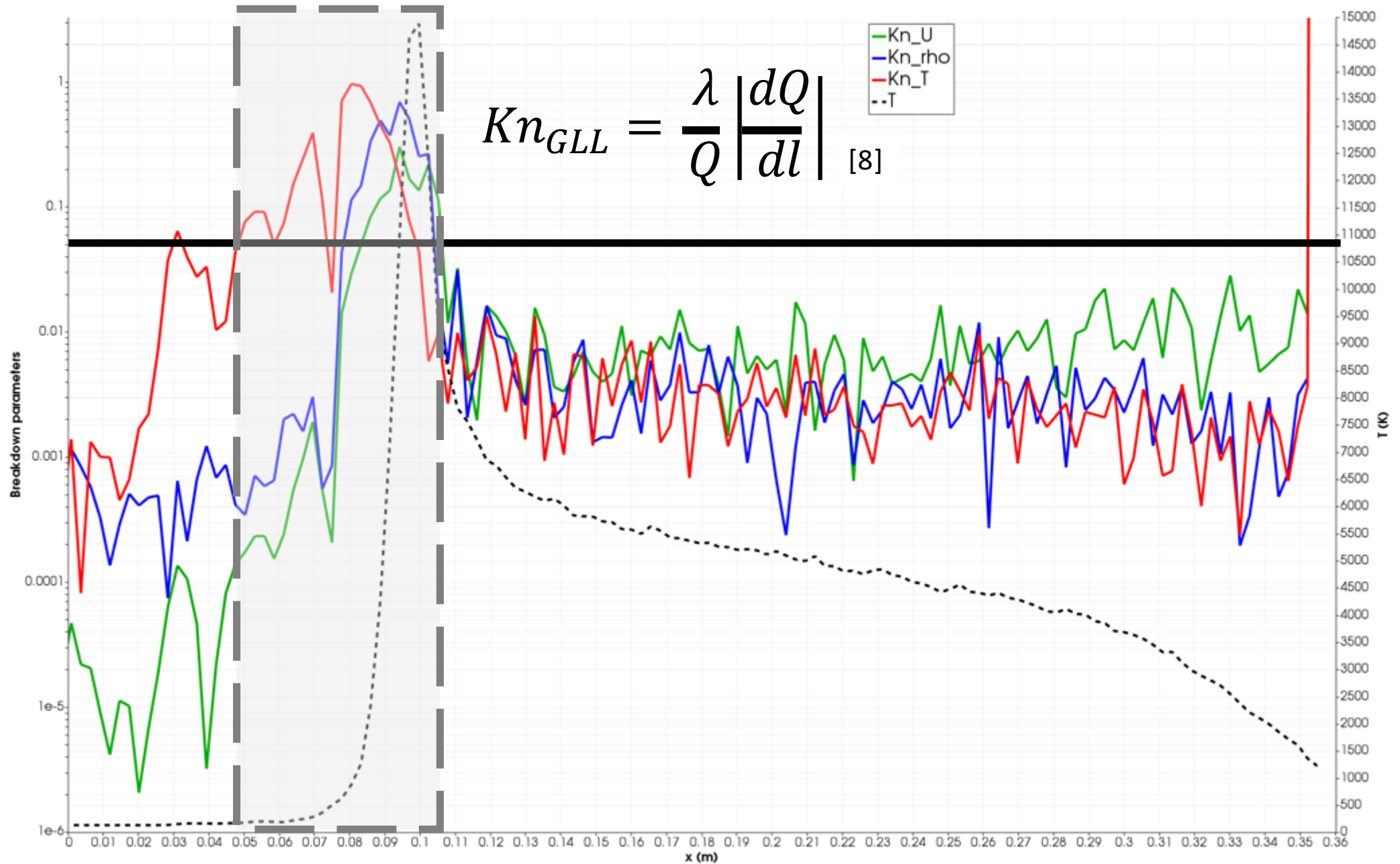




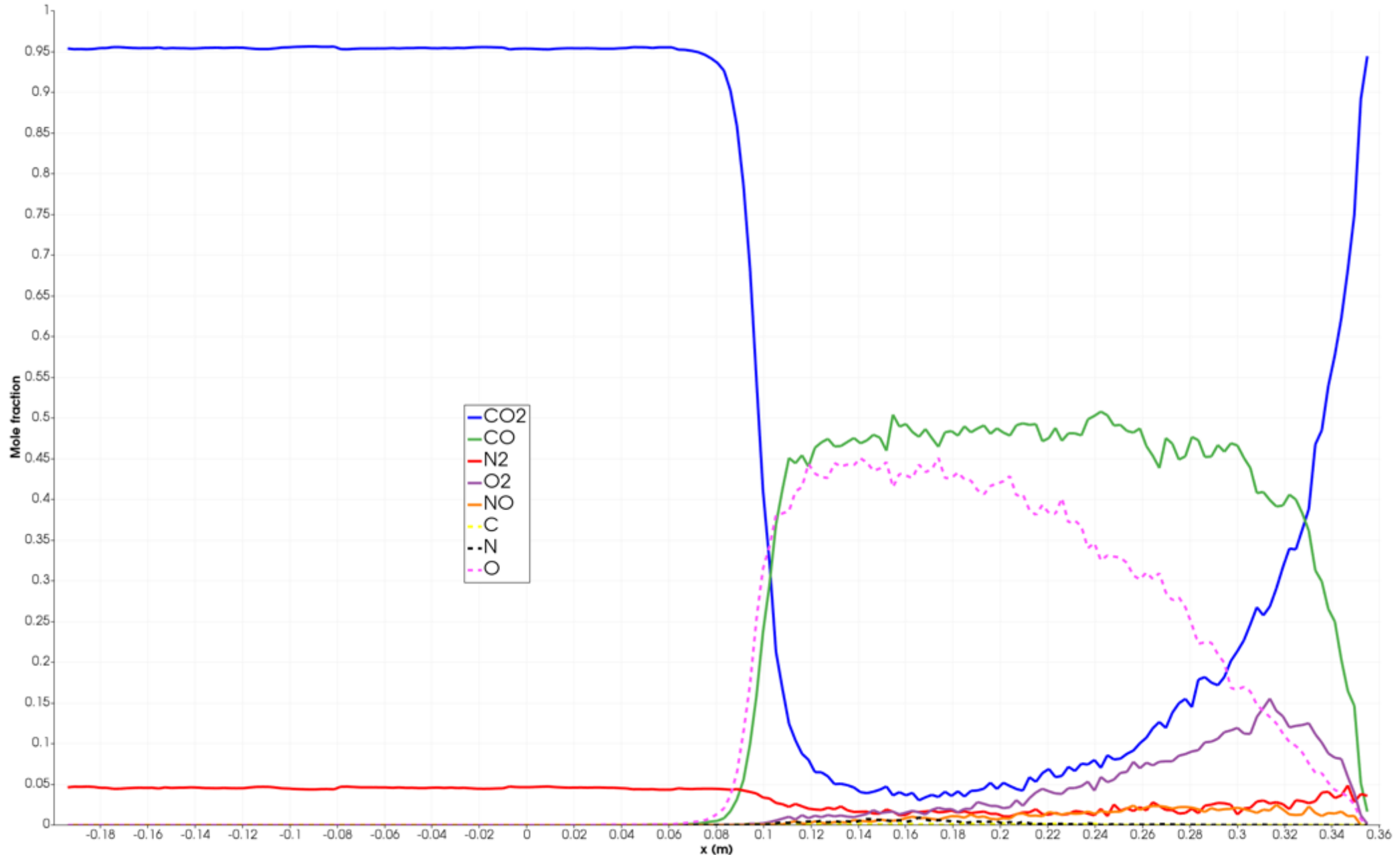
Continuum breakdown parameters: CFD



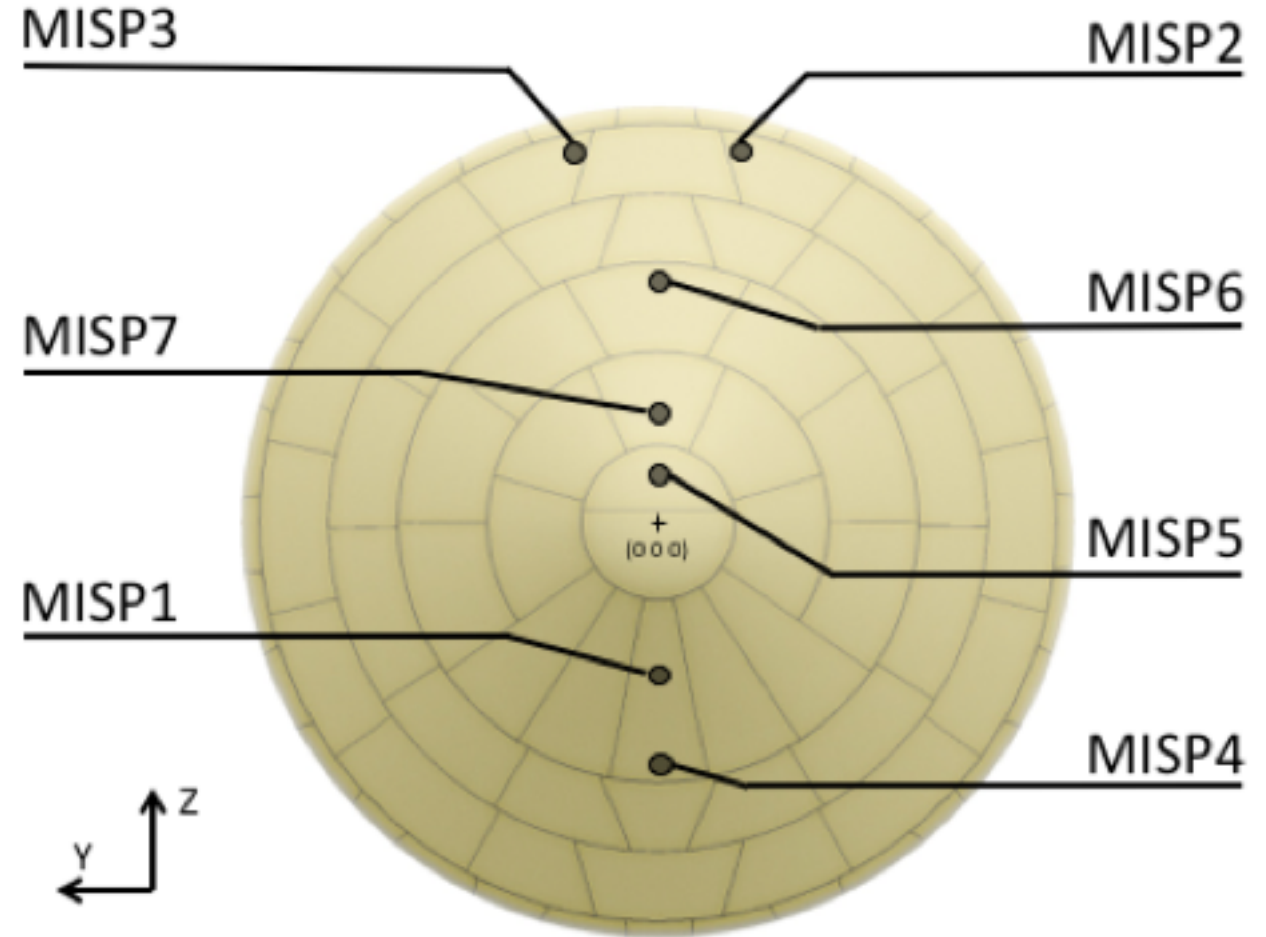
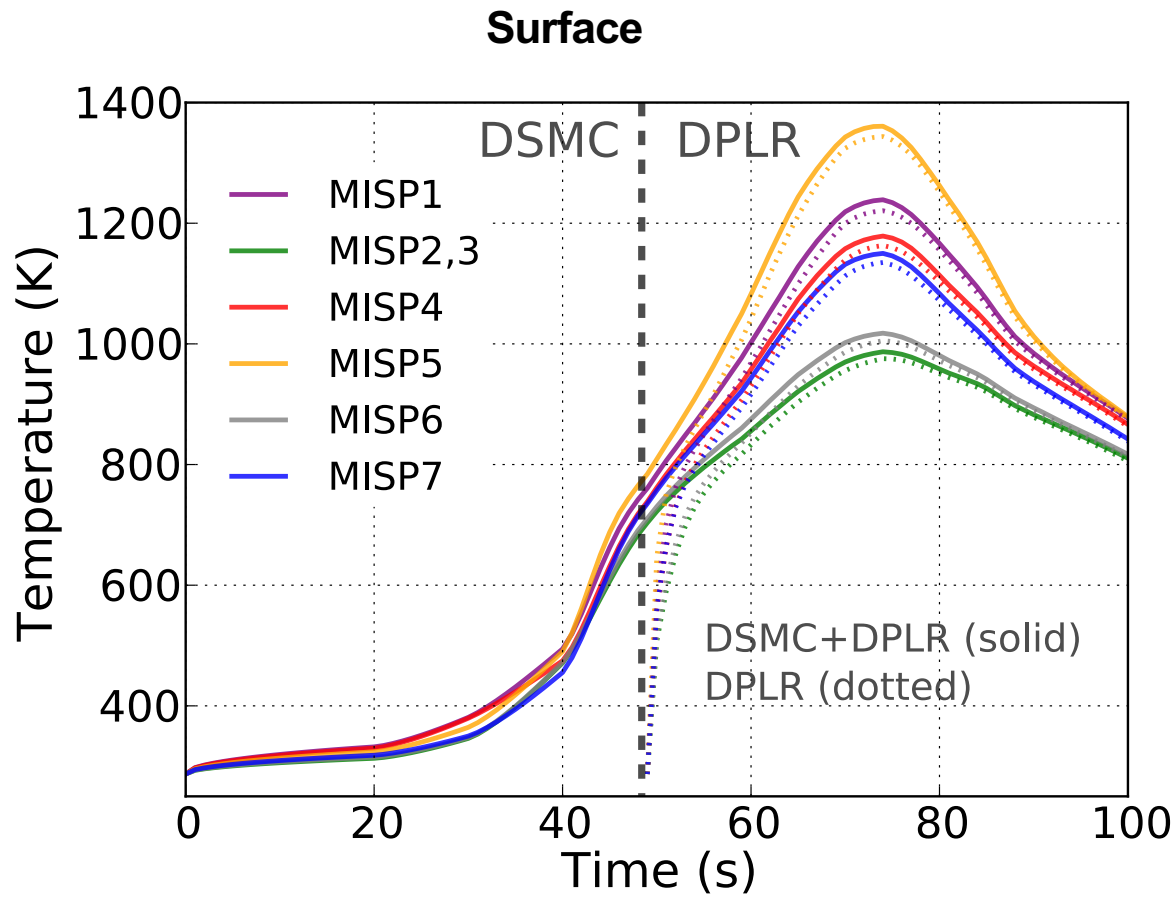
Continuum breakdown parameters: DSMC



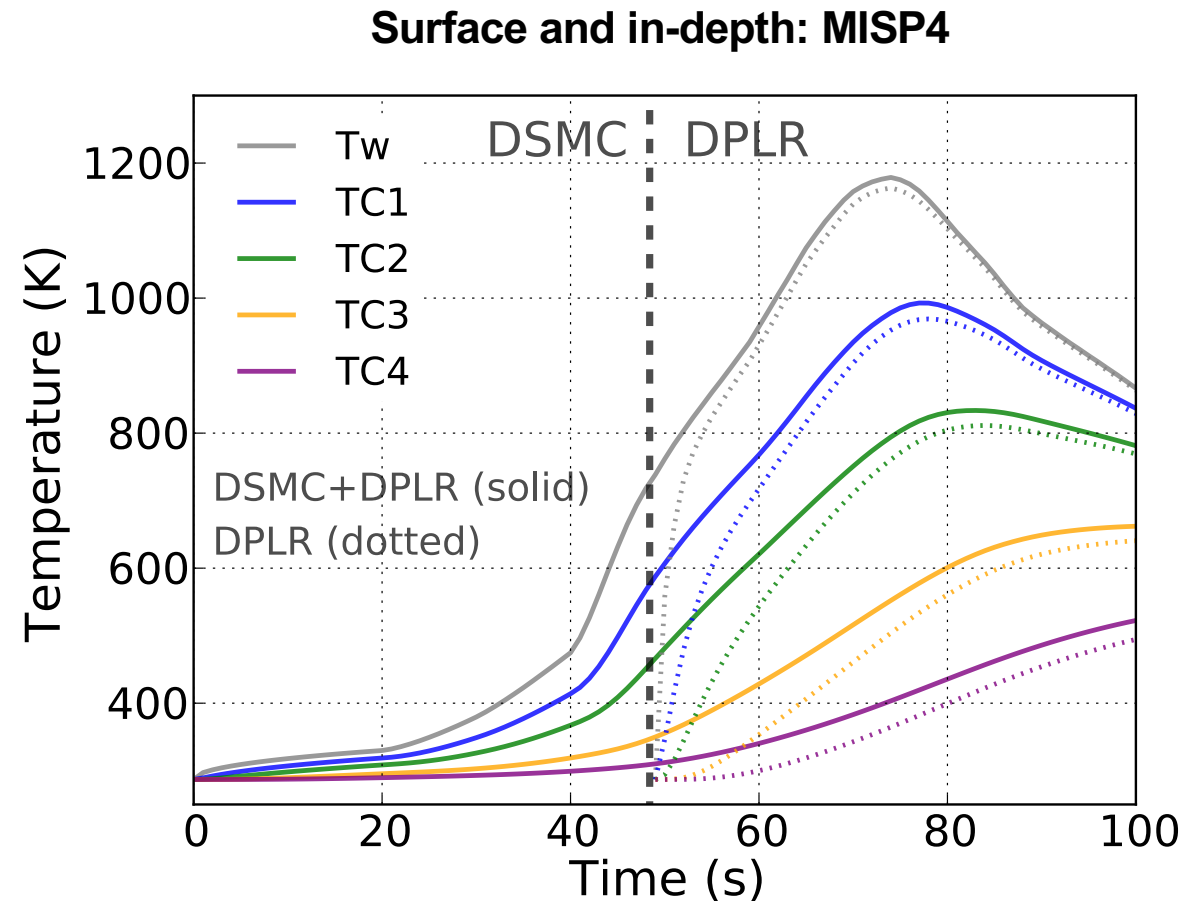
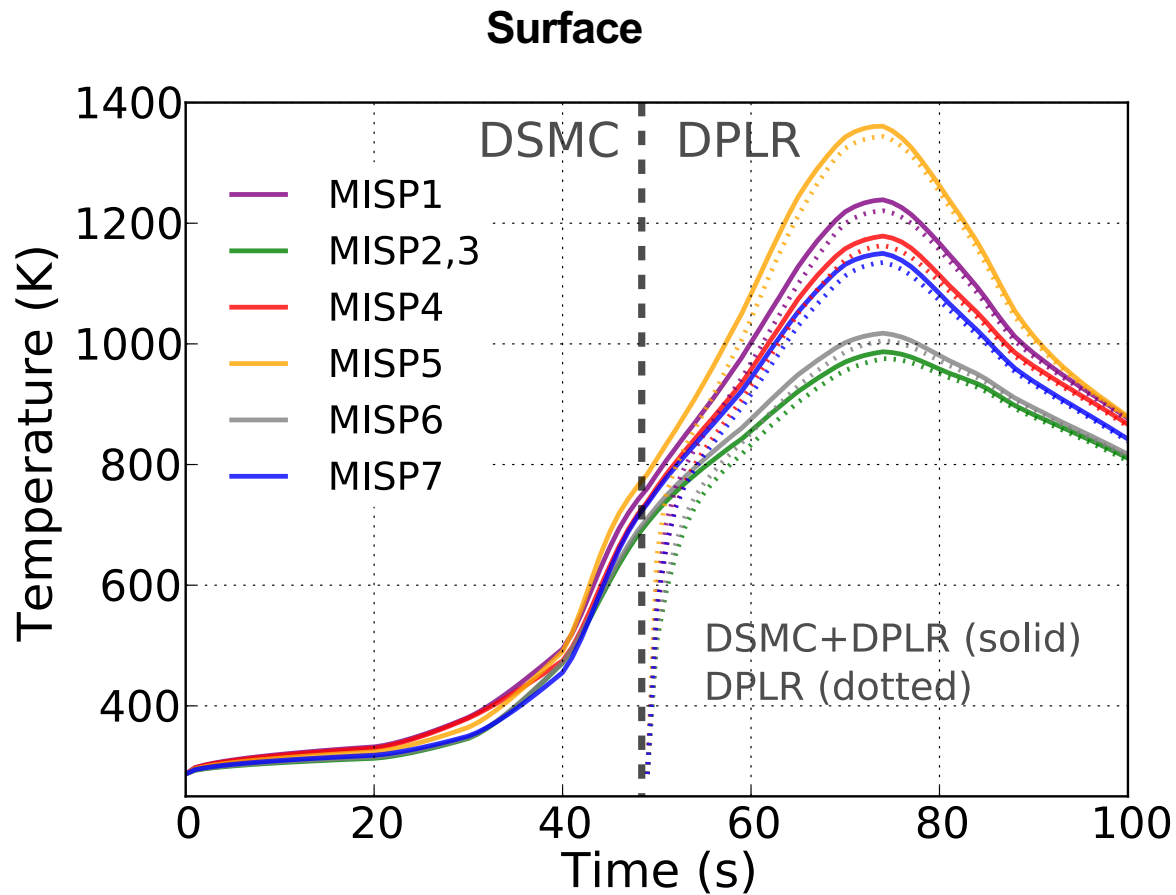
The 48.4s of entry point: DSMC mole fractions



Temperature from PATO



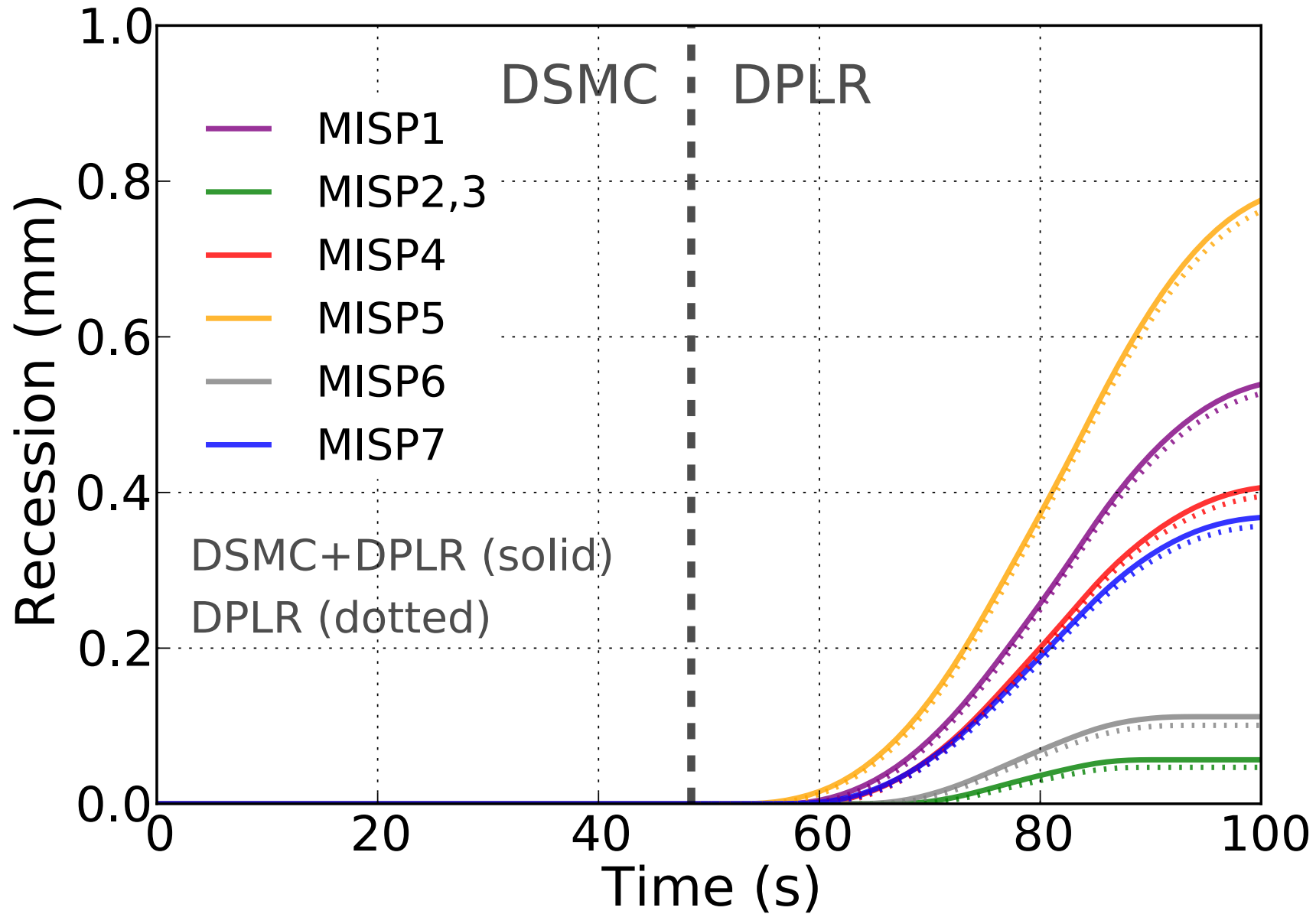
Temperature from PATO



- **Addition of DSMC results significantly modify temperature prediction for first 60s of Entry Interface**



Recession from PATO





credit: T. Sandstrom, NASA Ames



Conclusion

Hypersonic environment (DPLR)

- Laminar
- Super-catalytic wall
- Non-blowing

(SPARTA)

- High T transport calibration
- Parker + Millikan White + Park for relaxation
- Discrete vibrational levels

(common)

- Super-catalytic wall with radiative equilibrium
- Mitcheltree 8 species reaction model



DSMC simulations from 20 to 48.4s

- Shock narrows with decreasing altitude
- Compute surface pressure and heat flux

Shock standoff offset at 48.4s

- Continuum breakdown?
- Differences between models?



Conclusion

Hypersonic environment (DPLR)

- Laminar
- Super-catalytic wall
- Non-blowing

(SPARTA)

- High T transport calibration
- Parker + Millikan White + Park for relaxation
- Discrete vibrational levels
- **(common)**
- Super-catalytic wall with radiative equilibrium
- Mitcheltree 8 species reaction model

Soft coupling



Porous material response (PATO)

- Pyrolysis
- CMA-type BL approx.
- No finite-rate
- Equilibrium

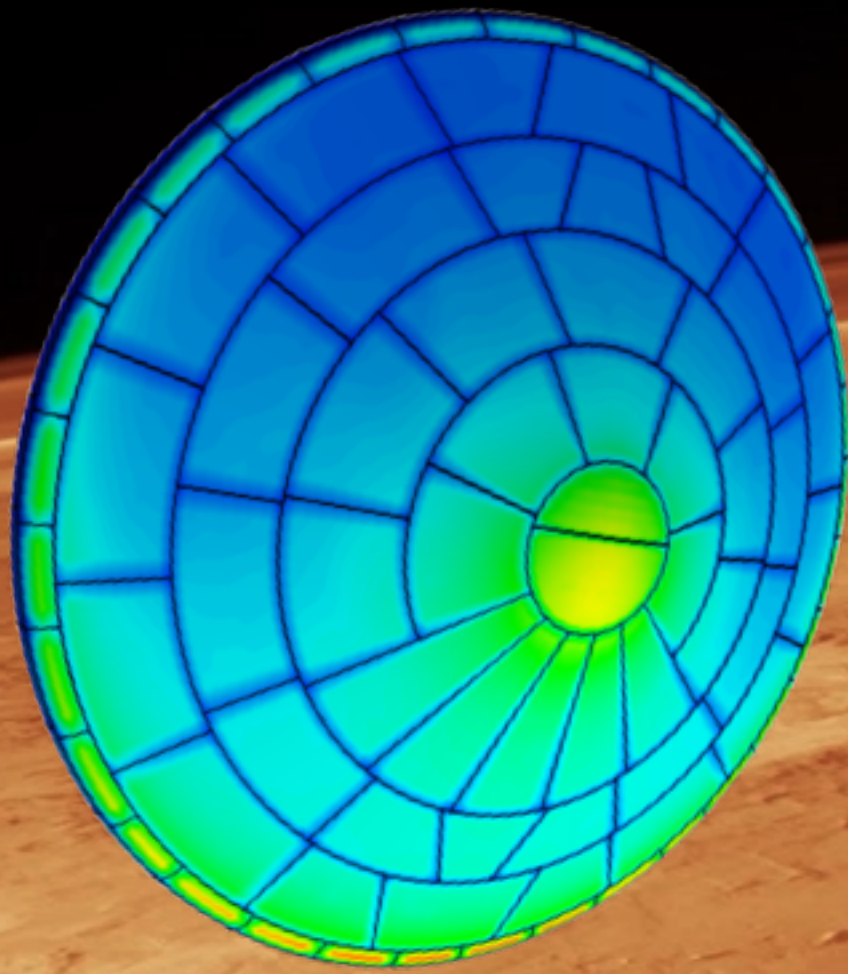
↓ Outputs

- Temperature
- Recession

References



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- [2] M. J. Wright, T. White, N. Mangini, Data Parallel Line Relaxation (DPLR) Code User Manual: Acadia-Version 4.01.
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- [6] K. Swaminathan-Gopalan, K. A. Stephani, Recommended direct simulation Monte Carlo collision model parameters for modeling ionized air transport processes, Physics of Fluids, 28, 027101 (2016).
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Questions ?

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