Aerothermodynamic Analysis of Hypersonic Reentry Vehicles

MASTER PROJECT PRESENTATION

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EPFL

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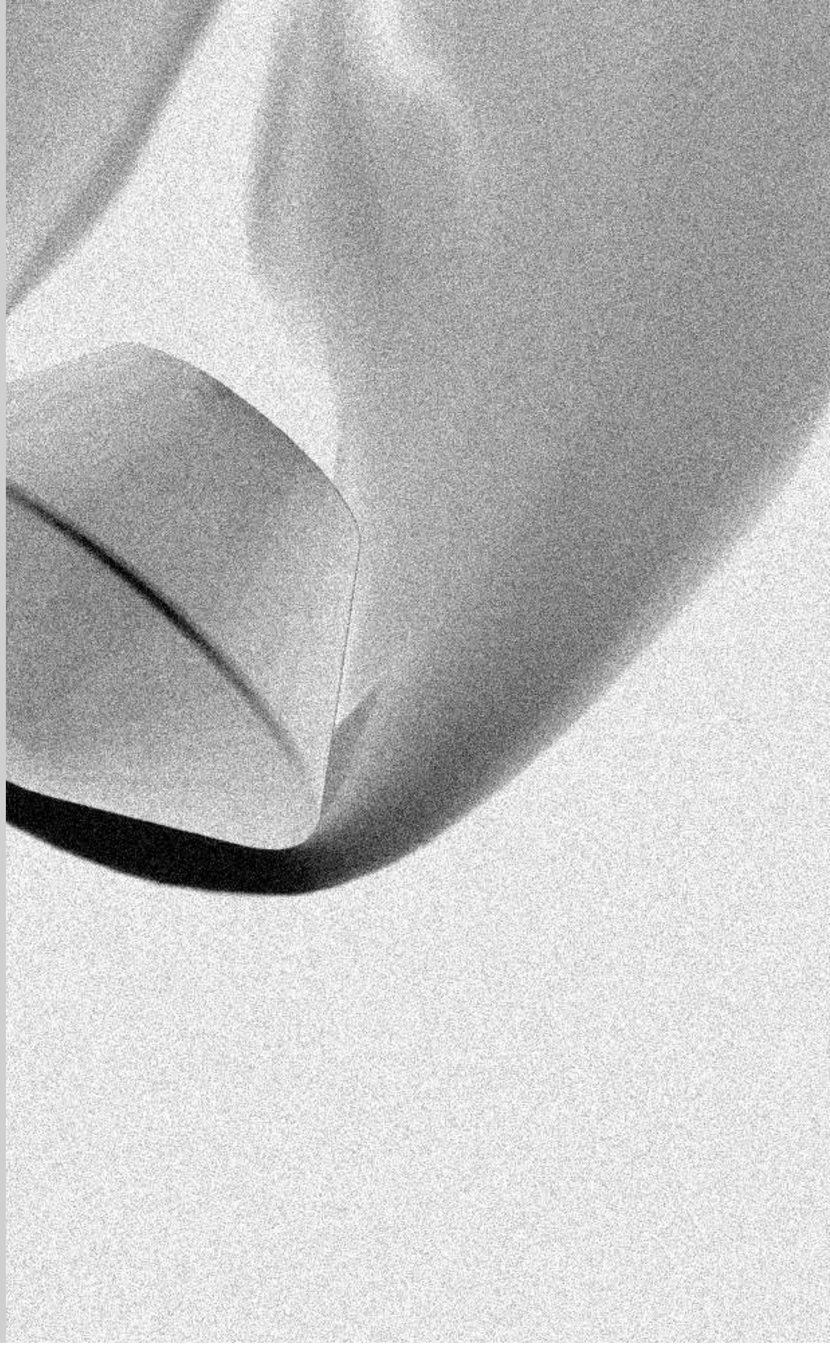

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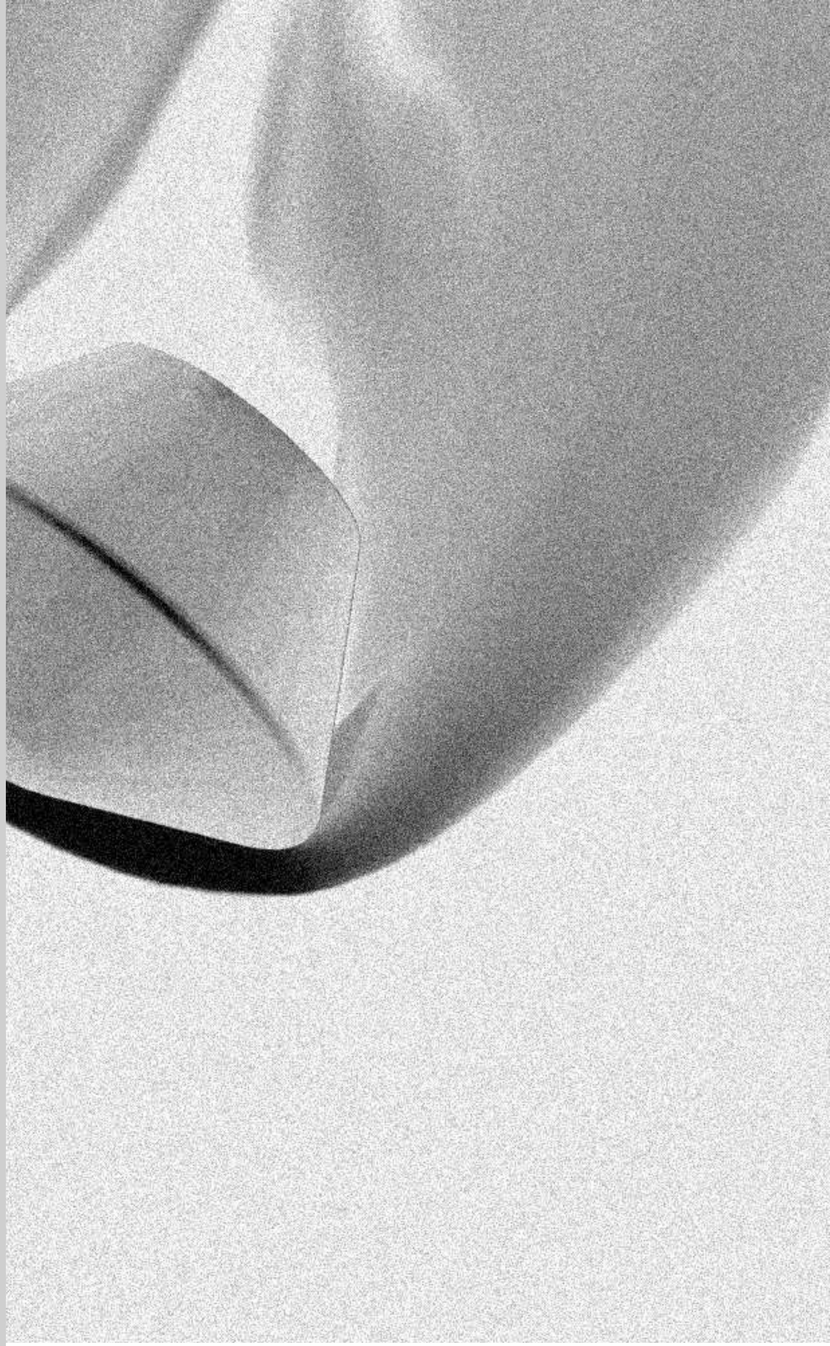

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1.2 Ablation Phenomenon

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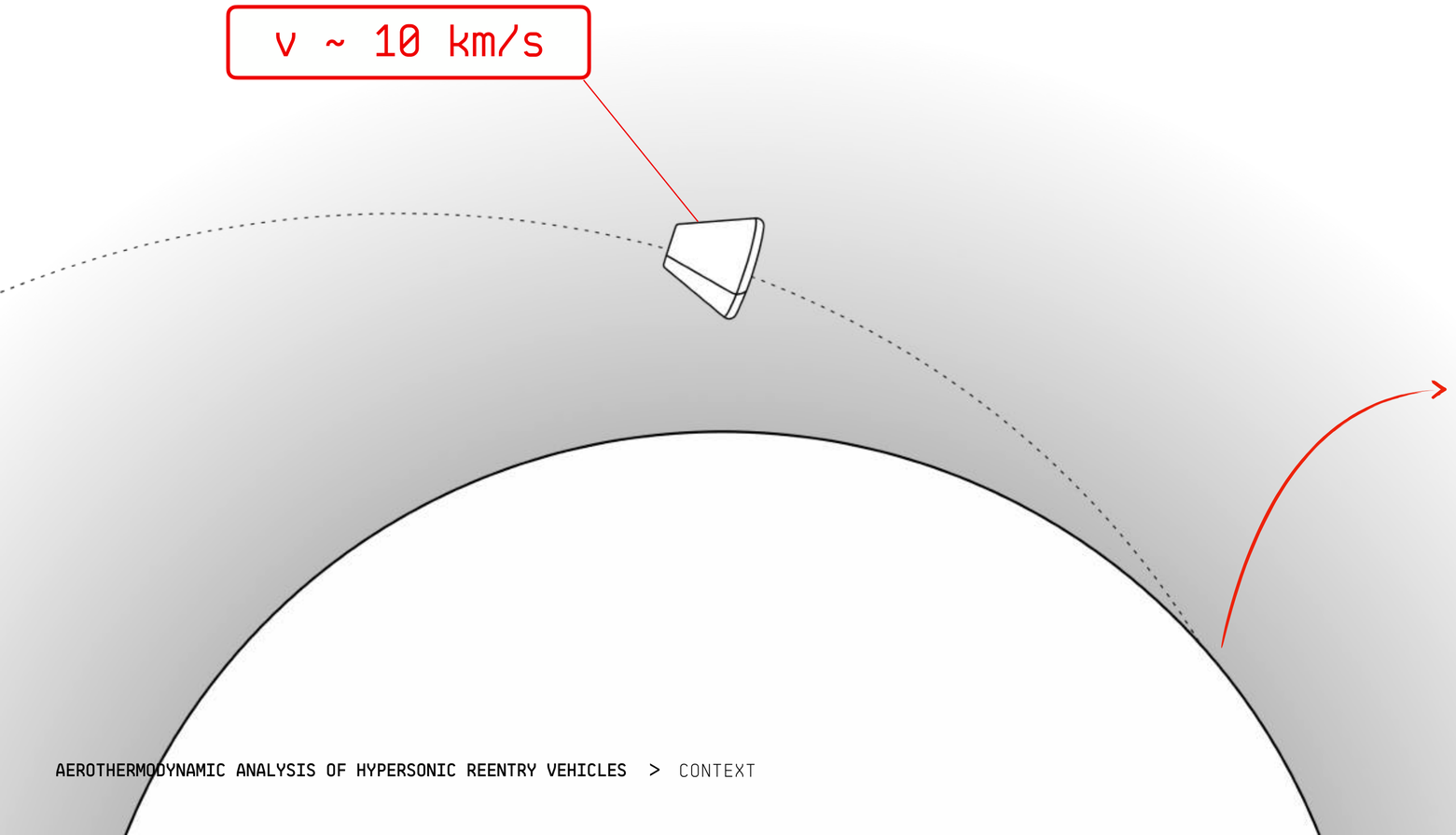
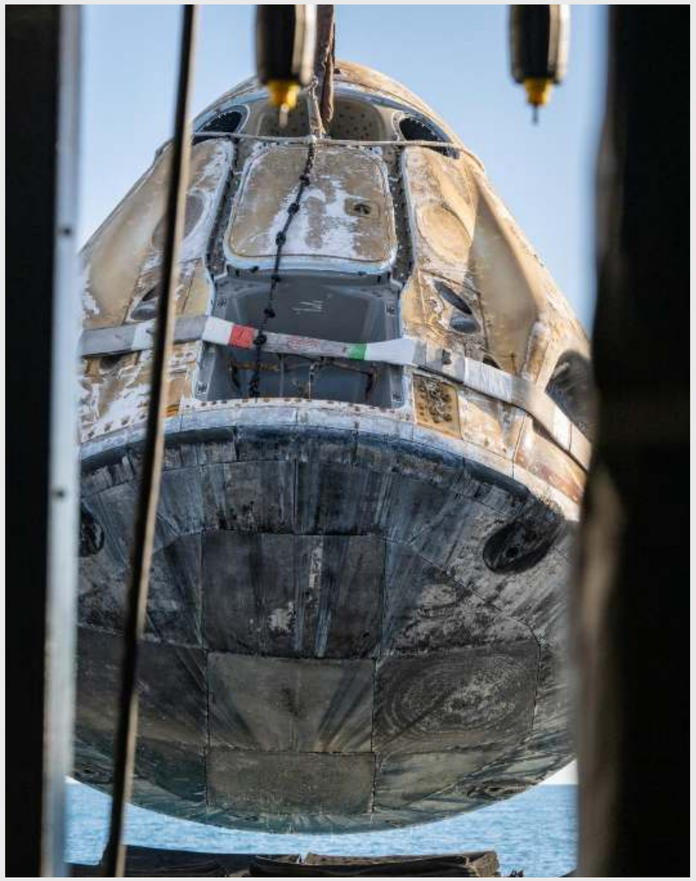
Atmospheric Reentry





APOLLO 11 COMMAND MODULE
NASA, USS HORNET, HAWAII, JULY 1969

Atmospheric Reentry



NASA-SPACE X CREW 9 MODULE
NASA, TALLAHASEE FL, 2025



APOLLO 11 COMMAND MODULE
NASA, USS HORNET, HAWAII, JULY 1969

Atmospheric Reentry





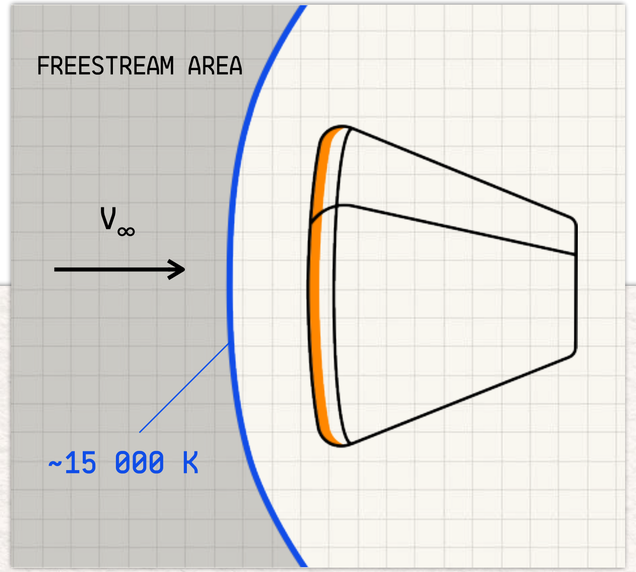
CONTEXT

Atmospheric Reentry



NASA, 2025

Aerothermodynamic Processes

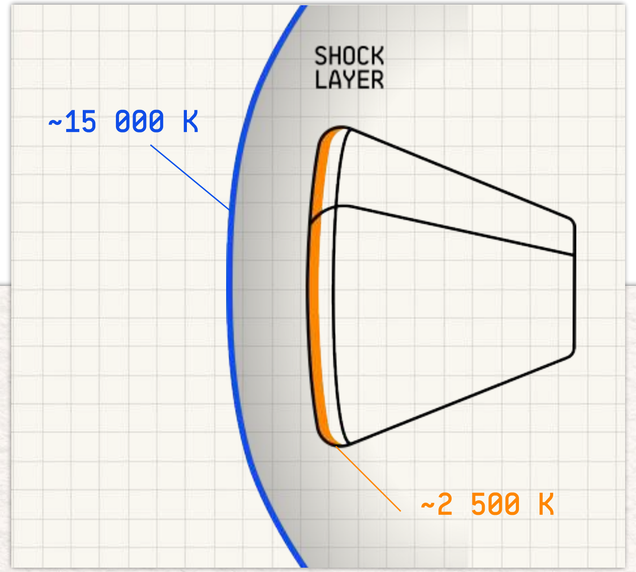


Towards Hypersonic Flow

FREESTREAM AREA

ALTITUDE LOSS → AIR DENSITY INCREASE → HIGH FREESTREAM ENERGY → GAS COMPRESSION NEAR VEHICLE → STRONG BOW SHOCK

Aerothermodynamic Processes



From Hypersonic Flow to Heat Load

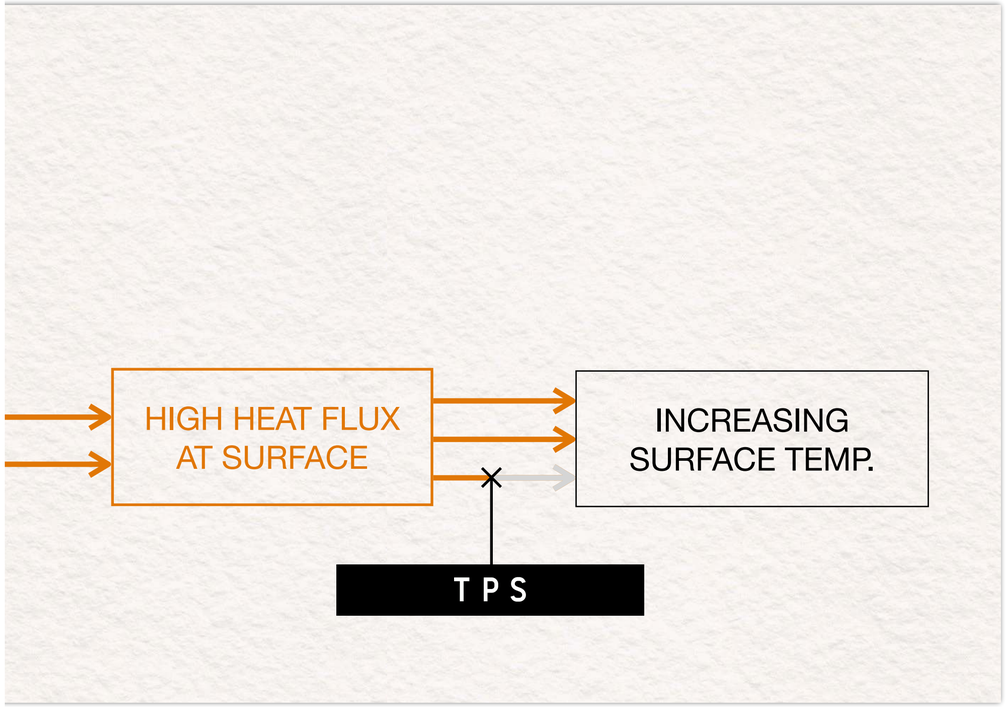
SHOCK LAYER

STRONG BOW SHOCK → HIGH TEMPERATURE AND CHEMICAL REACTIONS → ENERGY TRANSFER THROUGH THE B.L. → HIGH HEAT FLUX AT SURFACE → INCREASING SURFACE TEMP.

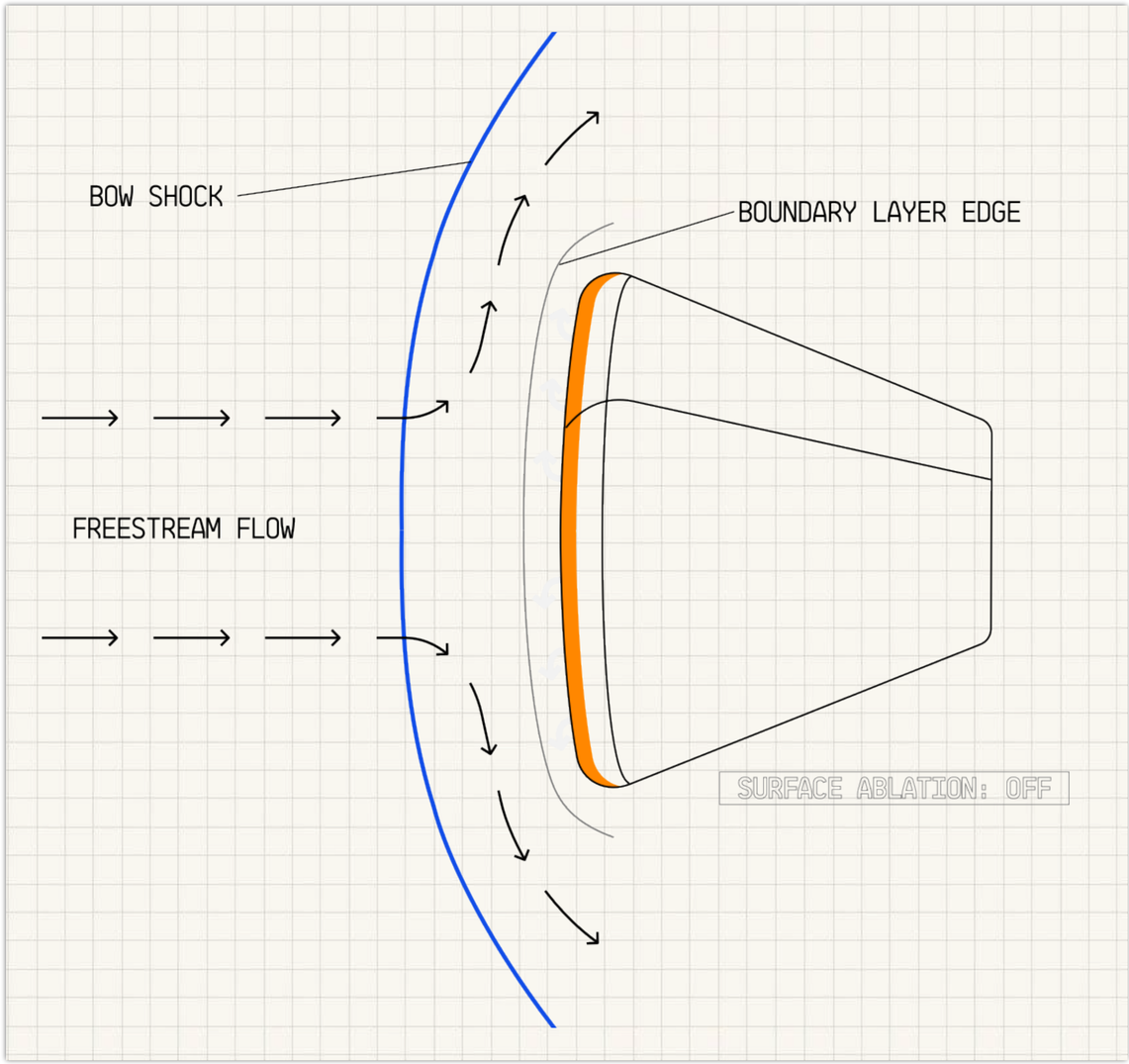
- dissociation
- exchange
- recombination and ionisation

ATMOSPHERIC REENTRY

Surface Ablation

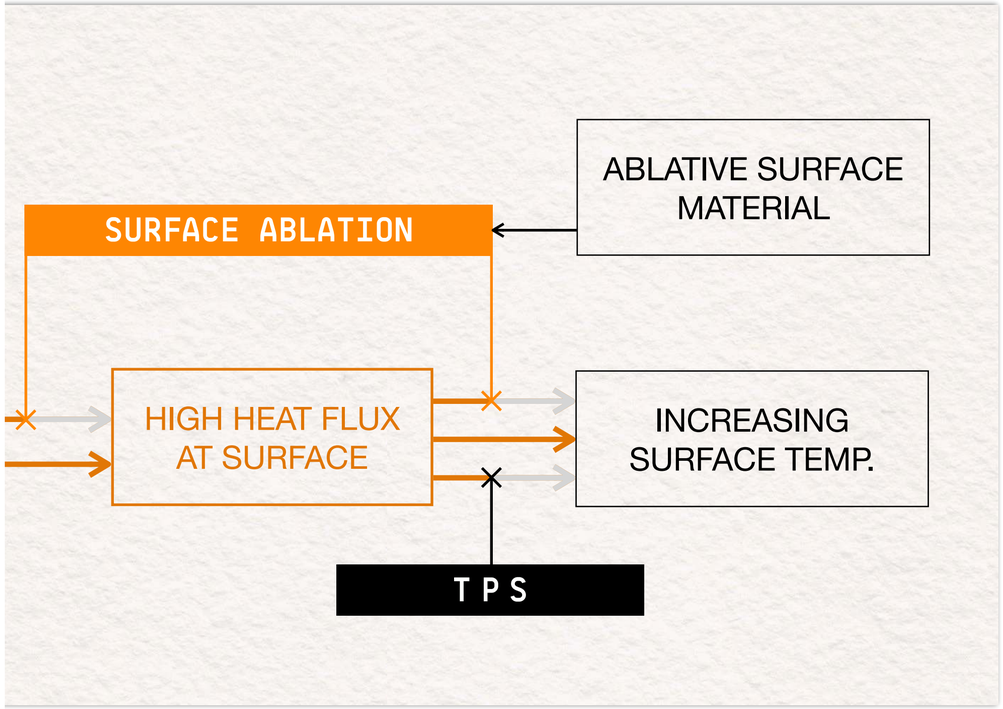


TPS DESIGN		
	Instantaneous peak heating	-> MATERIAL
	Cumulative thermal load	-> THICKNESS



ATMOSPHERIC REENTRY

Surface Ablation



TPS DESIGN		
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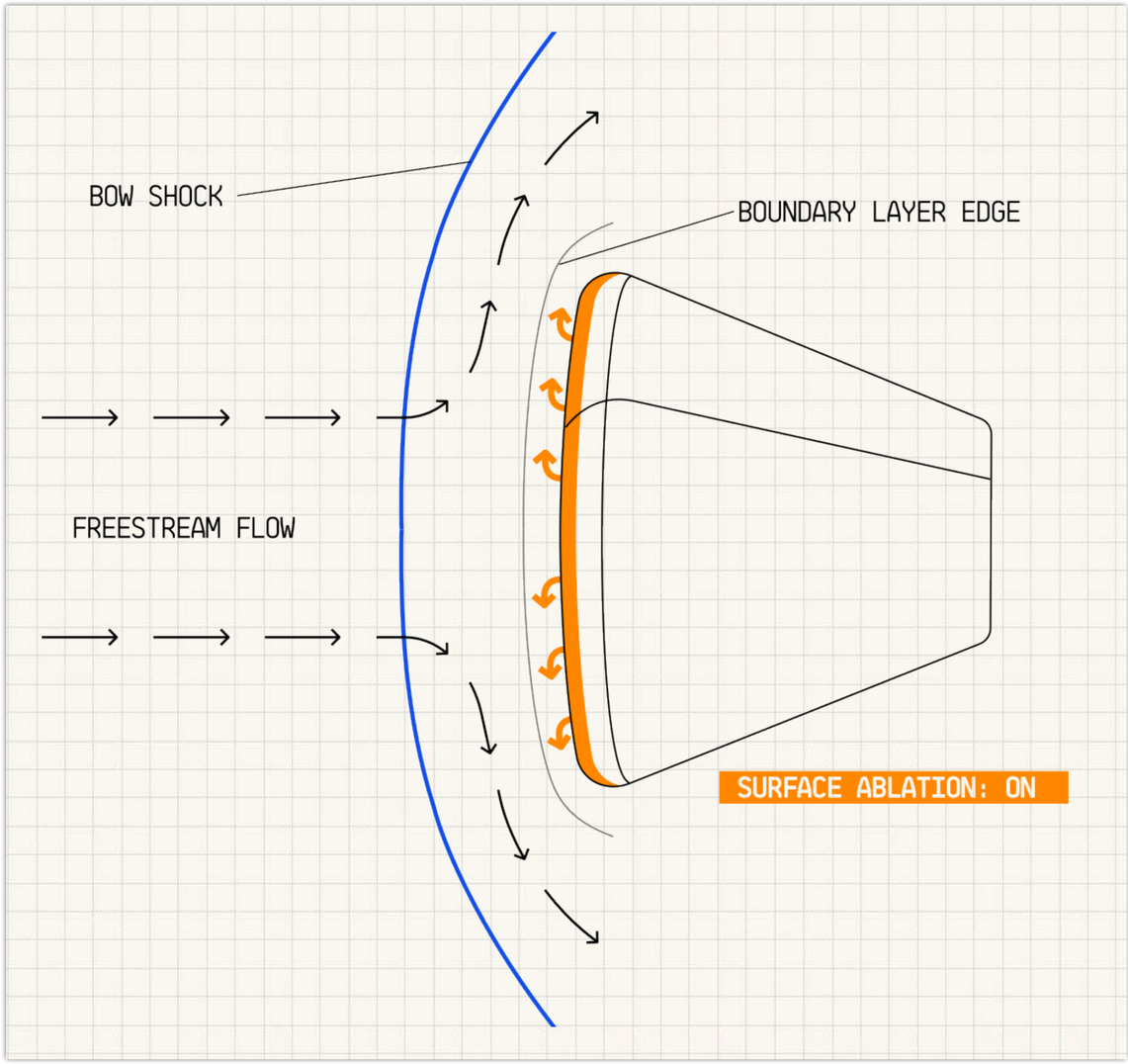


Surface Ablation

What is Ablation ?

ABLATIVE MATERIAL

⌄

SURFACE CHEMICAL REACTIONS

⌄

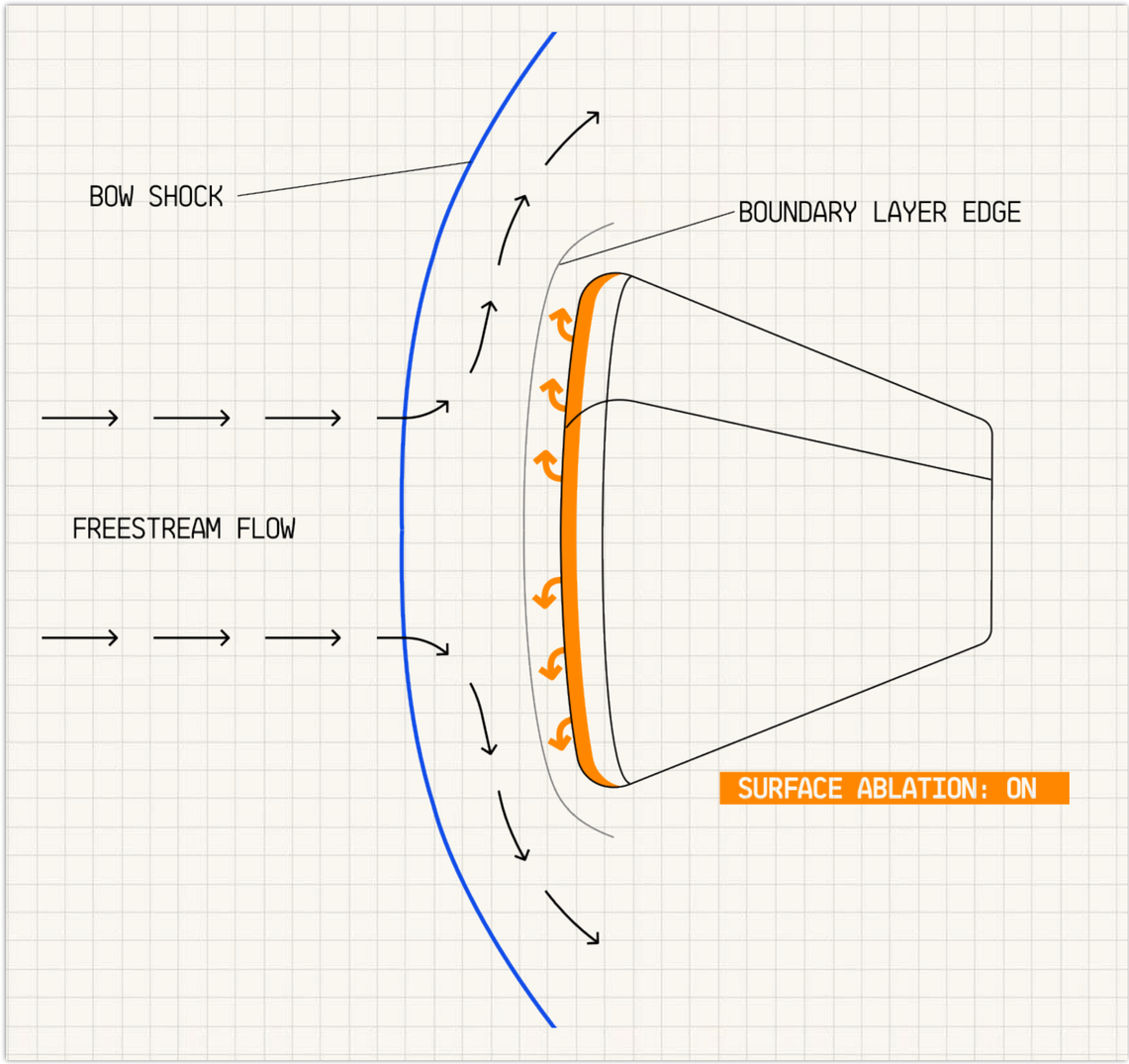
BLOWING NORMAL VELOCITY

⌄

BOUNDARY LAYER THICKENING

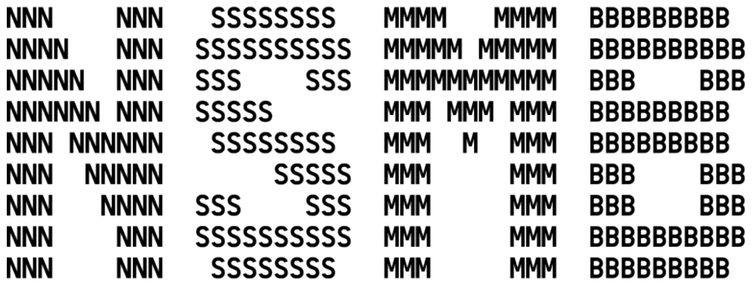
⌄

HEAT FLUX DECREASES



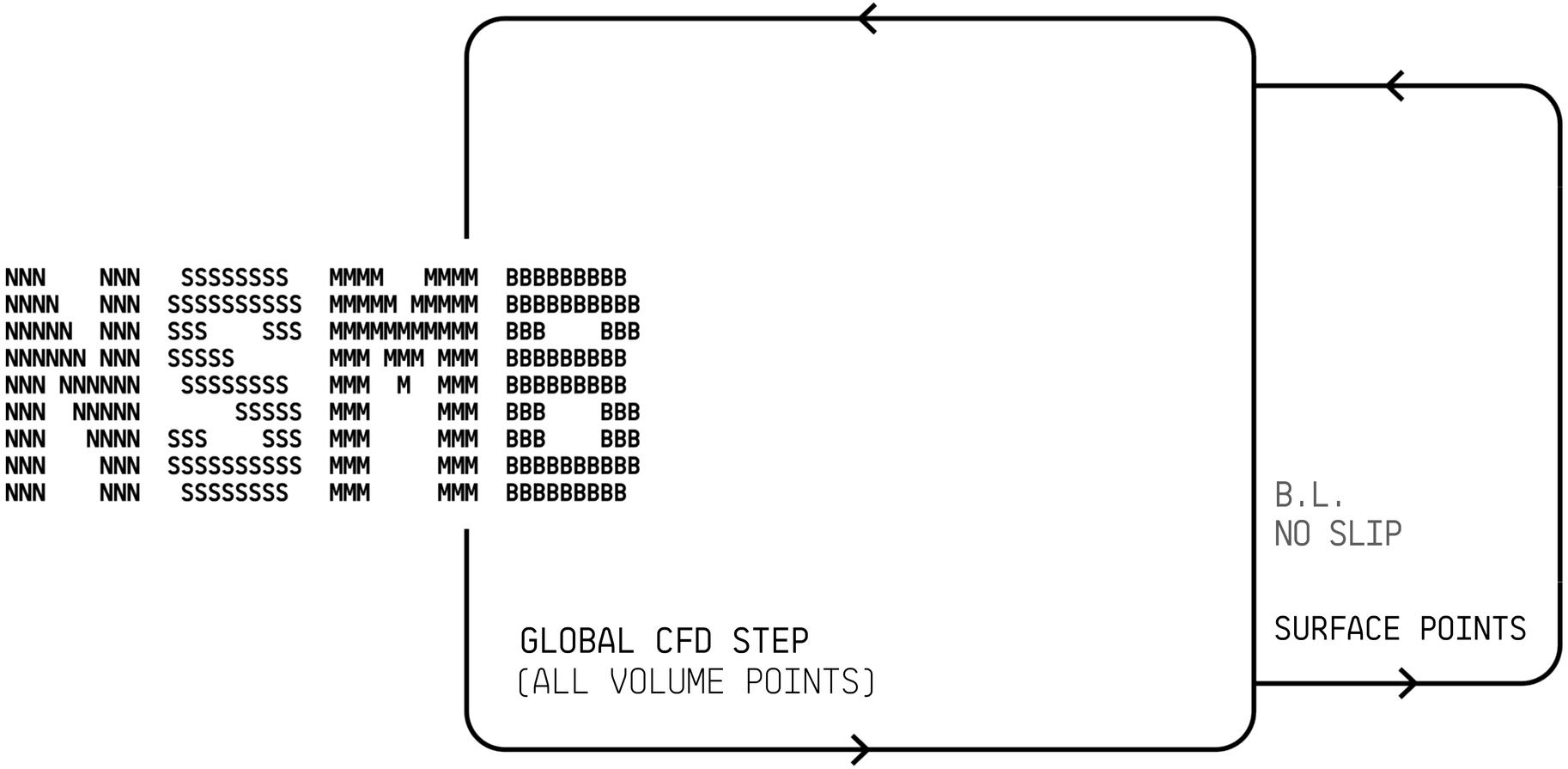
ATMOSPHERIC REENTRY

A New Module for NSMB

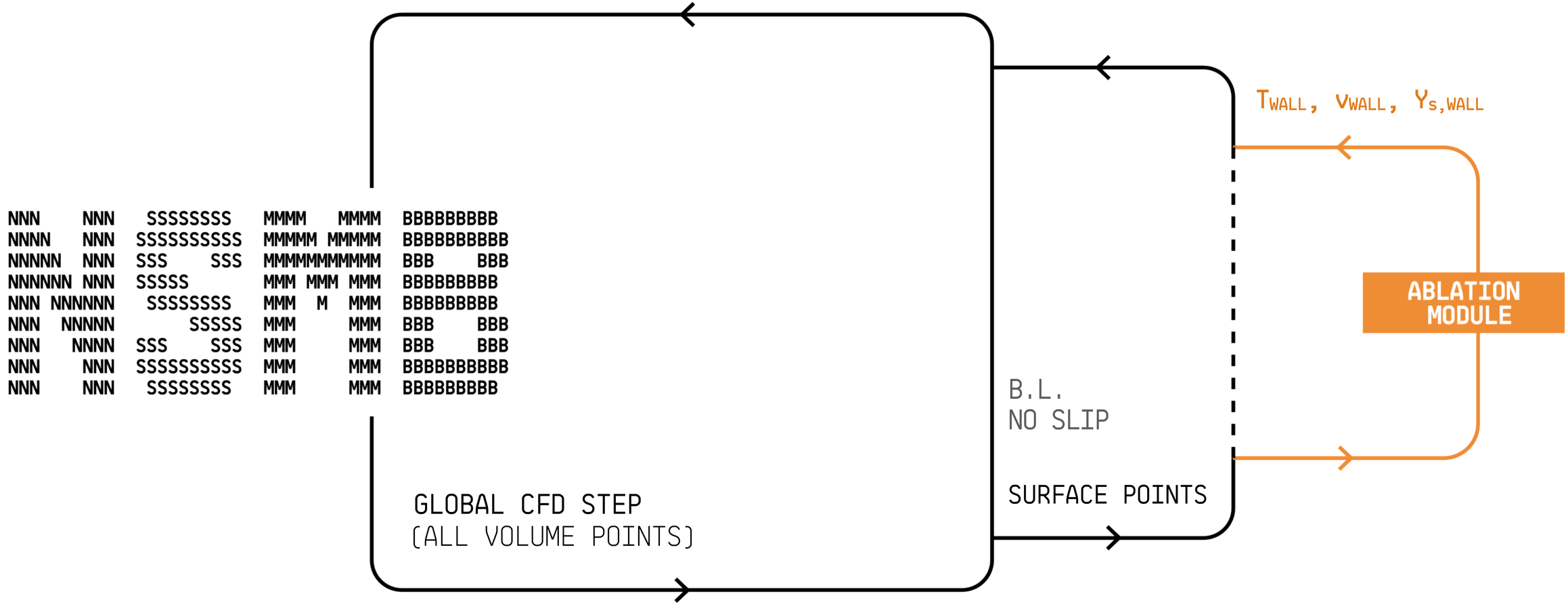


- FORTRAN
- COMPRESSIBLE FLOW SOLVER
- STRUCTURED AND MULTI-BLOCKS GRID
- DYNAMIC FAR-FIELD SHOCK ADAPTATION
- EXTENSIVELY VALIDATED IN HYPERSONIC REGIMES

A New Module for NSMB



A New Module for NSMB



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2.1 Validity of the Navier-Stokes Equations

2.2 Chemical and Thermal Non-Equilibriums

2.3 Boundary Conditions

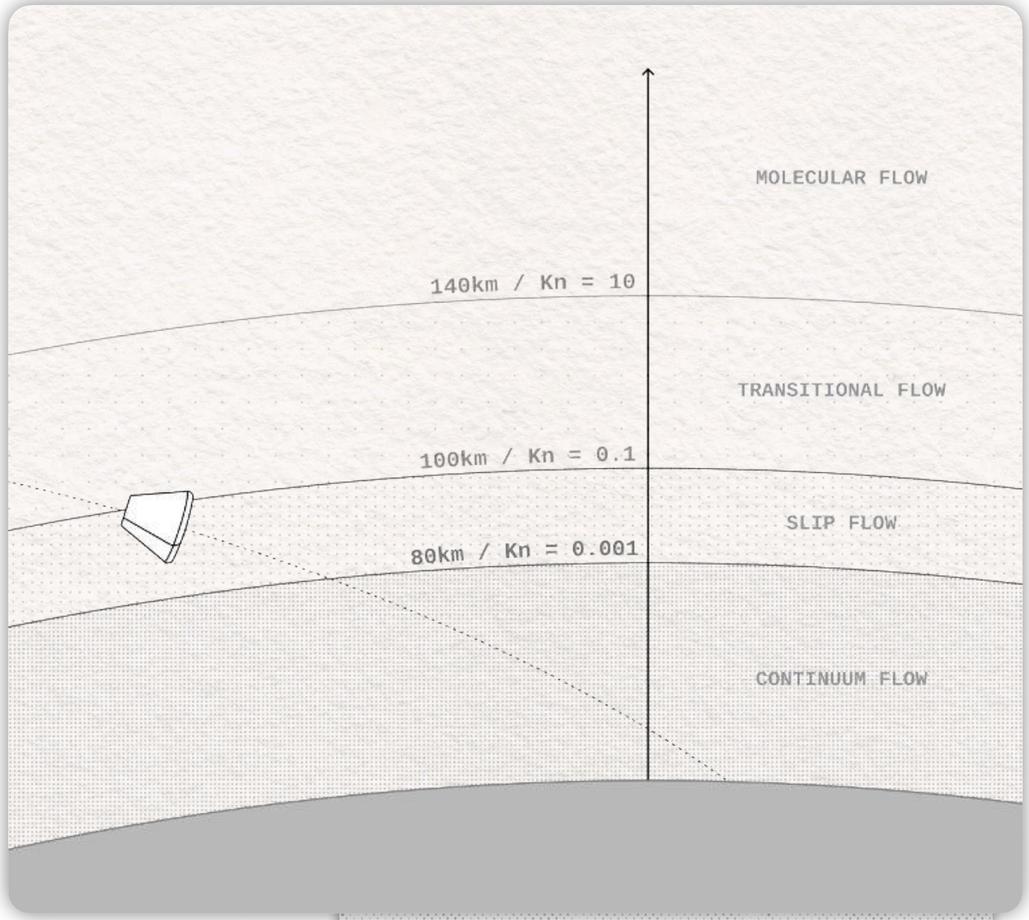
2.4 Chemistry Modelling

Validity of the Navier-Stokes Equations

Fluid should be considered as a ***continuum***

$$Kn = \frac{\lambda}{L} < 1 \times 10^{-3}$$

Beyond this range : *molecular flow*



Atmospheric layers and Knudsen number for a characteristic length of 1 meter at 1 atm.

Chemical and Thermal Non-Equilibrium

The hypersonic regime implies:

1 Chemical reaction time ≈ Characteristic flow time scale

2
- Molecular internal vibration becomes significant
- Vibrational temperature adjusts slower

Assumptions on the flow:

→ **CHEMICAL** NON-EQUILIBRIUM

↳ *Finite-rate chemical models*

→ **THERMAL** NON-EQUILIBRIUM

↳
- *2-temperature model* T_{tr} / T_{vib}
- *A controlling temperature:*

$$T_a = \sqrt{T_{tr} T_{vib}}$$

Wall Boundary Conditions

A CATALYTIC WALL

$$q_{\text{diff}} = -\rho_w \sum_s D_s h_s \left.\frac{\partial y_s}{\partial n}\right|_w$$

Catalytic wall condition affects the diffusive heat flux

HIGHER HEAT FLUX

NON-CATALYTIC

$$\left.\frac{\partial y_s}{\partial n}\right|_w = 0$$

No diffusive mass flux at the wall. Only conduction

EQUILIBRIUM CATALYTIC

$$y_{s,w} = y_{s,eq}(T_w, p_w)$$

Mass fractions at the wall are set by the equilibrium conditions at the wall.

FULLY-CATALYTIC

$$y_{s,w} = y_{s,fs}$$

Freestream mass fraction imposed at the wall. *(Induces max. Recomb)*

Wall Boundary Conditions

B ENERGY BALANCE

$$-\lambda_{tr}\frac{\partial T_{tr}}{\partial n}\bigg|_w - \lambda_{vib}\frac{\partial T_{vib}}{\partial n}\bigg|_w - \rho_w \sum_s D_s h_s \frac{\partial y_s}{\partial n}\bigg|_w = \varepsilon\sigma T_w^4$$



<- RADIATIVE EQUILIBRIUM

Wall Boundary Conditions

C ENERGY BALANCE WITH ABLATION

$$-\lambda_{tr}\frac{\partial T_{tr}}{\partial n}\bigg|_w - \lambda_{vib}\frac{\partial T_{vib}}{\partial n}\bigg|_w - \rho_w \sum_s D_s h_s \frac{\partial y_s}{\partial n}\bigg|_w = \varepsilon\sigma T_w^4 + \dot{m}\sum_s y_{s,w} h_s$$

INJECT $\dot{m}$

MASS BALANCE >

$$\rho_w D_s \frac{\partial y_s}{\partial n}\bigg|_w - \dot{\omega}_s + y_{s,w}\dot{m} = 0$$

> GET $\dot{\omega}_s$ >

$$\dot{m} = \sum_s \dot{\omega}_s$$

Chemistry Modelling

CHEMICAL ENVIRONMENT

Defines the chemical species available for the chemistry models.

Air Species

N_2, O_2, O, N, NO

Ablation Species

C, C_2, C_3, CO, CO_2, CN

Fluid Chemistry Model

Final-rate chemistry modelling chemical reactions in the fluid domain.

Probability of reaction i :

$$k_i = C_i T^{n_i} \exp\left(\frac{-\theta_i}{T}\right)$$

Surface Chemistry Model

Models the chemical reactions occurring at the surface using finite-rate chemistry.

Production rate of species s :

$$\dot{\omega}_s = \beta_s \cdot \rho_w y_s \; f(T_w)$$

Chemistry Modelling

Three Surface Models

Park 4

Park, Chen & Milos
1983

$C_{(s)}$	+ O	$\rightleftharpoons$ CO	$\beta_O = 0.63\, e^{-\frac{1160}{T_w}}$
$2C_{(s)}$	+ O_2	$\rightleftharpoons$ 2CO	$\beta_{O_2} = 0.25$
$C_{(s)}$	+ N	$\rightleftharpoons$ CN	$\beta_N = 0.3$
$3C_{(s)}$		$\rightleftharpoons$ C_3	$\alpha_{C_3} = 1.0$

Park 5

Park, Le Maout
2007

$C_{(s)}$	+ O	$\rightleftharpoons$ CO	$\beta_O = 0.63\, e^{-\frac{1160}{T_w}}$
$2C_{(s)}$	+ O_2	$\rightleftharpoons$ 2CO	$\beta_{O_2} = \frac{1.43 \times 10^{-3} + 0.01 e^{-1450/T_w}}{1 + 2.0 \times 10^{-4} e^{13000/T_w}}$
$C_{(s)}$	+ N	$\rightleftharpoons$ CN	$\beta_N = 0.001$
N	+ N	$\rightleftharpoons$ N_2	$\beta_{N_2} = 0.05$
$3C_{(s)}$		$\rightleftharpoons$ C_3	$\alpha_{C_3} = 0.03$

Chemistry Modelling

Three Surface Models

Park 4

Park, Chen & Milos
1983

$C_{(s)}$	+ O $\rightleftharpoons$	CO	$\beta_O = 0.63\, e^{-\frac{1160}{T_w}}$
$2C_{(s)}$	+ O_2 $\rightleftharpoons$	2CO	$\beta_{O_2} = 0.25$
$C_{(s)}$	+ N $\rightleftharpoons$	CN	$\beta_N = 0.3$
$3C_{(s)}$	$\rightleftharpoons$	C_3	$\alpha_{C_3} = 1.0$

Park-Palmer

Park, Palmer, Mortensen
2012

$C_{(s)}$	+ O $\rightleftharpoons$	CO	$\beta_O = 0.63\, e^{-\frac{1160}{T_w}}$
$C_{(s)}$	+ O_2 $\rightleftharpoons$	CO + O	$\beta_{O_2} = \frac{1.43 \times 10^{-3} + 0.01 e^{-1450/T_w}}{1 + 2.0 \times 10^{-4} e^{13000/T_w}}$
O	+ O $\rightleftharpoons$	O_2	$\beta_O = 0.63\, e^{-\frac{1160}{T_w}}$
$C_{(s)}$	$\rightleftharpoons$	C	$\alpha_C = 0.14$
$2C_{(s)}$	$\rightleftharpoons$	C_2	$\alpha_{C_2} = 0.26$
$3C_{(s)}$	$\rightleftharpoons$	C_3	$\alpha_{C_3} = 0.03$

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3.2 Newton-Raphson Method

NUMERICAL IMPLEMENTATION

System Formulation

A ENERGY BALANCE - DISCRETISED

$$f_E = -\lambda_{tr}\frac{T_{tr,in} - T_w}{\Delta n} - \lambda_{vib}\frac{T_{vib,in} - T_w}{\Delta n} - \rho_w \sum_{s=1}^{n_{ys}} h_s D_s \frac{y_{s,in} - y_{s,w}}{\Delta n} + \varepsilon\sigma T_w^4 + \dot{m} h_{mix}$$

B MASS BALANCE - DISCRETISED

$$f_s = -\rho_w D_w \frac{y_{s,in} - y_{s,w}}{\Delta n} - \dot{\omega}_s + y_{s,w}\dot{m}$$

$$X = \begin{bmatrix} y_{1,w} \\ y_{2,w} \\ \vdots \\ y_{n_{ys},w} \\ T_w \end{bmatrix} \qquad F(X) = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_{n_{ys}} \\ f_E \end{bmatrix} = 0$$

NUMERICAL IMPLEMENTATION

System Formulation

LINEARISE, ORDER 1	$F(X) = 0 \quad \rightarrow \quad J \cdot dX = -F$

$$J_{i,n_{ys}+1} = \frac{f_i(X + \delta T \cdot e_{n_{ys}+1}) - f_i(X)}{\delta T} := \frac{\Delta_T f_i}{\delta T}$$

$$J_{i,j} = \frac{f_i(X + \delta m_j \cdot e_j) - f_i(X)}{\delta m_j} := \frac{\Delta_j f_i}{\delta m_j}$$

$$i \in [1, n_{ys} + 1]$$

$$\begin{pmatrix} \frac{\Delta_1 f_1}{\delta m_1} & \frac{\Delta_2 f_1}{\delta m_2} & \cdots & \frac{\Delta_{n_{ys}} f_1}{\delta m_{n_{ys}}} & \frac{\Delta_T f_1}{\delta T} \\ \vdots & & & \vdots & \vdots \\ \frac{\Delta_1 f_{n_{ys}}}{\delta m_1} & \frac{\Delta_2 f_{n_{ys}}}{\delta m_2} & \cdots & \frac{\Delta_{n_{ys}} f_{n_{ys}}}{\delta m_{n_{ys}}} & \frac{\Delta_T f_{n_{ys}}}{\delta T} \\ \frac{\Delta_1 f_E}{\delta m_1} & \frac{\Delta_2 f_E}{\delta m_2} & \cdots & \frac{\Delta_{n_{ys}} f_E}{\delta m_{n_{ys}}} & \frac{\Delta_T f_E}{\delta T} \end{pmatrix}$$

Mass fraction perturbations (δm_j)

Temp. perturbations (δT)

NUMERICAL IMPLEMENTATION

System Formulation

LINEARISE, ORDER 1	$F(X) = 0 \quad \rightarrow \quad J \cdot dX = -F$

$$J_{i,n_{ys}+1} = \frac{f_i(X + \delta T \cdot e_{n_{ys}+1}) - f_i(X)}{\delta T} := \frac{\Delta_T f_i}{\delta T}$$

$$J_{i,j} = \frac{f_i(X + \delta m_j \cdot e_j) - f_i(X)}{\delta m_j} := \frac{\Delta_j f_i}{\delta m_j}$$

$$i \in [1, n_{ys} + 1]$$

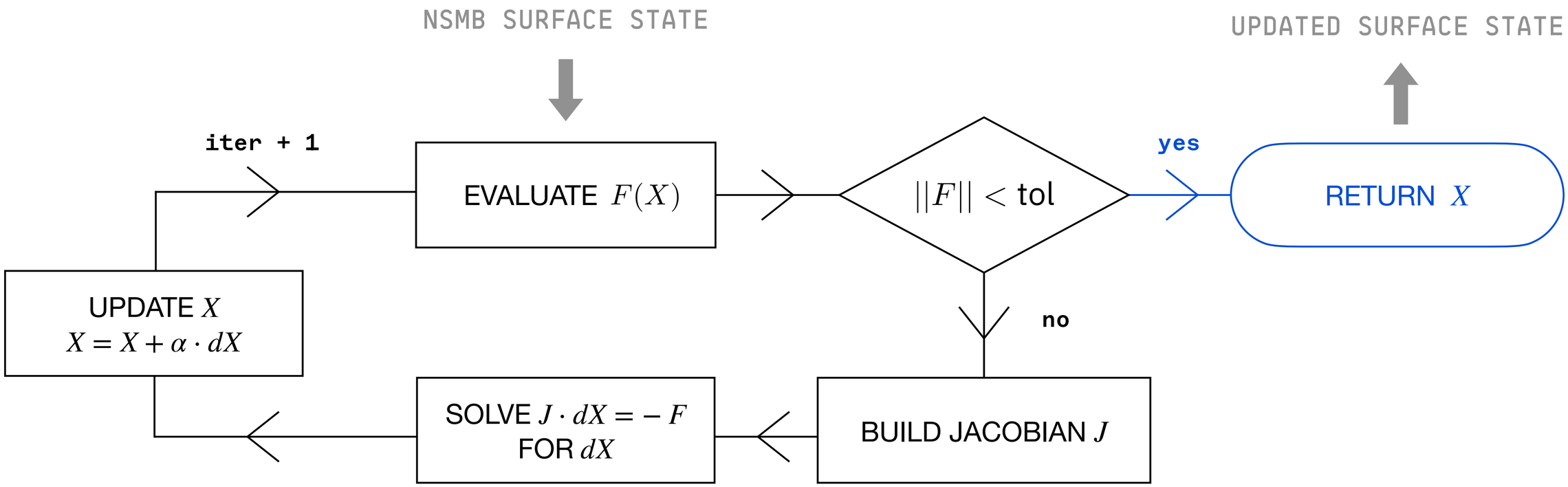
$$\begin{pmatrix} \frac{\Delta_1 f_1}{\delta m_1} & \frac{\Delta_2 f_1}{\delta m_2} & \cdots & \frac{\Delta_{n_{ys}} f_1}{\delta m_{n_{ys}}} & \frac{\Delta_T f_1}{\delta T} \\ \vdots & & & \vdots & \vdots \\ \frac{\Delta_1 f_{n_{ys}}}{\delta m_1} & \frac{\Delta_2 f_{n_{ys}}}{\delta m_2} & \cdots & \frac{\Delta_{n_{ys}} f_{n_{ys}}}{\delta m_{n_{ys}}} & \frac{\Delta_T f_{n_{ys}}}{\delta T} \\ \frac{\Delta_1 f_E}{\delta m_1} & \frac{\Delta_2 f_E}{\delta m_2} & \cdots & \frac{\Delta_{n_{ys}} f_E}{\delta m_{n_{ys}}} & \frac{\Delta_T f_E}{\delta T} \end{pmatrix}$$

Mass fraction perturbations (δm_j)

Temp. perturbations (δT)

NUMERICAL IMPLEMENTATION

Newton-Raphson Method



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4.2 Catalytic Test Case

4.3 Ablation Cases

4.4 The Stardust SRC

Test Geometries Overview

Simple Sphere

LE MAOUT



A

PANT Geometry

MORTENSEN



B

Sphere-Cone

CHEN & MILOS



C

Stardust SRC

GUPTA



D

VALIDATION

A **Catalytic** *(no ablation)*

Simple Sphere

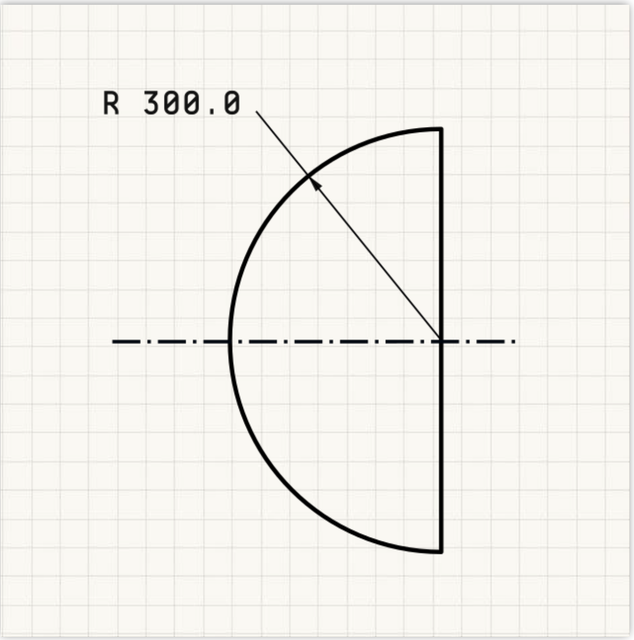
LE MAOUT



A

Freestream Conditions

M_∞	31.6	-
ρ_∞	7.795×10^{-4}	kg/m^3
T_∞	276	K
Y_{N_2}	0.7635	-
Y_{O_2}	0.2365	-



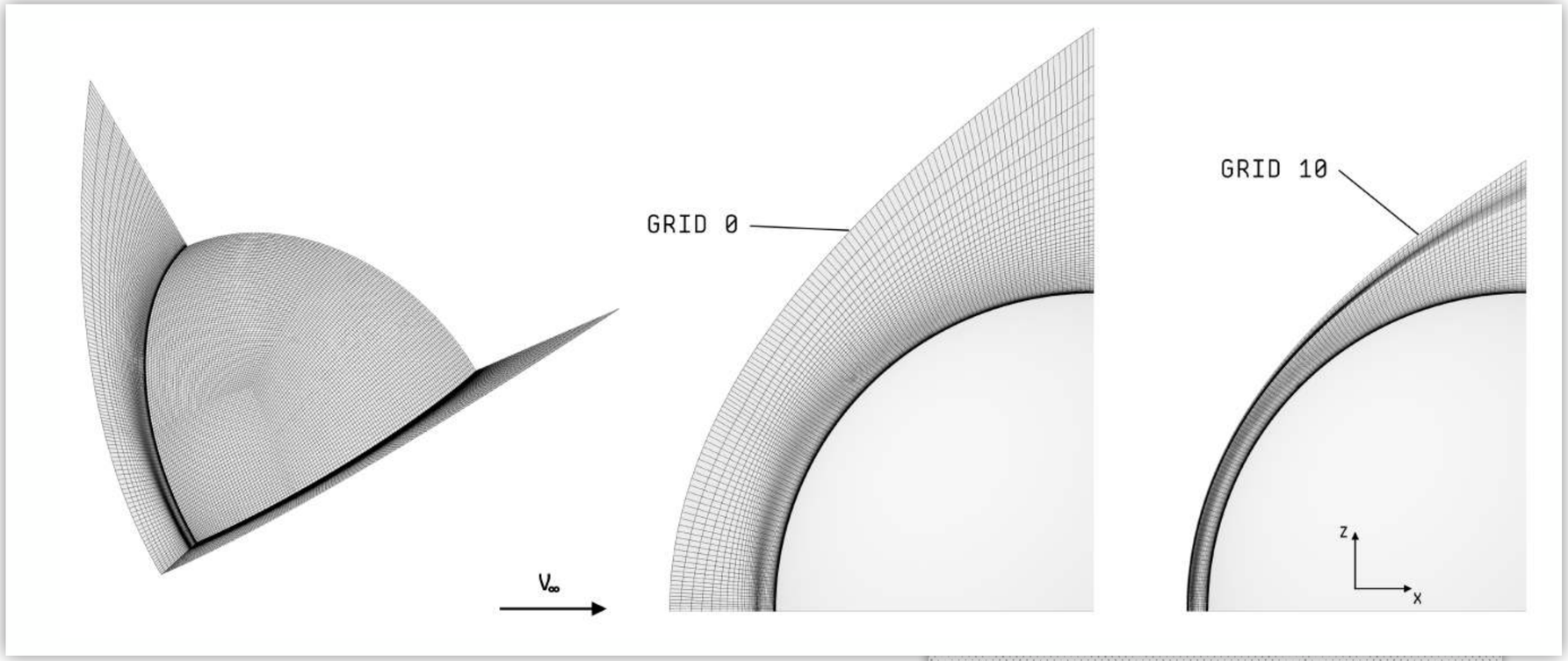
VALIDATION

A **Catalytic** *(no ablation)*

Simple Sphere

LE MAOUT



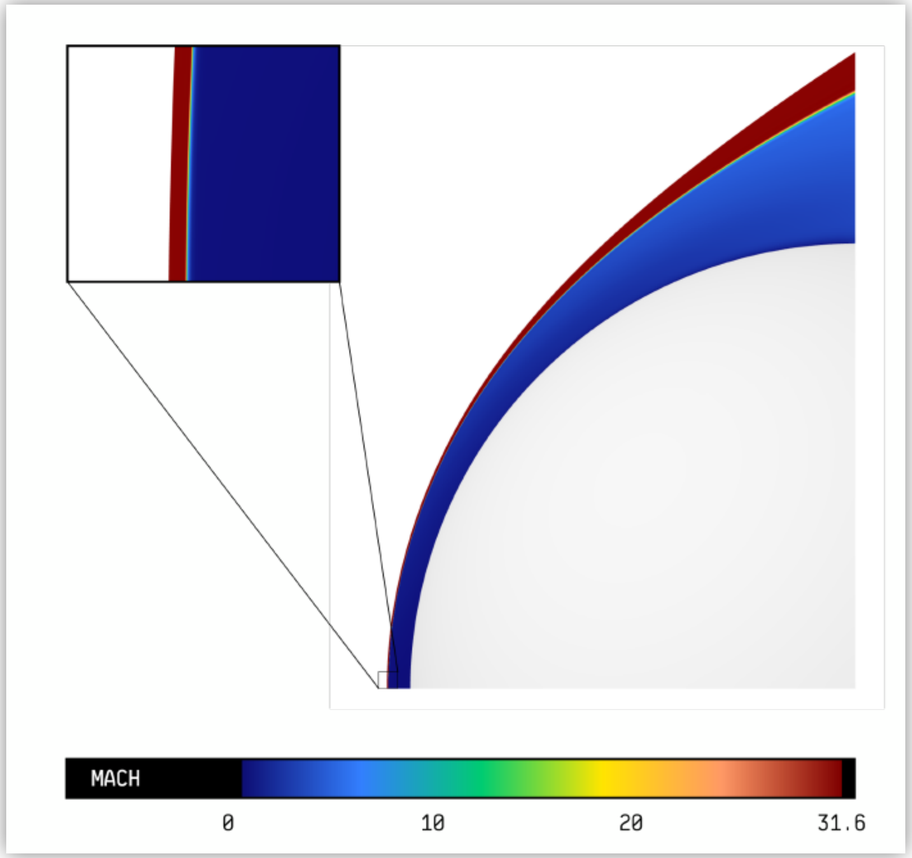


SIMPLE SPHERE MESH OVERVIEW

VALIDATION

A **Catalytic** *(no ablation)*

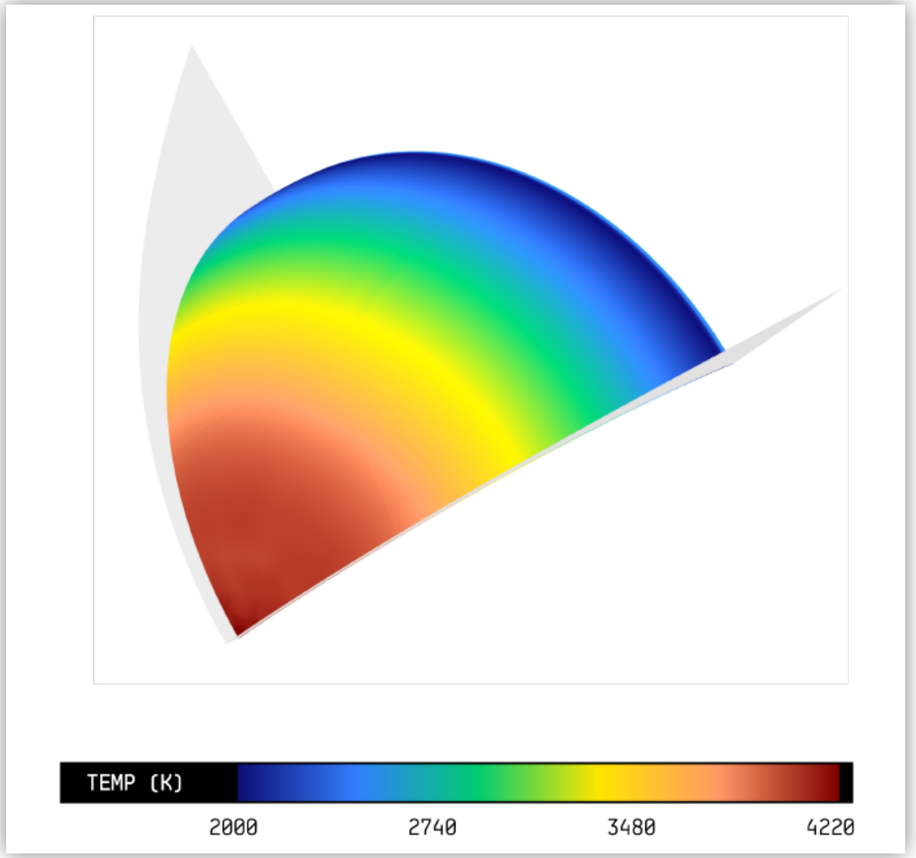
Fully Catalytic Surface



Contours for fully catalytic surface condition.

< MACH ON Z0 PLANE

SURFACE TEMPERATURE >

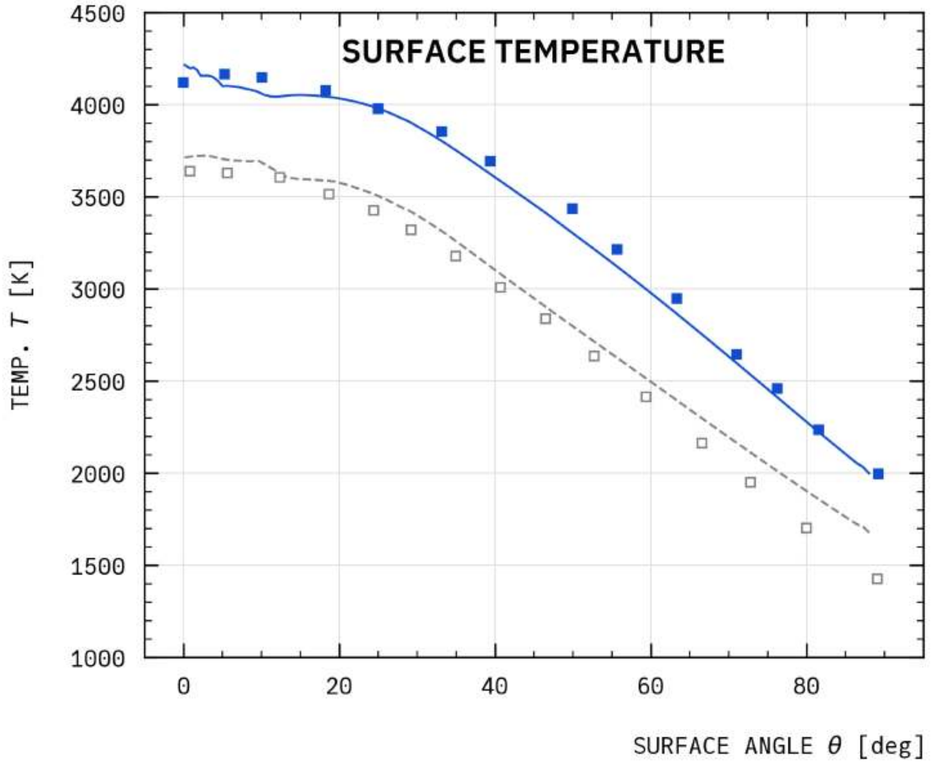


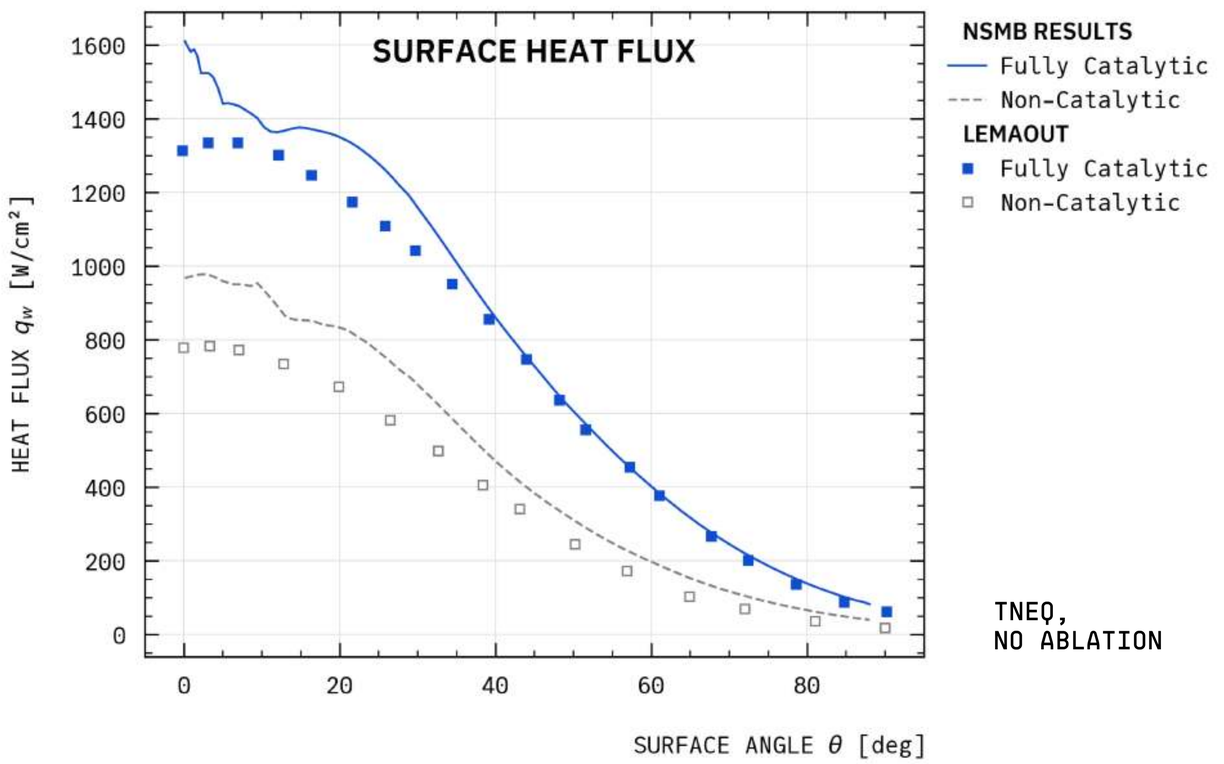
VALIDATION

A **Catalytic** *(no ablation)*

Catalytic Types Comparison

REFERENCE:
V. Le Maout, 2025





TNEQ,
NO ABLATION

VALIDATION

B PANT *(Passive NoseTip Technology)*

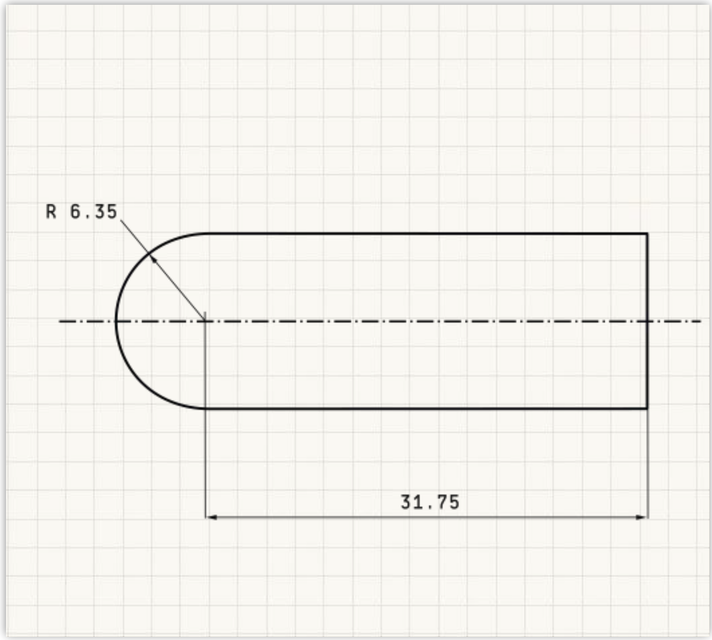
PANT Geometry

MORTENSEN



Freestream Conditions

M_∞	15.99	-
ρ_∞	2.4093×10^{-2}	kg/m^3
P_∞	2026.0	Pa
Y_{N_2}	0.7635	-
Y_{O_2}	0.2365	-



Reference Surface Model	PARK-PALMER

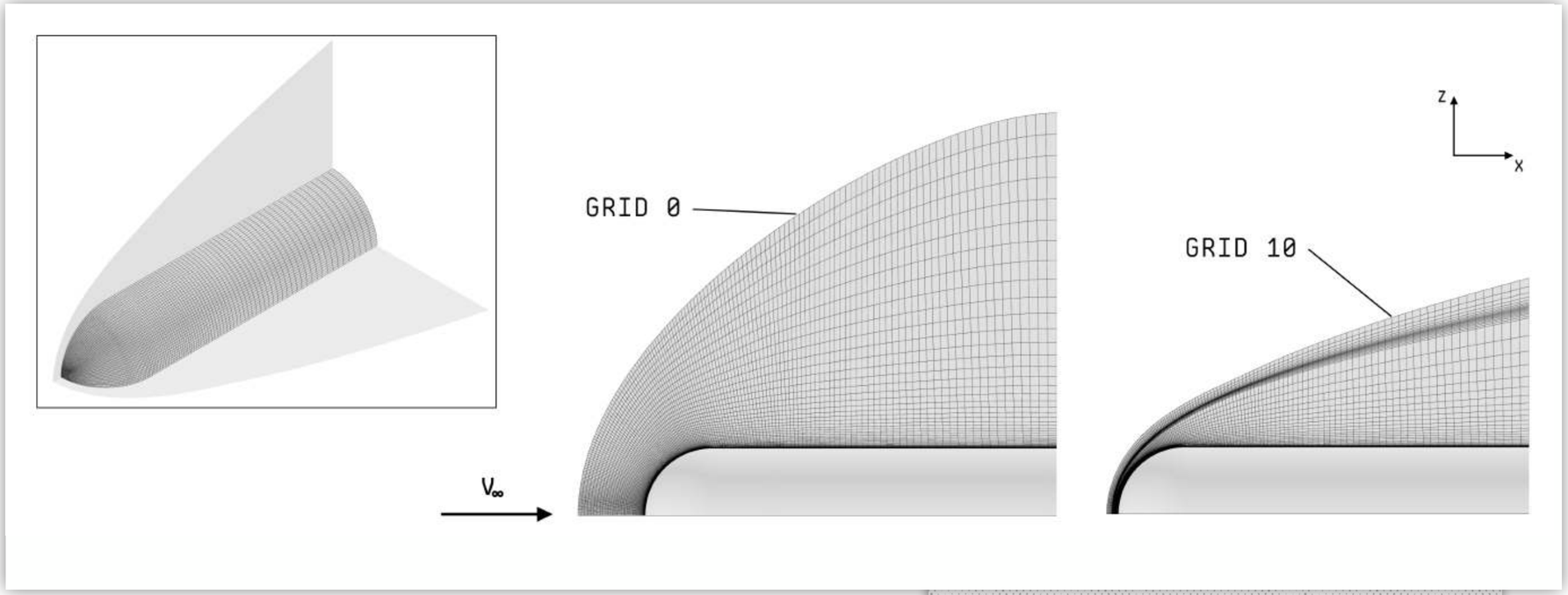
VALIDATION

B PANT (Passive NoseTip Technology)

PANT Geometry

MORTENSEN



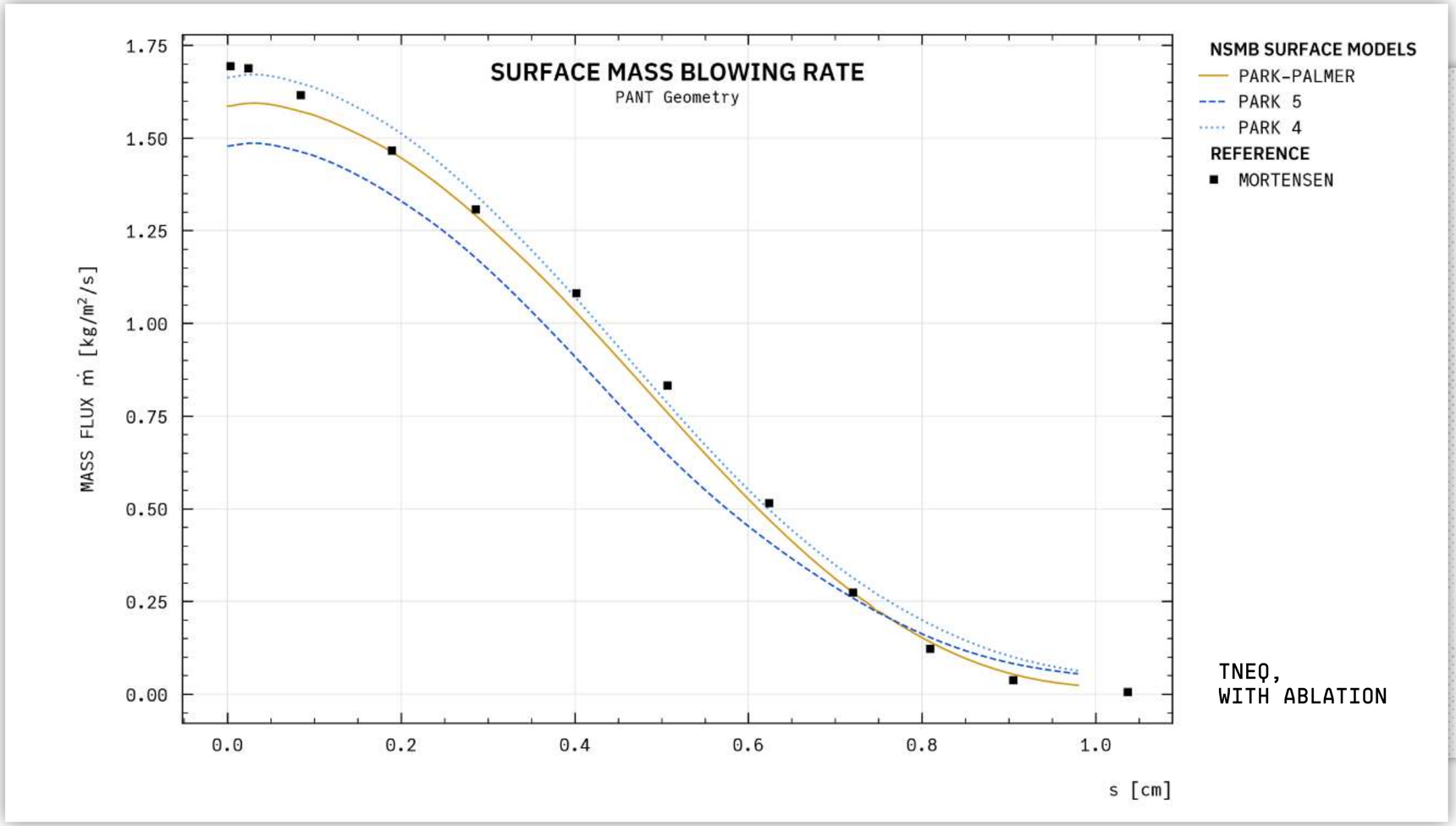


PANT GEOMETRY MESH OVERVIEW

VALIDATION

B PANT (Passive NoseTip Technology)

REFERENCE :
C. Mortensen, 2012



PARK-PALMER

Error at peak blow : **- 5.8%**
Mean error : **- 0.03 kg/s/m²**

PARK 5

Error at peak blow : **- 12.9%**
Mean error : **- 0.10 kg/s/m²**

PARK 4

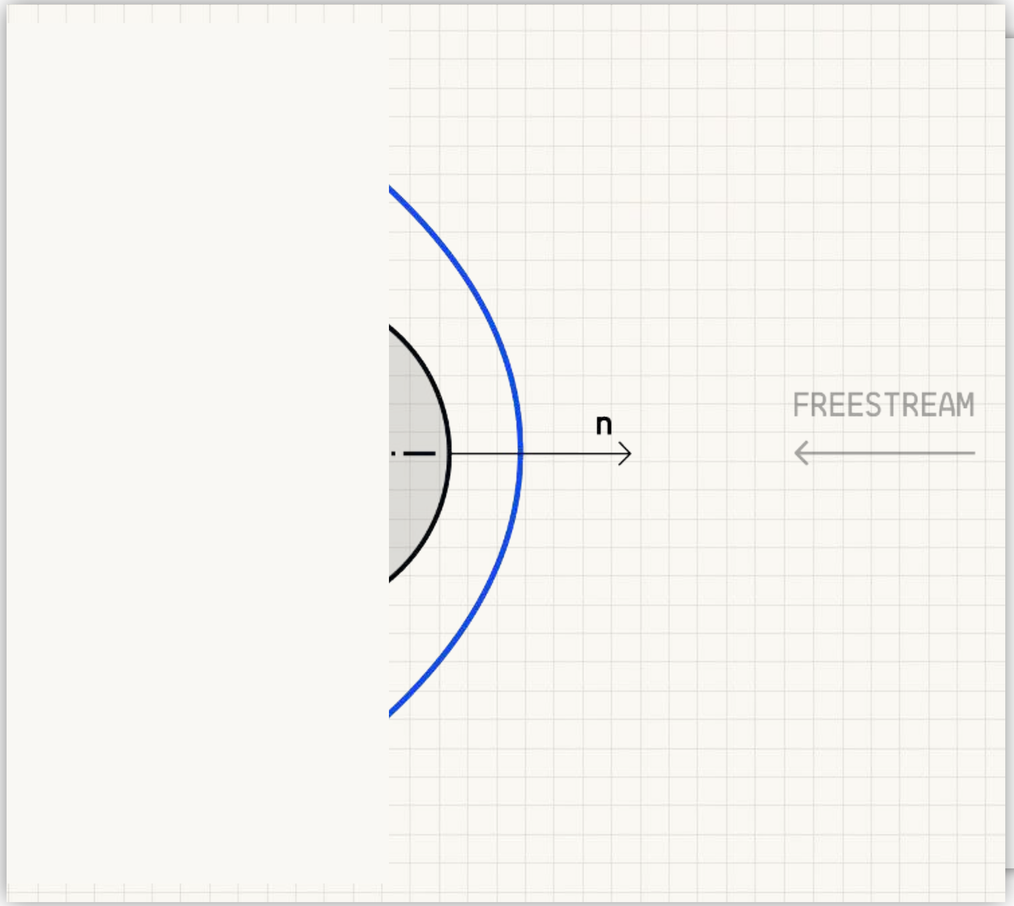
Error at peak blow : **+ 1.7%**
Mean error : **+ 0.02 kg/s/m²**

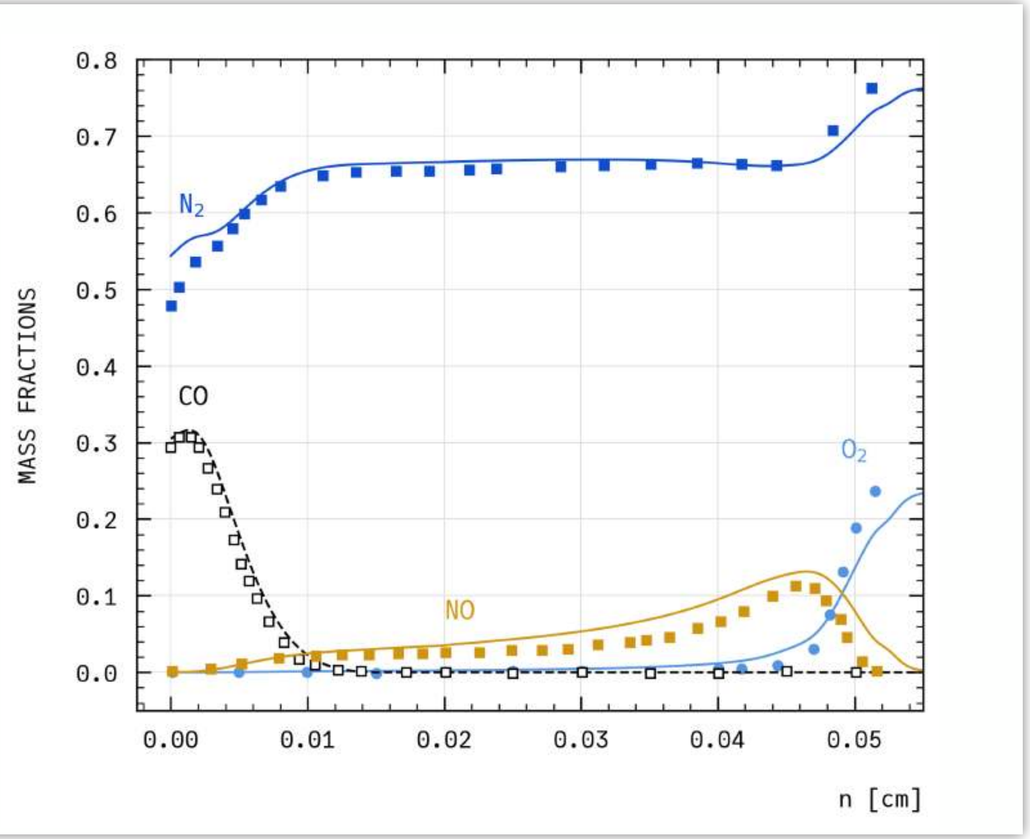
VALIDATION

B PANT (Passive NoseTip Technology)

Species Mass Fractions

REFERENCE:
C. Mortensen, 2012





VALIDATION

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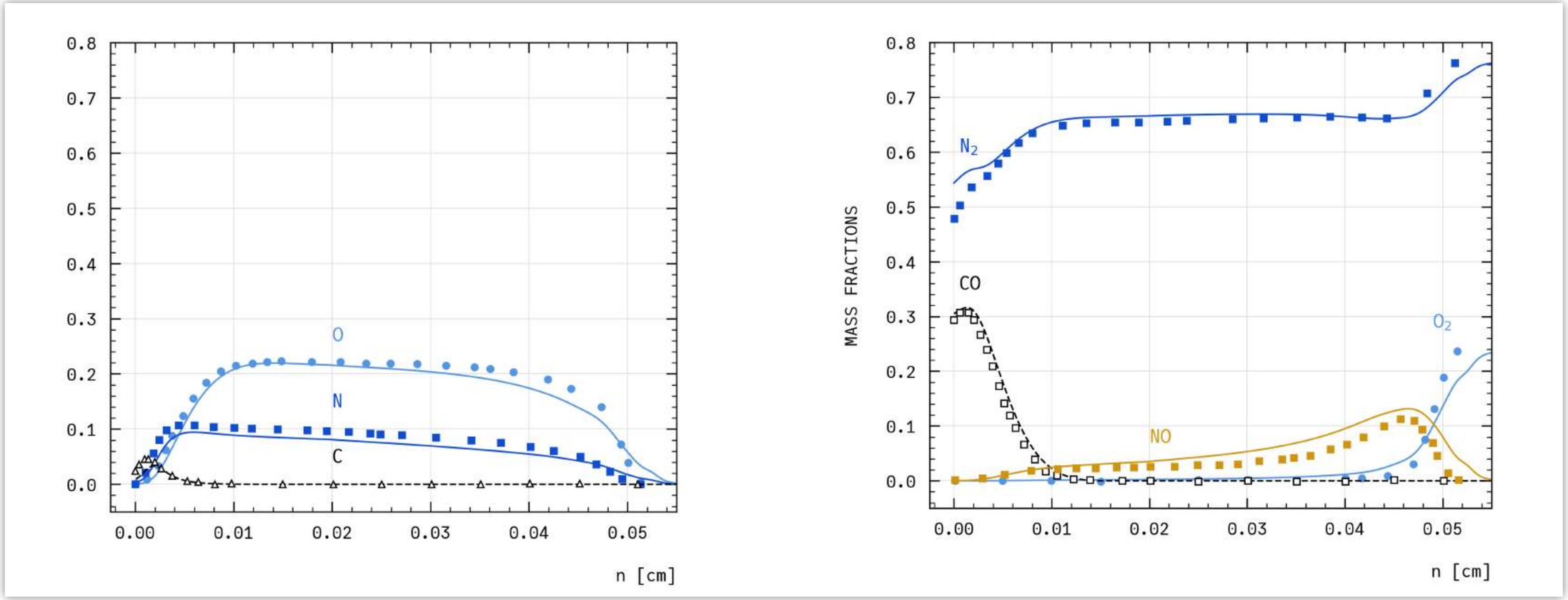
Species Mass Fractions

REFERENCE:
C. Mortensen, 2012



VALIDATION

C Sphere-Cone

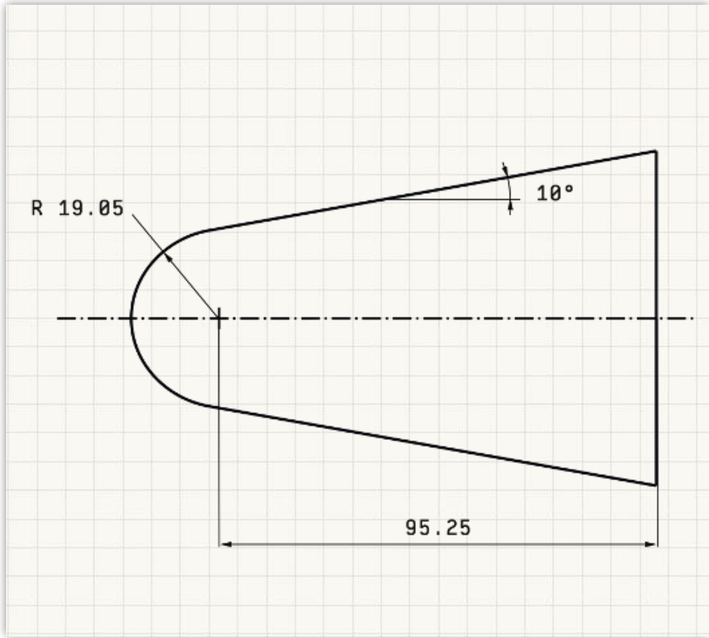
Sphere-Cone

CHEN & MILOS



Freestream Conditions

M_∞	5.8434	-
ρ_∞	3.0×10^{-3}	kg/m^3
P_∞	1671.36	Pa
Y_{NO}	0.0046	-
Y_{N_2}	0.6169	-
Y_N	0.1212	-
Y_N	0.2573	-



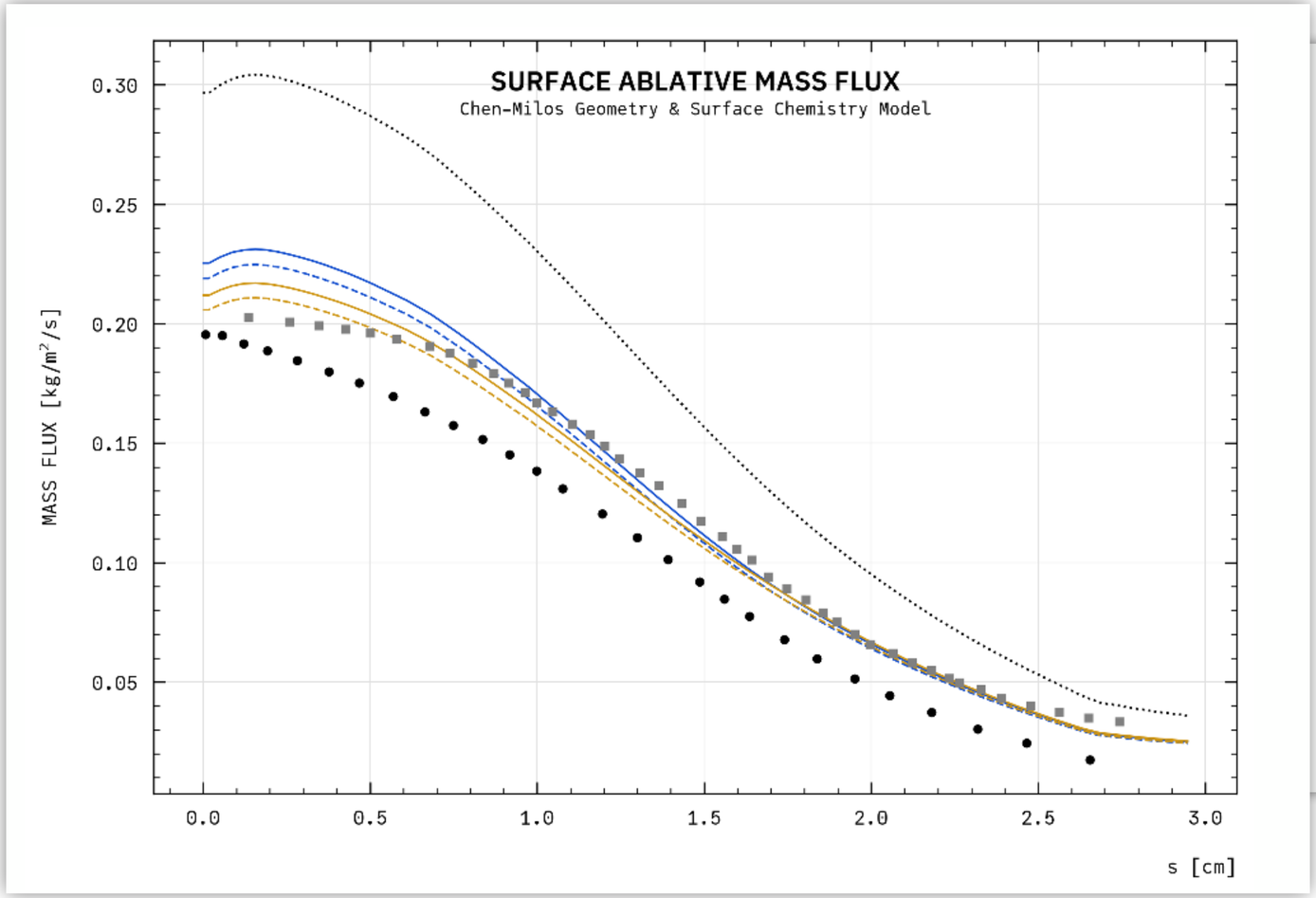
Reference Surface Model	PARK 4

VALIDATION

C Sphere-Cone

Surface Chemistry Model Sensitivity

REFERENCES:
C. Mortensen, 2012
Y.K. Chen & F.S. Milos, 2005



NSMB RESULTS

- A - $\beta_{C_3} = 1$, $\beta_N = 0.3$
- B - $\beta_{C_3} = 1$, $\beta_N = 0.003$
- D - $\beta_{C_3} = 1$, $\beta_N = 0.001$
- C - $\beta_{C_3} = 0.1$, $\beta_N = 0.003$
- E - $\beta_{C_3} = 0.1$, $\beta_N = 0.001$

REFERENCES

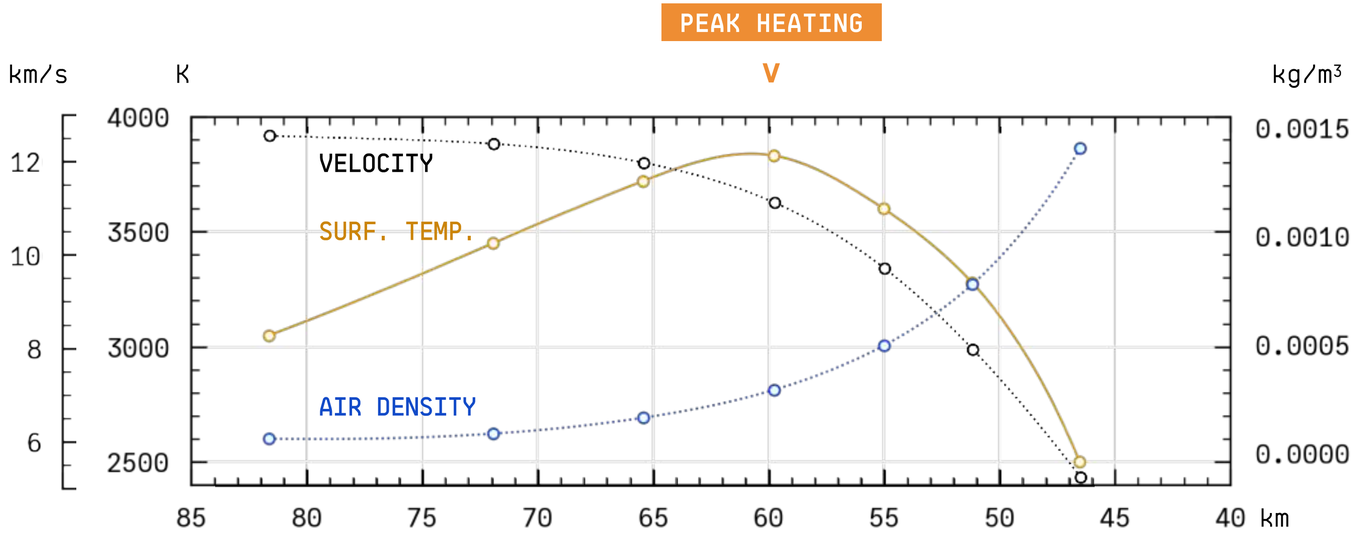
- Mortensen (2012)
- Chen & Milos (2005)

TNEQ,
WITH ABLATION

D Stardust SRC



STARDUST SRC, DROP TESTING
NASA, UTAH, 1998



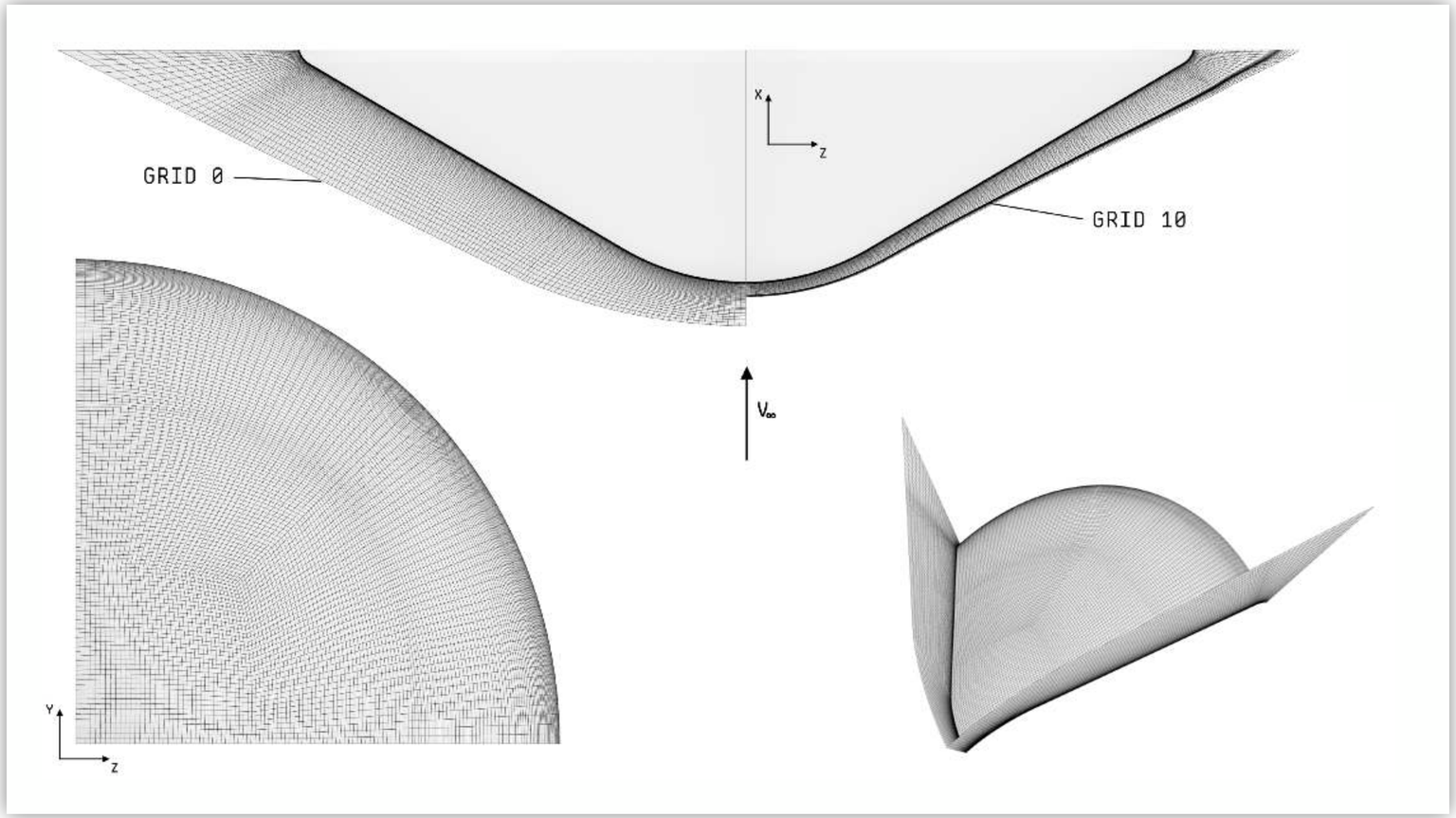
	ALTITUDE [km]	VELOCITY [m/s]	DENSITY [kg/m³]	MAX SURF. TEMPERATURE [K]
	81.64	12590.4	9.63e-6	3050
	71.92	12413.4	1.29e-5	3450
	65.44	12004.0	1.06e-4	3720
Peak Heating	59.77	11136.7	2.34e-4	3830
	55.02	9718.7	4.39e-4	3600
	51.19	7956.9	7.21e-4	3280
	46.51	5178.9	1.35e-3	2500

D Stardust SRC

Stardust SRC

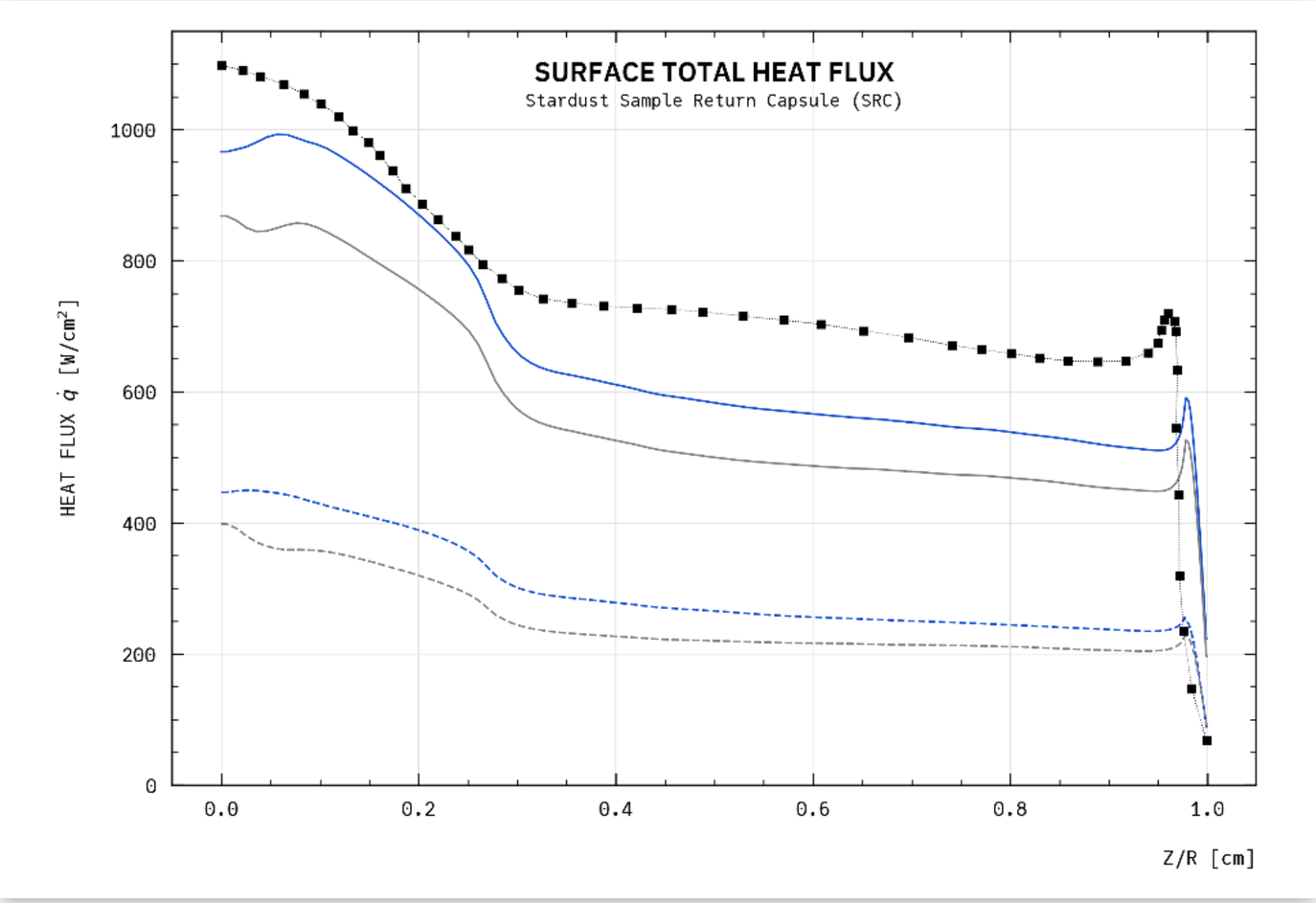
GUPTA





VALIDATION

D Stardust - Catalytic Test



NSMB RESULTS

- NEQ - Fully Catalytic
- NEQ - Non-Catalytic
- TNEQ - Fully Catalytic
- TNEQ - Non-Catalytic

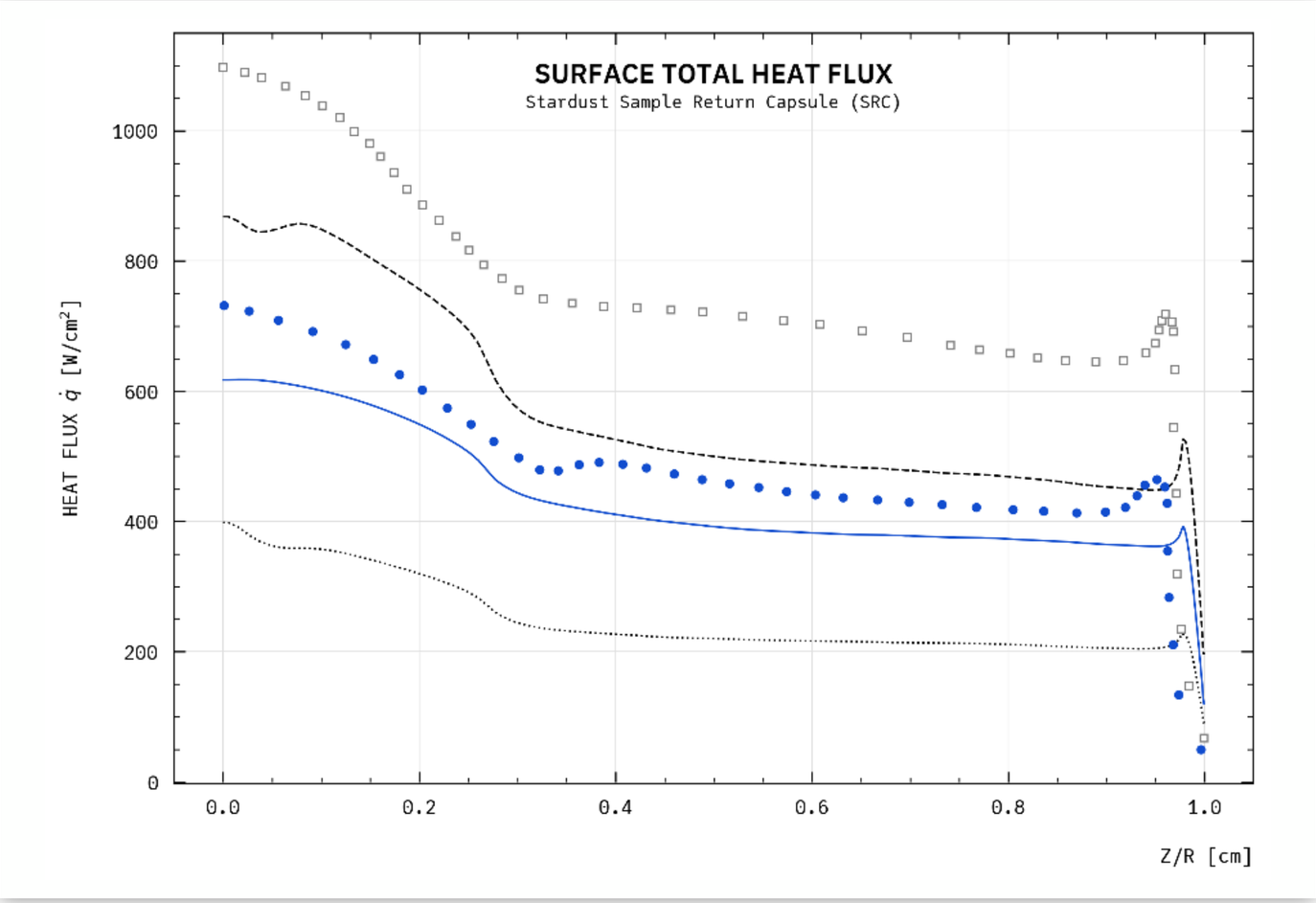
REFERENCE

- Gupta - Fully Catalytic

REFERENCE:
R.N. Gupta, 2012

VALIDATION

D Stardust - *Surface Ablation*



NSMB RESULTS

- PARK 5
- Fully Catalytic
- Non-Catalytic

GUPTA

- With Ablation
- Fully Catalytic

REFERENCE:
R.N. Gupta, 2012

Summary

- New ablation module for the NSMB solver
- Promising results on four geometries
- Ready for additional validations
  - *Surface chemistry models*
  - *More advanced geometries*

