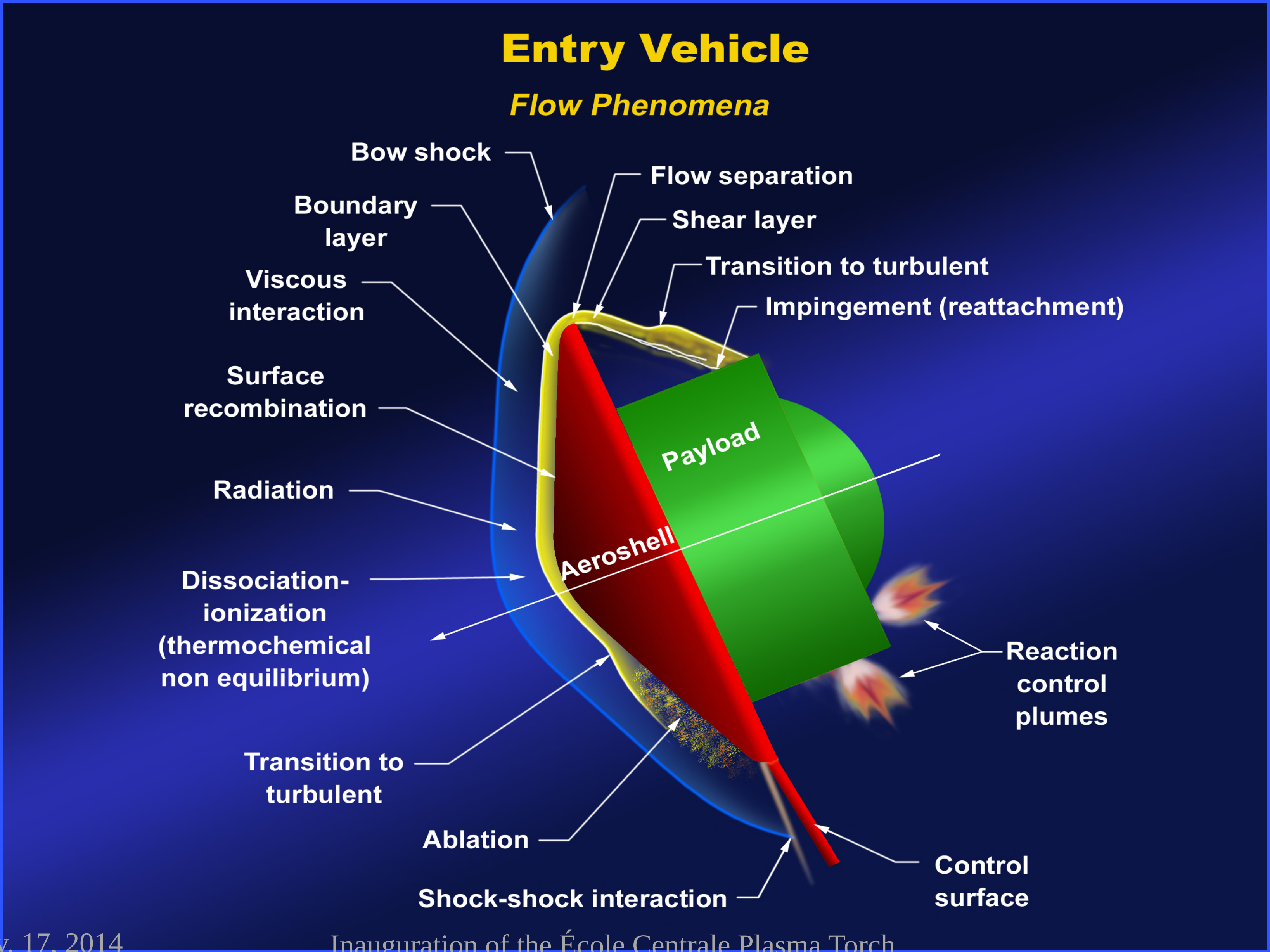
Light Weight Ablator Response Model Development & Challenges

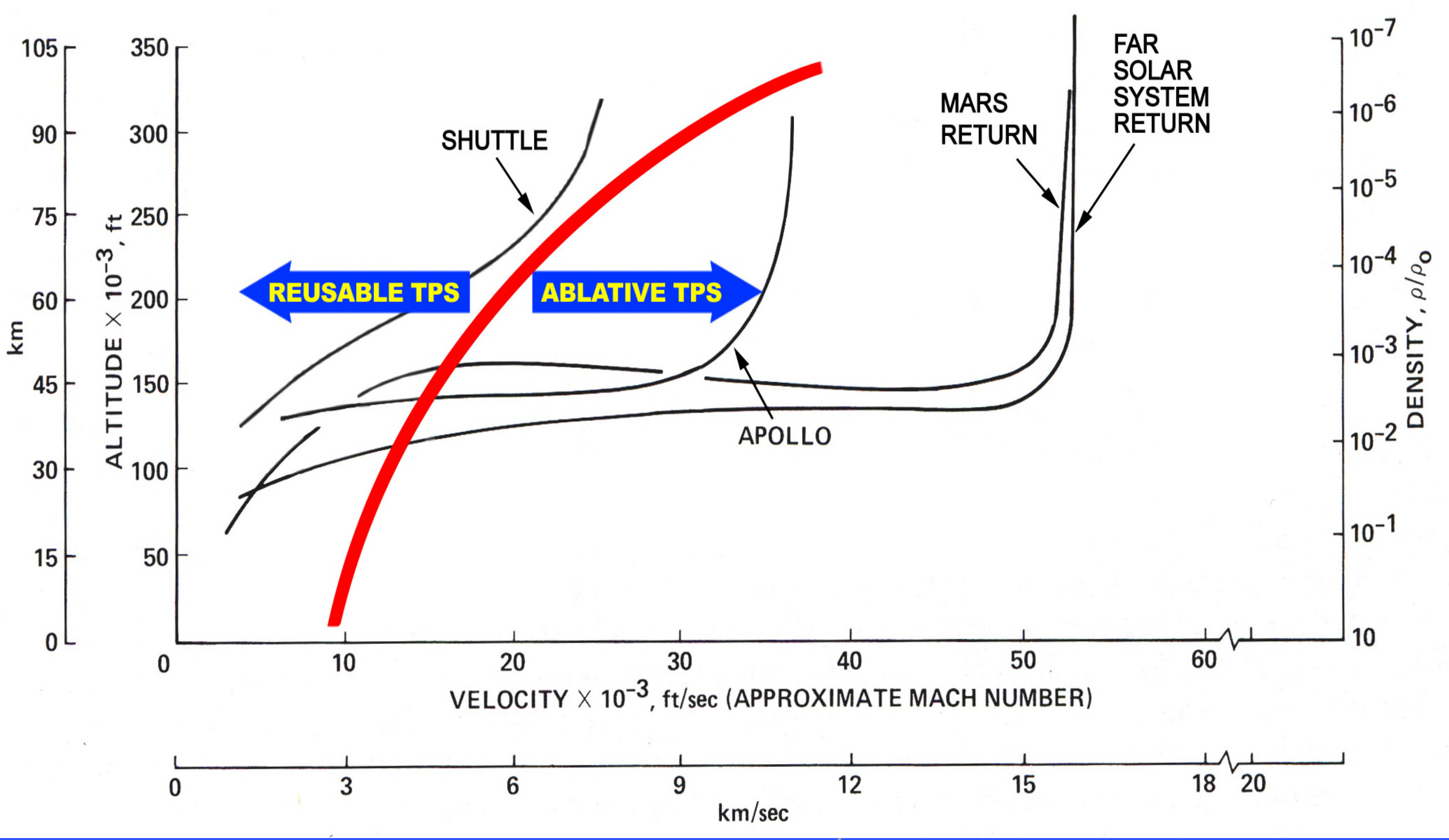
N. N. Mansour
NASA Ames Research Center

Needs for Thermal Protection Systems (TPS)



TPS Systems

Two type of TPS materials



NASA - Space Exploration

Current thinking

- Low Earth Orbits (LEO) – Private providers
- Beyond LEO – Both Private & NASA providers

➢ Ablators will play a major role in NASA's atmospheric entry missions

Phenolic Impregnated Carbon Ablator (PICA)

Carbon-Phenolic class of ablators

Mars Science Laboratory (MSL) heatshield

PICA: member of the family of Lightweight Carbon Ablators (LCAs) that was developed at NASA Ames Research Center as a lightweight thermal protection system (TPS) material for the Stardust mission

carbon Fiberform™

+

resin

=

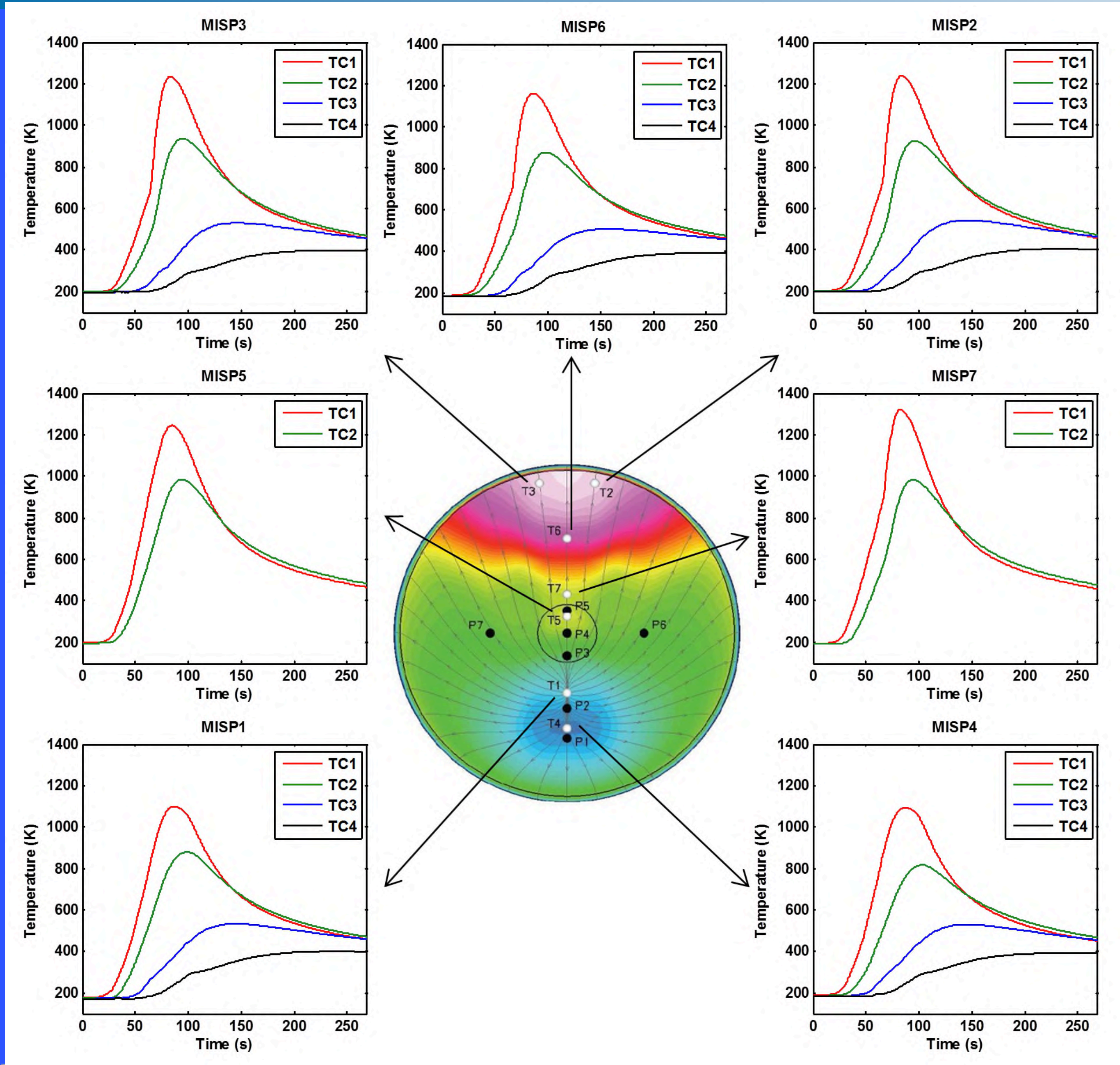
Dragon capsule, SpaceX

Widely used class of materials

- ✓ Stardust
- ✓ MSL
- ✓ Dragon
- ✓ AQ61
- ✓ …

Excellent Performance:
[250 W/cm² to 1100 W/cm²]

Flight data: MEDLI



Mahzari et al.
AIAA 2013-0185

Performance of Current State Of the Art

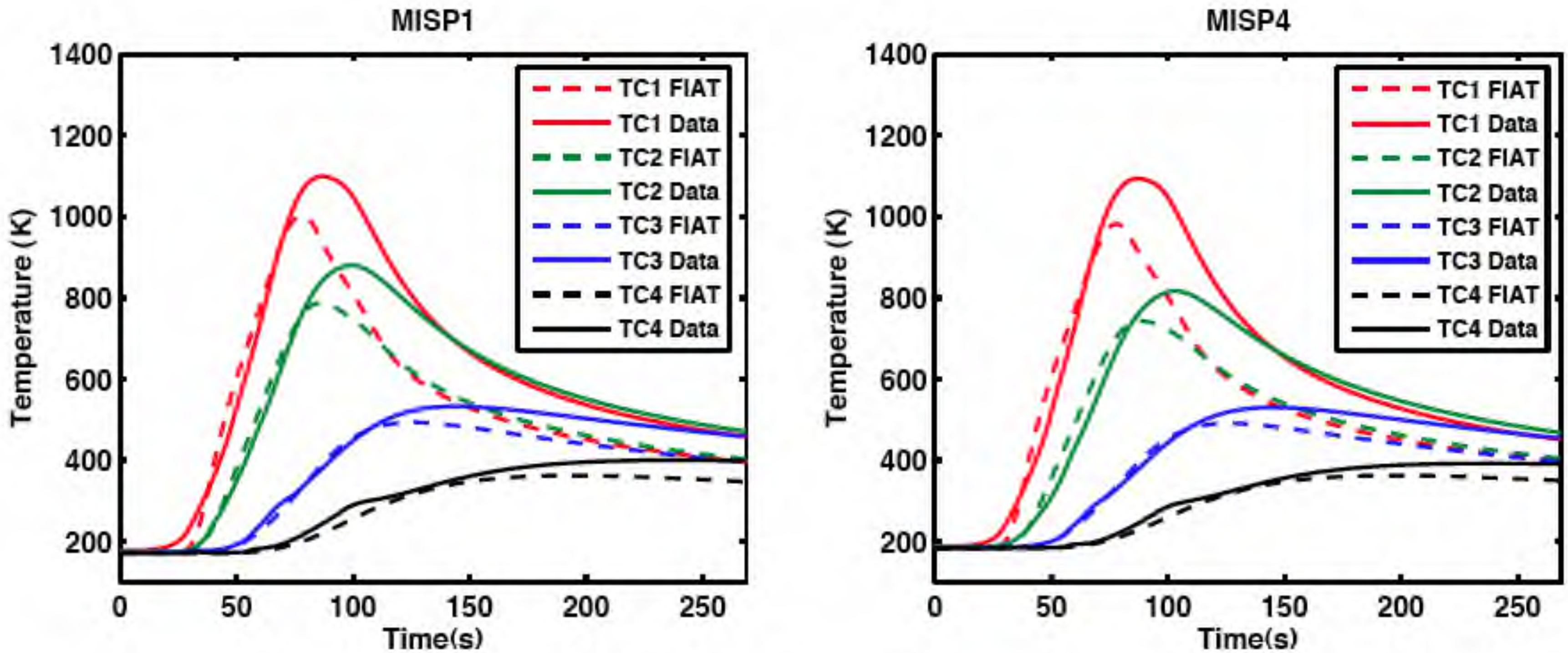


Figure 8. FIAT predictions compared with flight data for plugs 1 and 4.

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Performance of Current State Of the Art

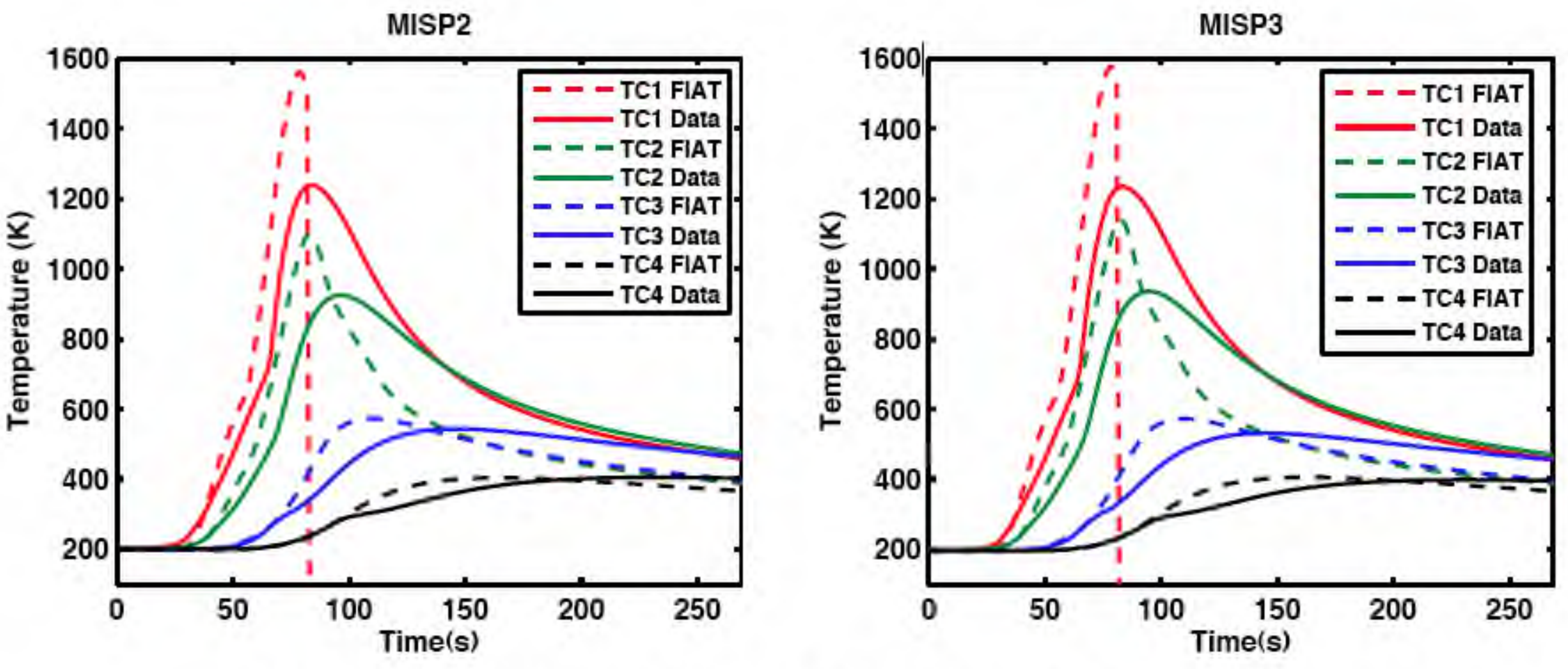

Figure 9. FIAT predictions compared with flight data for plugs 2 and 3.

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Flight data: MEDLI

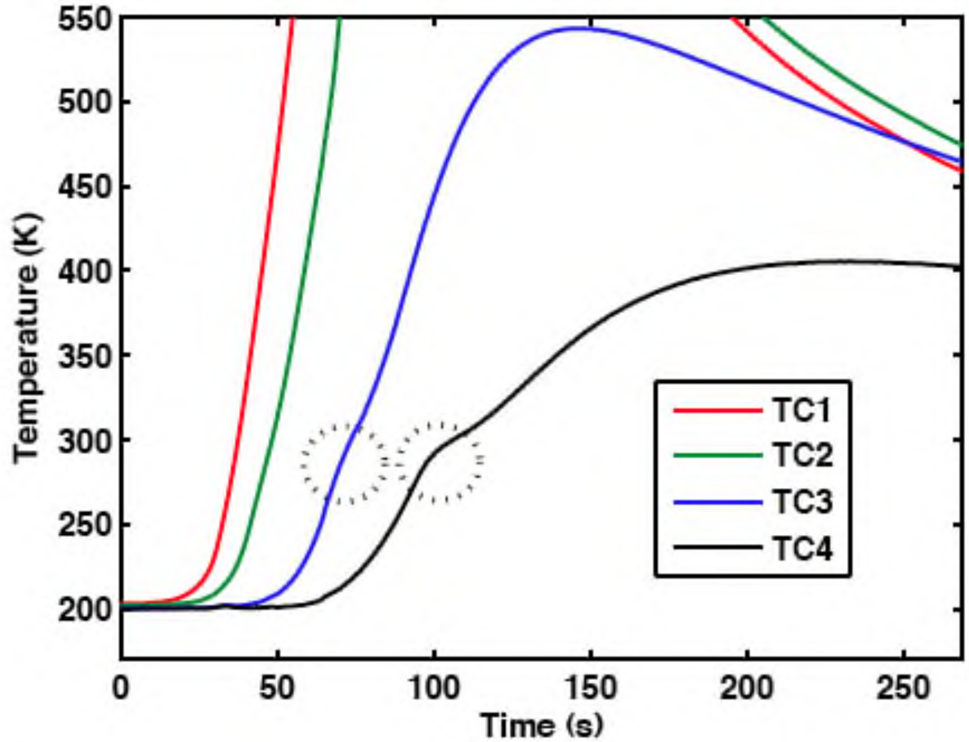

Figure 4. The "hump" observed in TC3 and TC4 data for plug 2 (seen also for other plugs).

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Historical standpoint (1968)

AN ANALYSIS OF THE COUPLED CHEMICALLY REACTING

BOUNDARY LAYER AND CHARRING ABLATOR

Part I

Summary Report

By Robert M. Kendall, Eugene P. Bartlett,
Roald A. Rindal, and Carl B. Moyer

6.3.3 Additions to the Physical Model

Since the CMA in-depth computation includes only the physics of the basic pyrolysis problem, specific materials with important additional subsurface events are not all well described by the program. Physical events here include coking and subsurface char erosion due to interaction with the pyrolysis gas, chemical kinetics of pyrolysis-gas cracking reactions as the gas flows through the char, thick liquid layer run-off (the present chemical programs account for only thin, nonviscous liquid-layer removal), additional subsurface chemical reactions such as carbon-silica reactions, thermal expansion effects, and mechanical damage to weak chars.

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

. Context

Today's standpoint (2008)

46th AIAA Aerospace Sciences Meeting and Exhibit
7 - 10 January 2008, Reno, Nevada

AIAA 2008-1202

Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material

Mairead Stackpoole[*], Steve Sepka[†] and Ioana Cozmuta[‡]
ELORET Corporation, Sunnyvale, CA, 94086

Dean Kontinos[§]
Ames Research Center, Moffett Field, CA, 94035

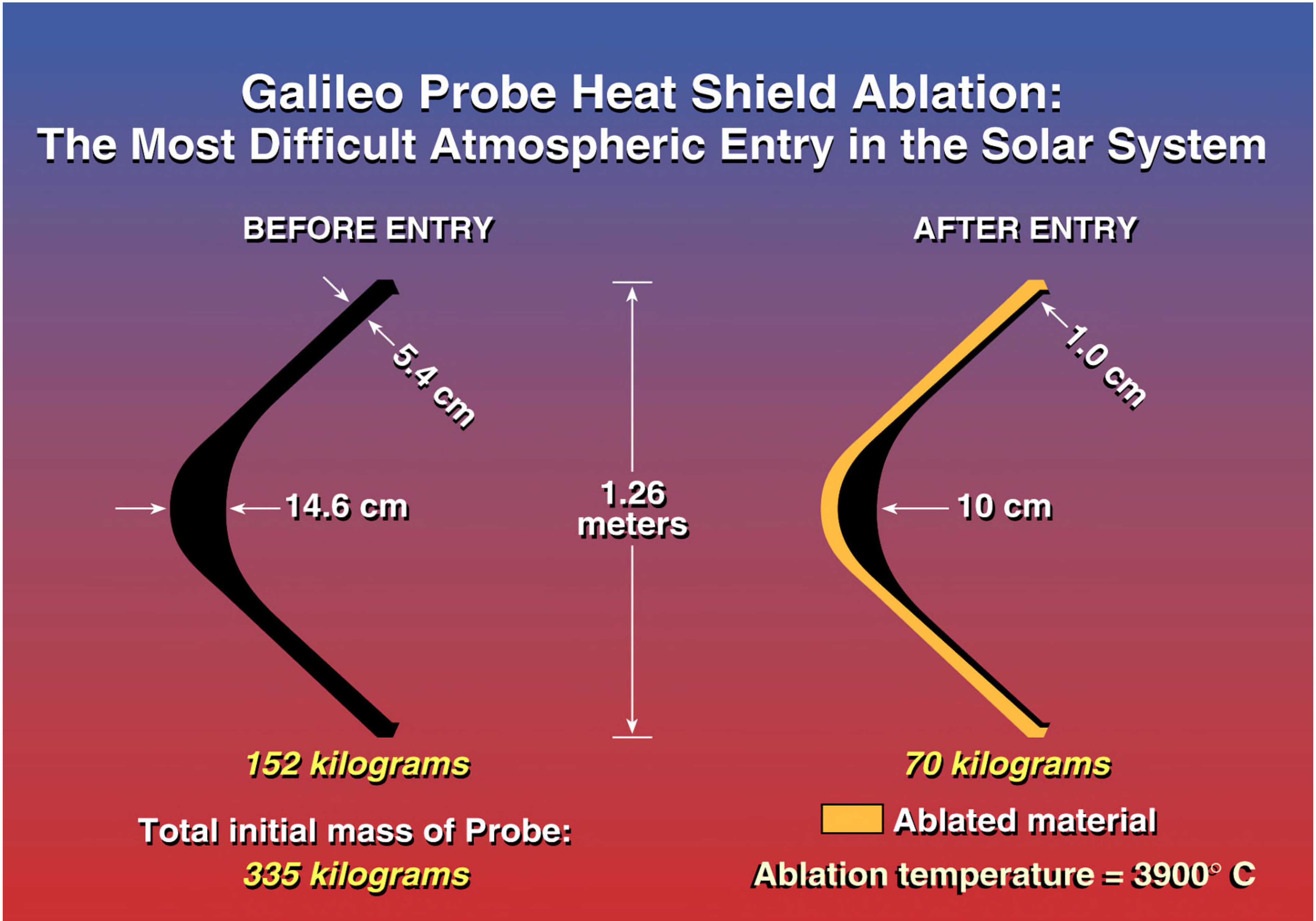
Phenolic Impregnated Carbon Ablator (PICA) was developed at NASA Ames Research

For the near stagnation core, the model over predicts recession by 61 percent. For the flank core, the difference in the predicted recession values is 25 percent. The discrepancies at the flank core are of the same order as differences between calculation and arc-jet tests against which the model was calibrated.[5] The over-prediction at the near-stagnation core is not fully understood.

strength assessment of remaining virgin PICA, an emissivity profile, a chemical analysis profile, and a microstructural analysis. Results show good agreement in comparisons of

Have we reached the limitations of Kendall's model (used in current codes)?

and the only degradation observed was that caused by heating on entry. A substantial amount of virgin PICA was present in all cores examined.



⟹ Final shape reconstructed using data from 10 ablation sensors in heatshield

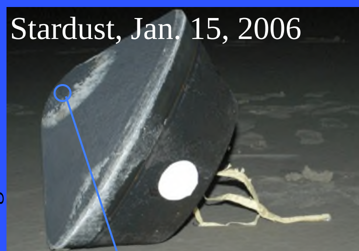
Chart from Rich Young, NASA ARC

Need: understand then build phenomenological models

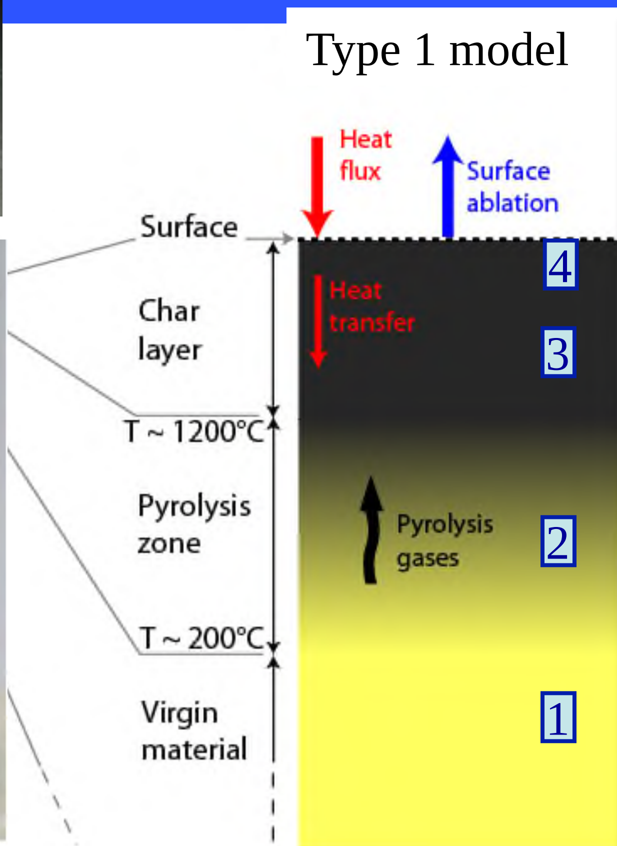
Steps	Methods
• Improve global understanding	→ Revisit the physics
• Determine the important phenomena	→ Analysis of the orders of magnitude
• Derive phenomenological models	→ Multiscale approach (micro-to-macro)
• Validate	→ Experiments on laboratory material
• 3D design (gap, holes, etc.)	→ Development of 3D simulation tool
• Couple to environment	→ Development of coupling tools (multi-physics)

Keep the study as general as possible, but the physics changes from one material to another, and from one atmospheric re-entry to another.

Image credit: NASA



Core - Stardust TPS [1]



4 - Partially ablated

Towards "High-Fidelity Model"

- **Type 1**: Heat transfer, pyrolysis, simplified transport of the pyrolysis gases, equilibrium chemistry, surface ablation (current state-of-the-art)
- **Type 2**: **Type 1** augmented with an averaged momentum equation for the transport of the pyrolysis gases
- **Type 3**: High-fidelity model (**Type 2** + finite-rate chemistry, multi-component diffusion, in-depth ablation/coking, explicit radiative transfer model, …)

SEM micrographs [1]

[1] M. Stackpoole *et al.*, Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material, AIAA 2008-1202

Phenomenology

Macroscopic phenomenology

Hypersonic flow

Long distance effects
- Radiation

Material/flow coupling
- Boundary layer transfers (heat and mass)
- Recombination/catalicity
- Ablation (oxidation, sublimation, spallation)

Material response (e.g. PATO/PAM)

Interface phenomena: Heat and mass balance (1),
Subsurface phenomena
- In-depth ablation (3)
- Penetration of radiation (3)
- Gas flow entering into the material (3)

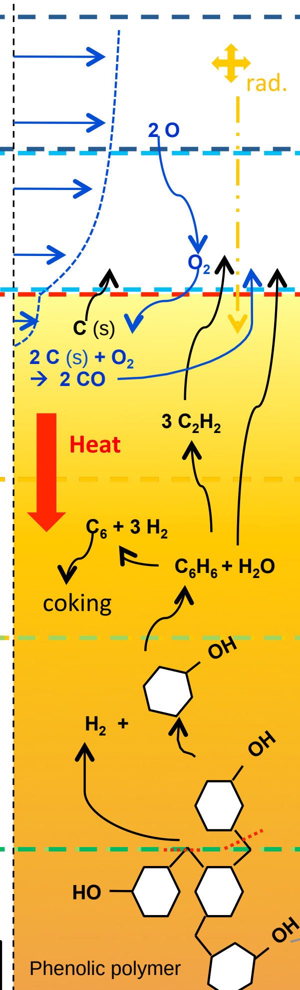
- Conduction heat transfer (1)
- Radiation heat transfer (empirical: 1, modeled: 3)
- Finite-rate chemistry of the pyrolysis gases (3)
- Coking (3)

- Multi-component diffusion (3)
- Convective transport (Darcy: 2, Klinkenberg: 3)
- Charring process (evolution of the density: 1, porosity: 2, tortuosity: 3, permeability: 2, effective conductivity: 1, effective surface area: 3)

- Phenolic-decomposition product (3)
- Phenolic-decomposition rate (1)

1 : in all material-response models (type 1)
2 : in some material-response models (type 2)
3 : in analysis material-response models (type 3)

Macroscopic illustration

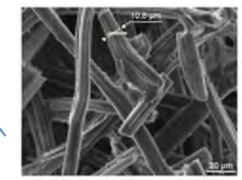


Non-viscous flow
≈ 6000 K
Boundary layer
≈ 3000 K
Ablation zone
≈ 1400 K
Coking zone
≈ 1200 K
Pyrolysis zone
≈ 400 K
Virgin material

Chemistry mechanisms (simplified illustration)

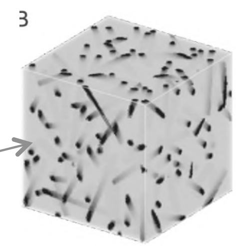
Microscopic illustration

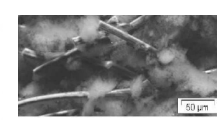
Gas/surface Interactions in porous fibrous media (3):
- in-depth ablation
- erosion
- in-depth recombination
- coupled heat transport (diffusion, convection, radiation)



Scanning Electron Microscopy (SEM) : Carbon preform

3D simulation of the ablation of a carbon/phenolic composite [Lachaud, 2010]

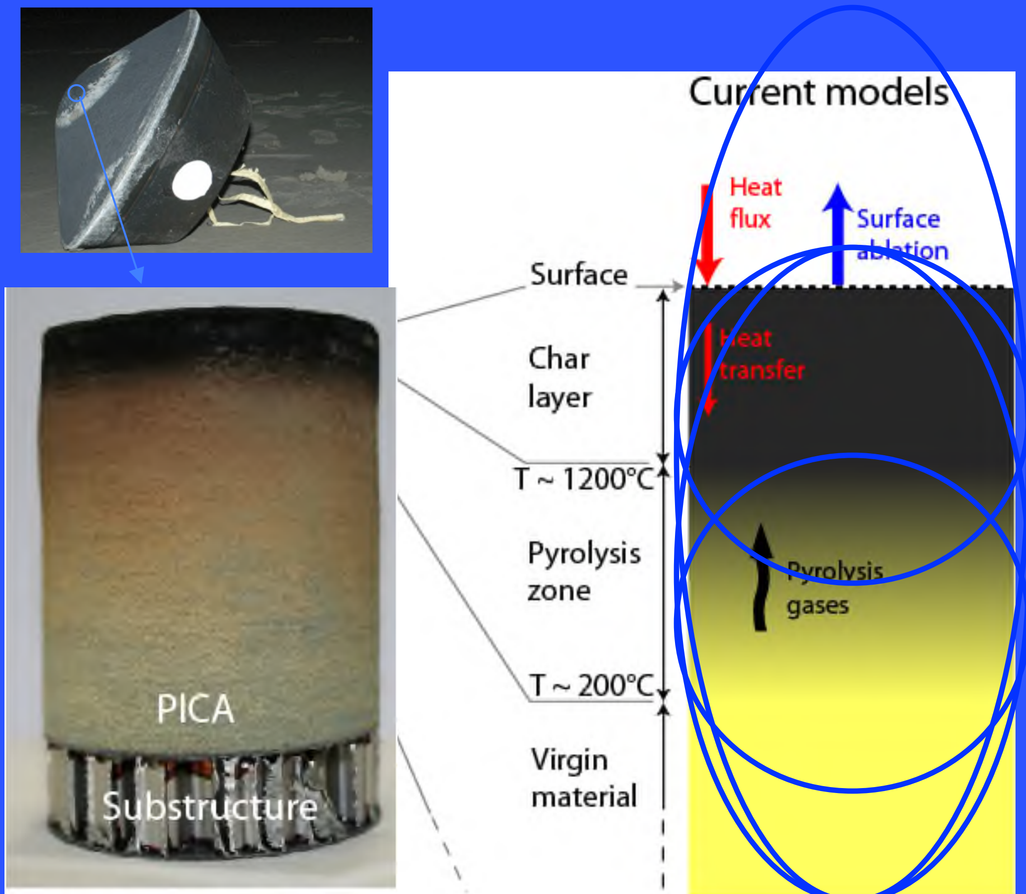




SEM: carbon/phenolic (virgin) [Stackpoole, 2008]

3D reconstitution of a carbon/phenolic composite

Building a model for PICA class



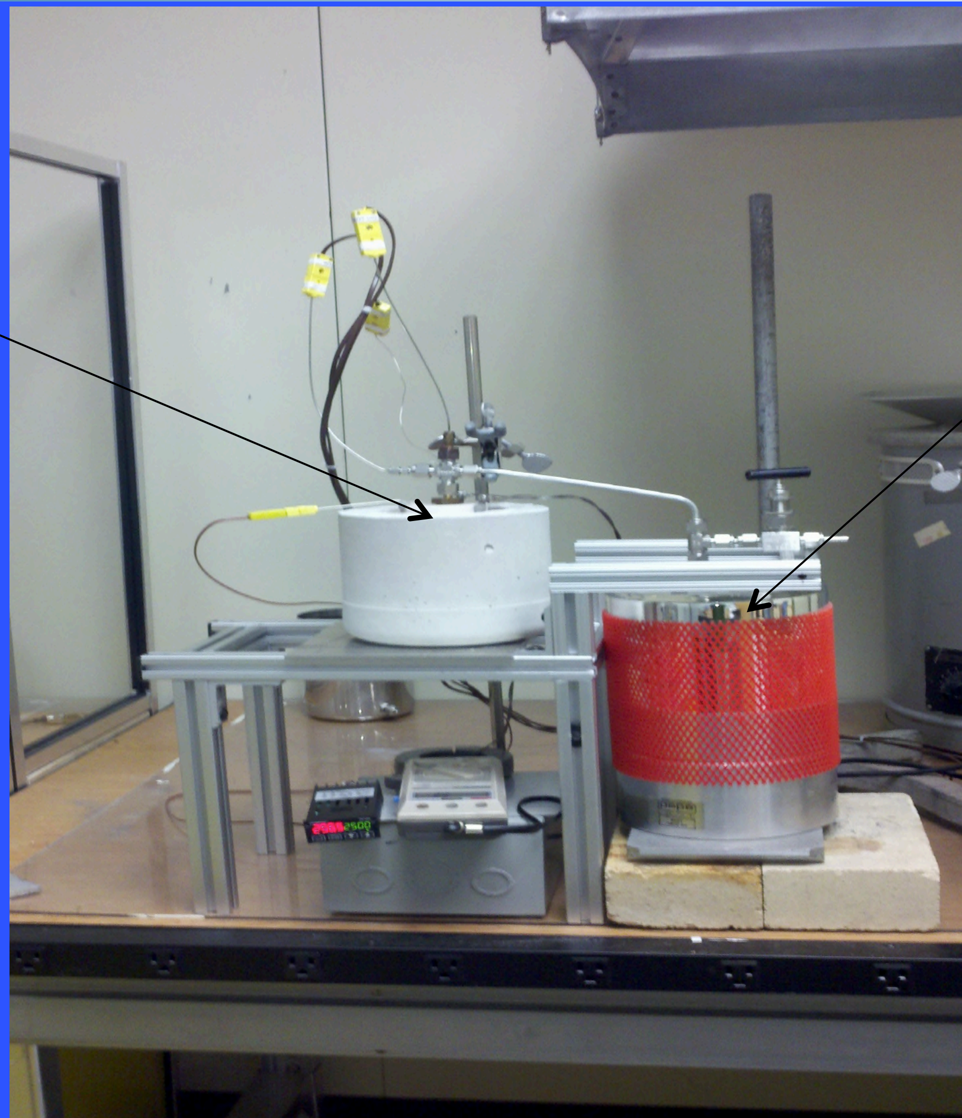
Core - Stardust TPS[1]

1. **Pyrolysis experiments and modeling**
   (TGA + mass spec/Flash heating)
2. **Ablation experiments and modeling**
   (Side arm reactor/etc.)
3. **Pyrolysis-ablation coupling**
   (ICP testing)
4. **Flow Env. Material Res. Coupling**
   (Flight data/ICP testing)

[1] M. Stackpoole *et al.*, Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material, AIAA 2008-1202

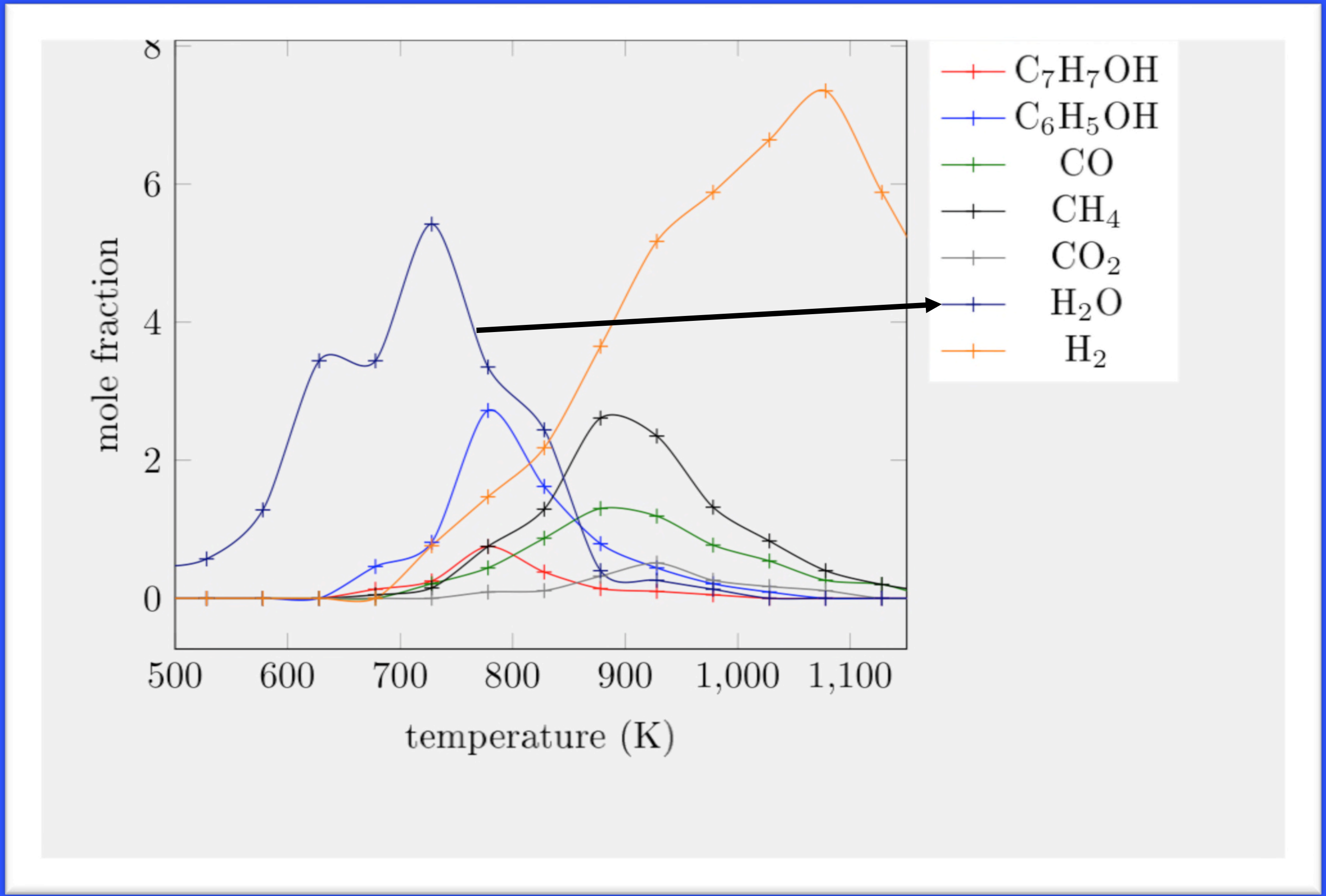
Pyrolysis experiments & modeling

Reactor



Condensor

Pyrolysis experiments & modeling



Pyrolysis experiments & modeling

Detailed model of the pyrolysis

For $j \in [1, N_p]$ pyrolysis reactions

$$PFR_j \rightarrow \sum_{i=1}^{N_g} \gamma_{ji} A_i$$

where PFR_j is a fictive solid species of the phenolic formaldehyde resin (PFR).

$$\rho_m = \rho_{mv} - \delta\rho_p \sum_{j=1}^{N_p} F_j \xi_j$$

where

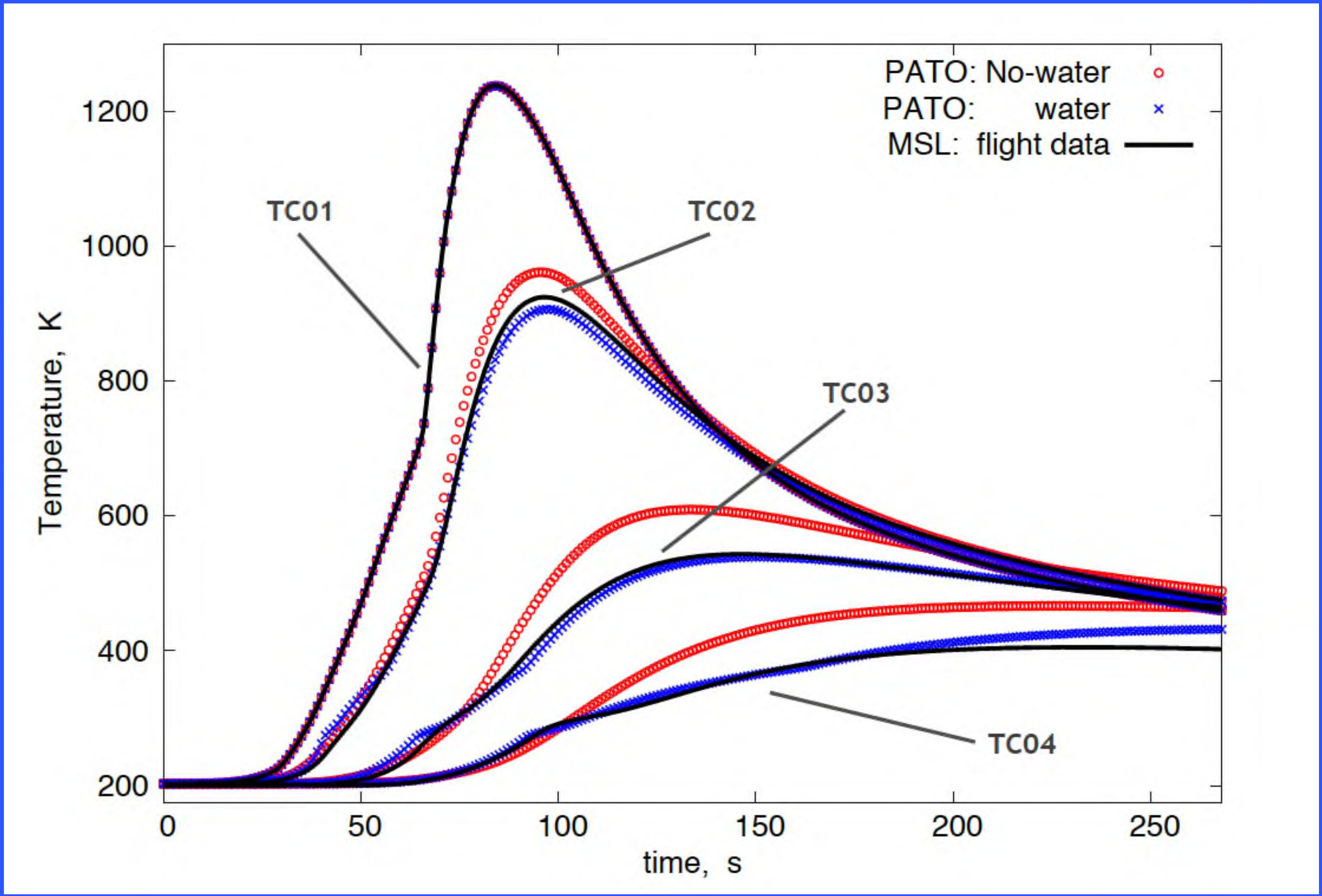
$$\frac{\partial_t \xi_j}{(1-\xi_j)^{m_j}} = T^{n_j} \mathcal{A}_j \exp\left(-\frac{\mathcal{E}_j}{\mathcal{R}T}\right)$$

$$\langle \pi_i \rangle^g = \epsilon_m \delta\rho_p \sum_{j=1}^{N_p} [\partial_t \xi_j \, F_j \, \widetilde{\gamma}_{ji}]$$

where

$$\widetilde{\gamma}_{ji} = \frac{\gamma_{ji}}{\sum_{k=1}^{N_g} \gamma_{jk} \mathcal{M}_k}$$

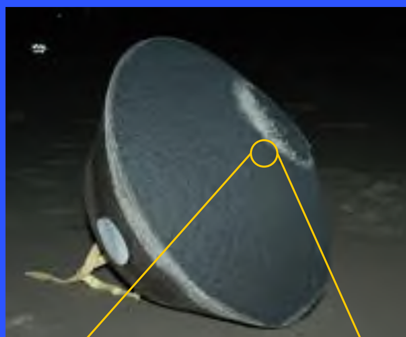
PATO validation study



Adding water effects reproduces the observed hump in the MEDLI data

High-fidelity modeling

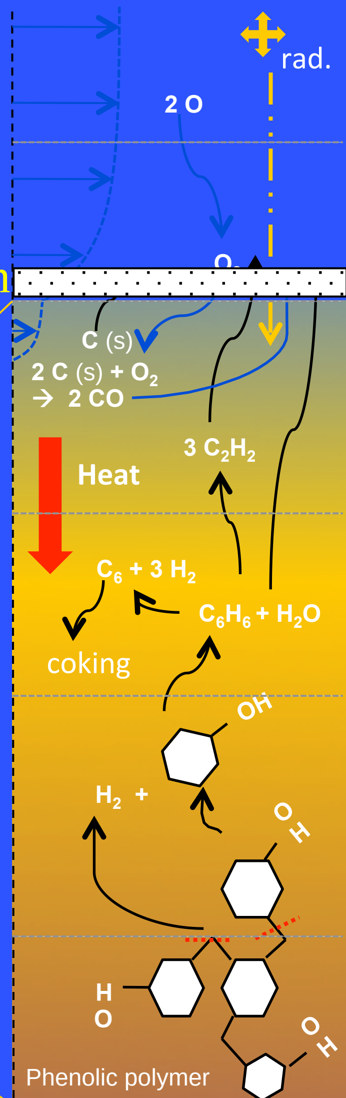
Stardust



TPS core

[Stackpoole *et al.*, AIAA 2008-1202]

Spallation



Macro illustration

Non-viscous flow

≈ 6000 K

Boundary layer

≈ 3000 K

Ablation zone

≈ 1400 K

Coking zone

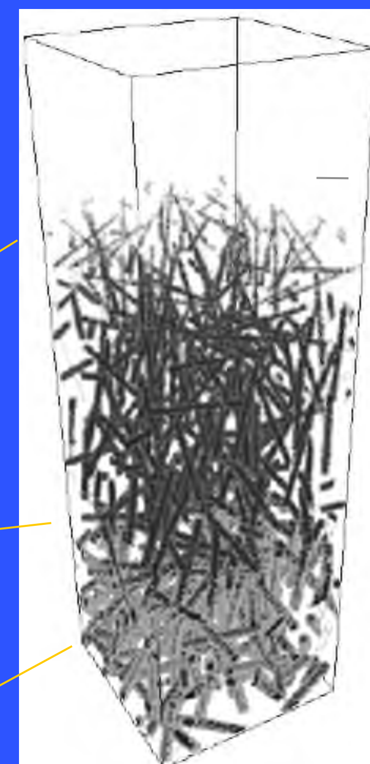
≈ 1200 K

Pyrolysis zone

≈ 400 K

Virgin material

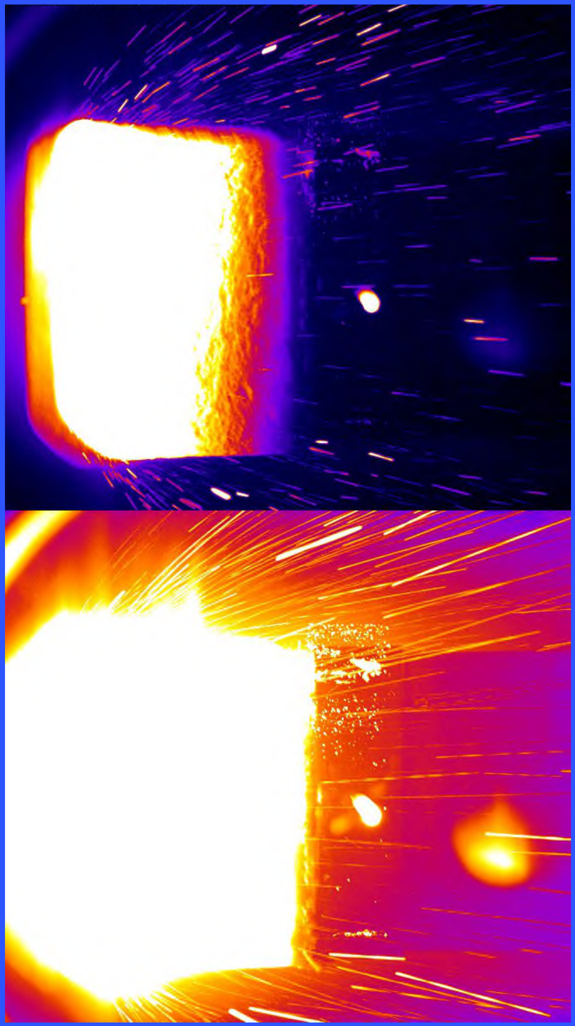
[Lachaud *et al.*, JSR, 47 (2010), 910-921]



Micro-scale simulation of carbon/phenolic ablation

HYMETS testing for spallation

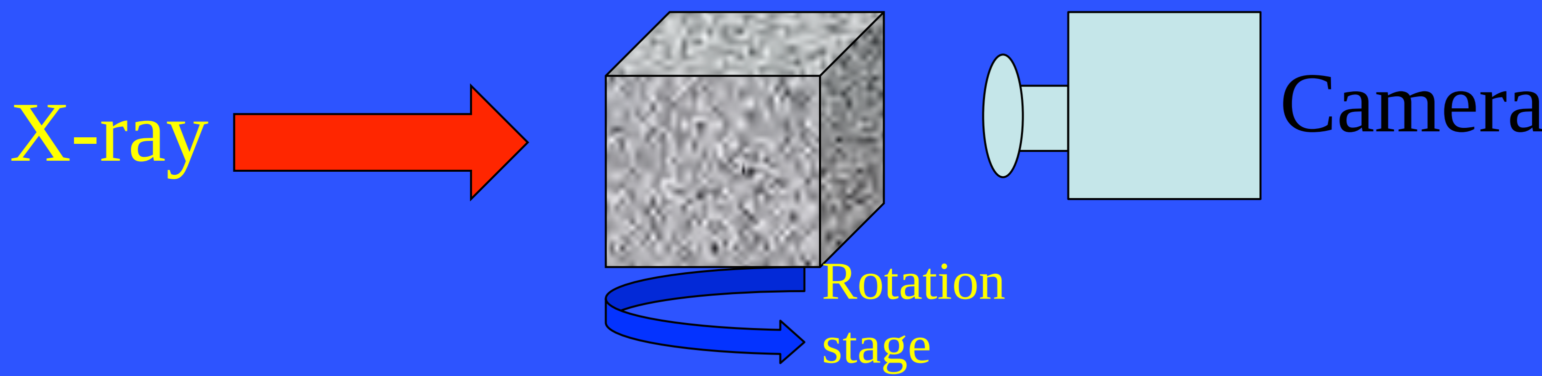
Term in FIAT is added to the B_c' to account for spallation



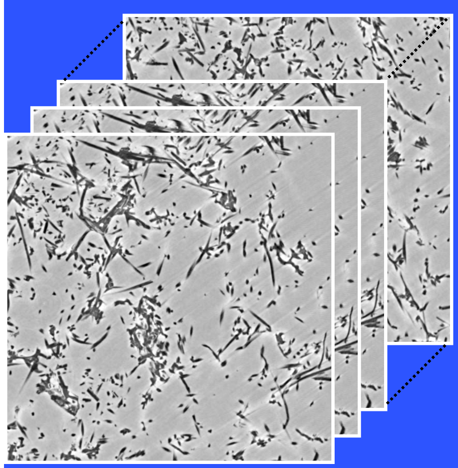
Dual-exposure camera still frames during FiberForm testing in the HYMETS arcjet. Images are combined from several frames (Credit: Jennifer Inman and Steve Jones).

Both Fiberform and PICA have been tested

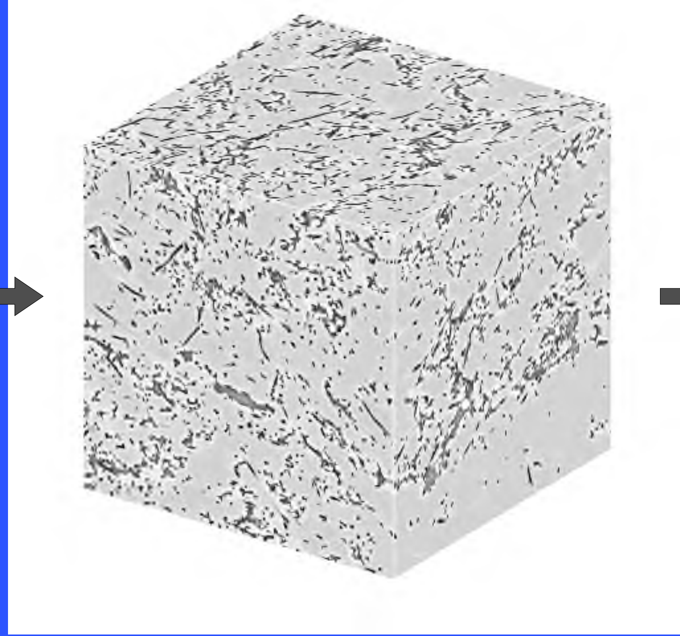
Tomography



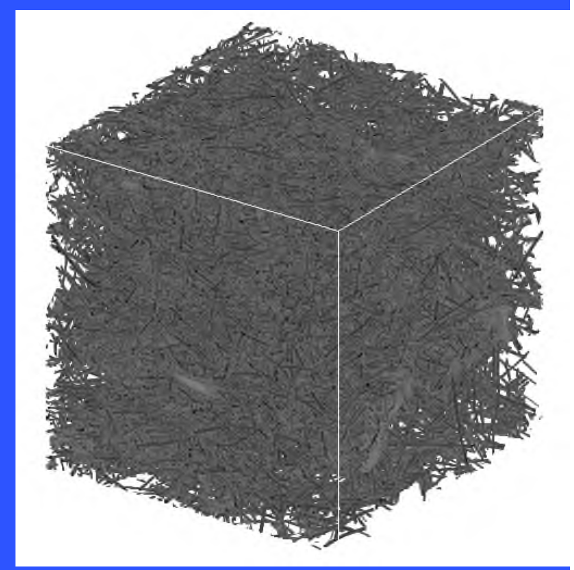
Tomographic reconstruction



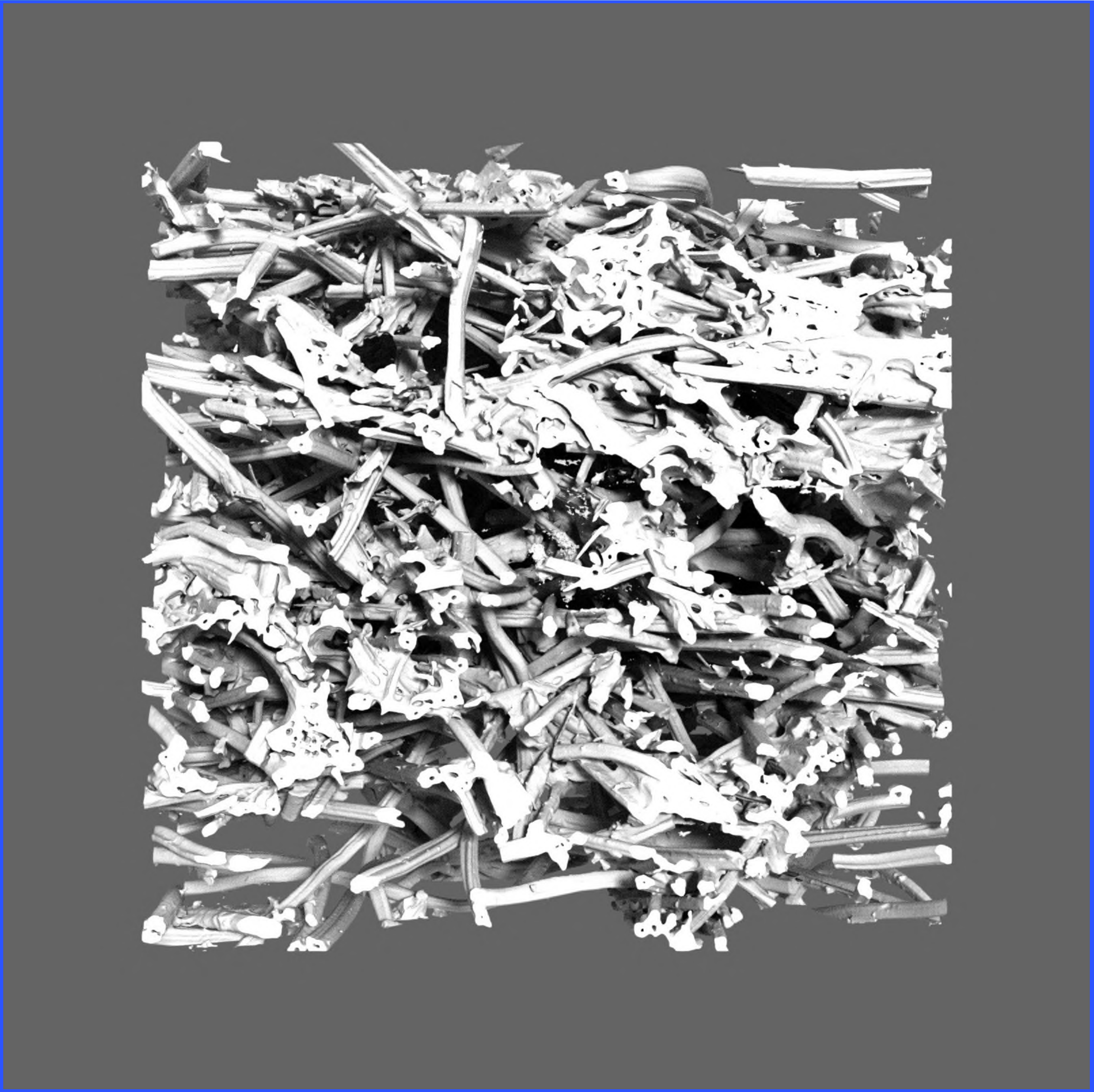
3D rendering



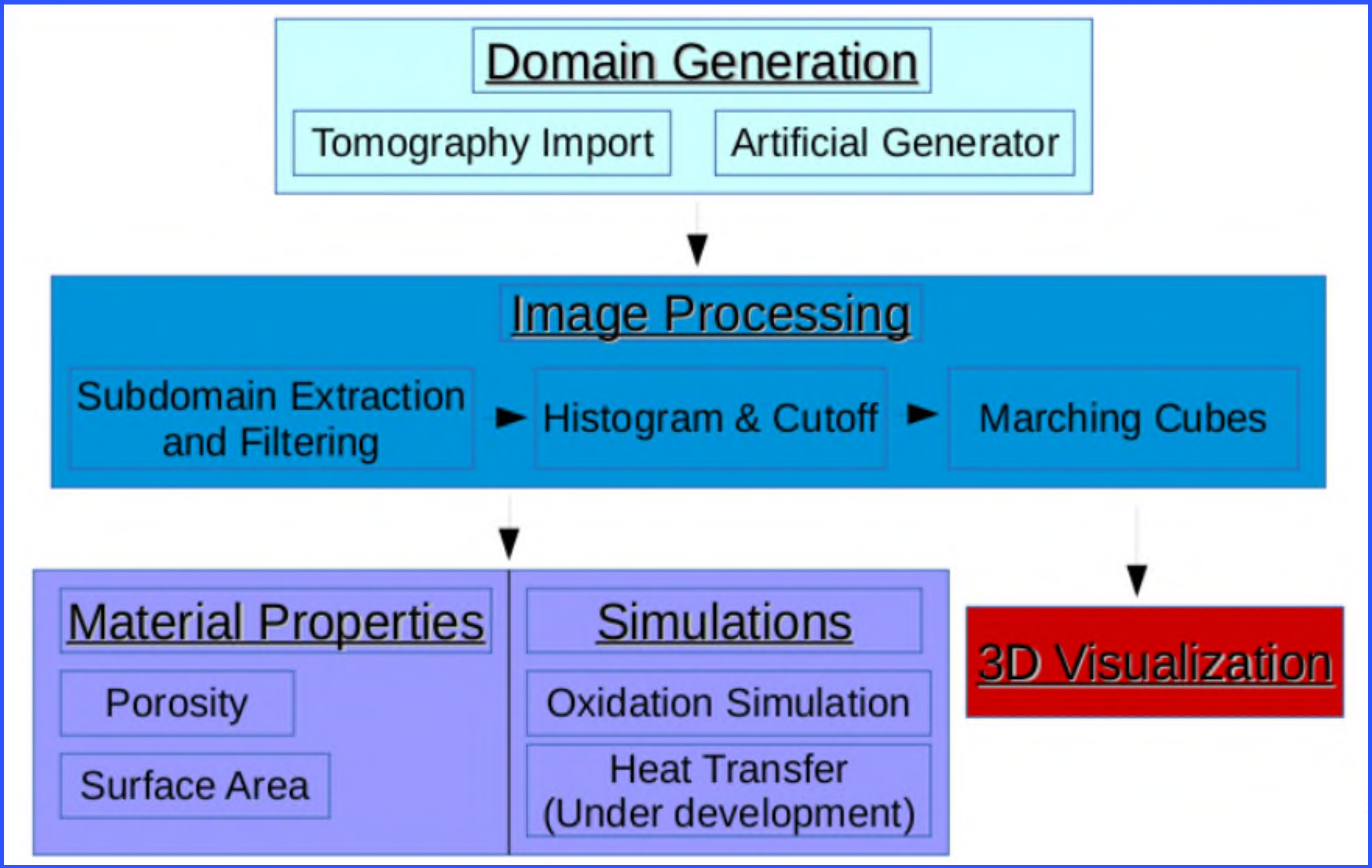
Thresholding



Tomography



Porous Media Analysis (PuMA) tool



Exact solution for an oxidizing fiber

$$A = \frac{k_m \Omega_m}{k_f \Omega_f} \qquad Sh = \frac{k_m R_f}{D}$$

A = reactivity contrast

k_m = reactivity matrix

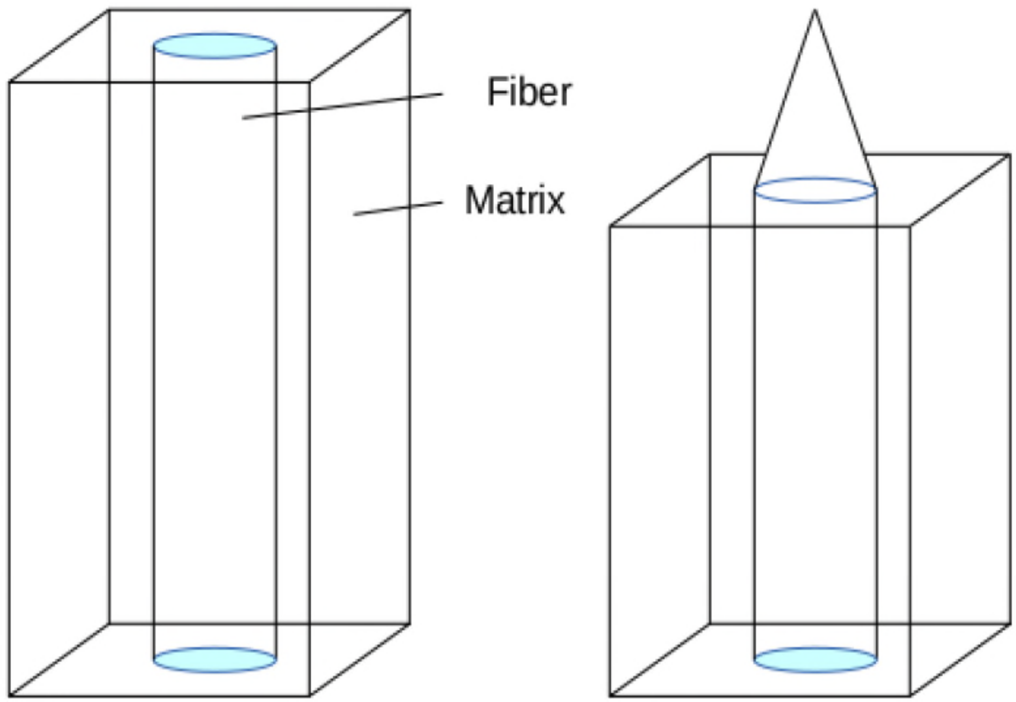
k_f = reactivity fiber

Ω_m = volume fraction matrix

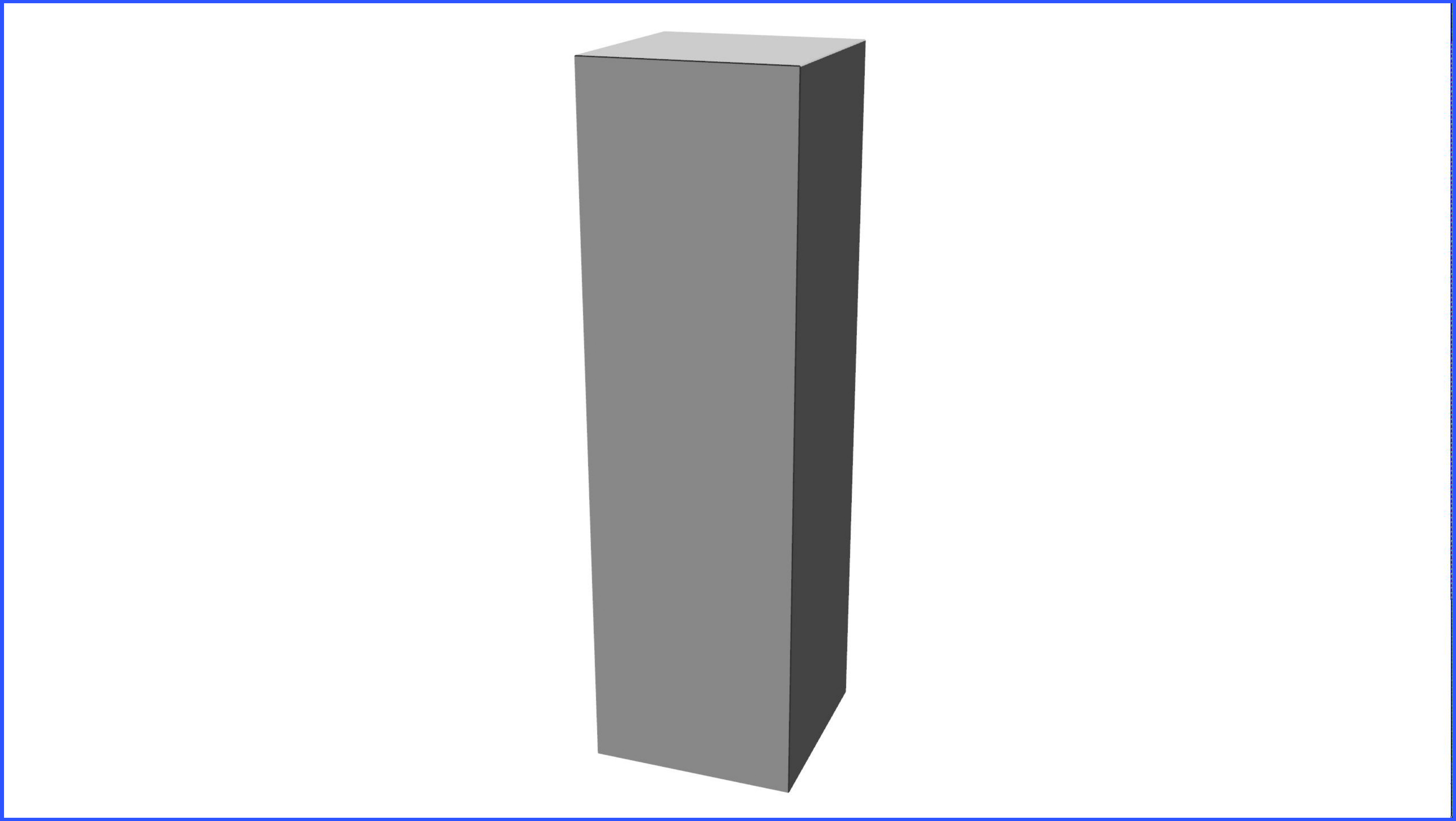
Ω_f = volume fraction fiber

Sh = sherwood number

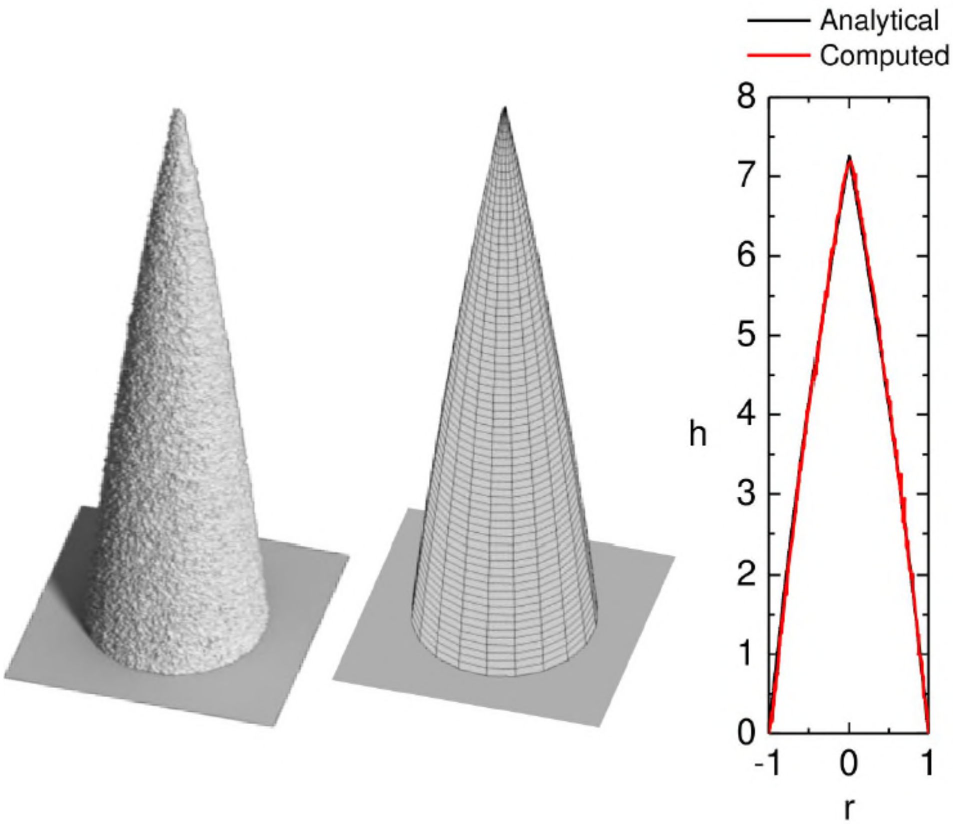
R_f = radius of fiber



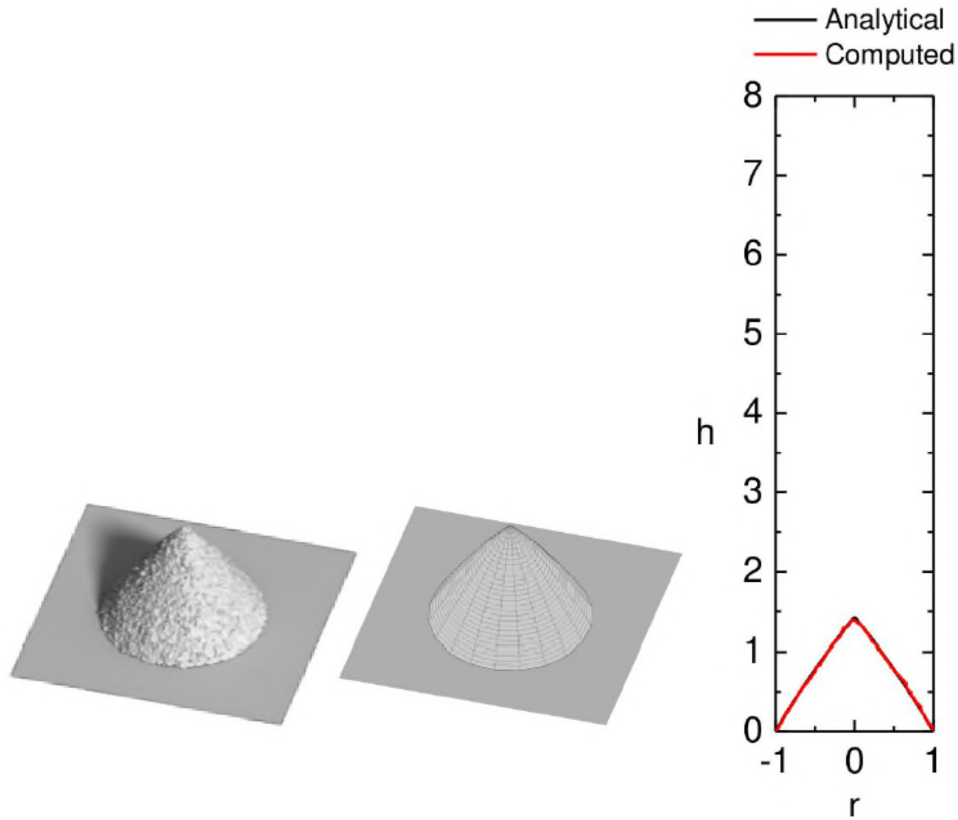
PuMA verification



Comparison to analytical solution

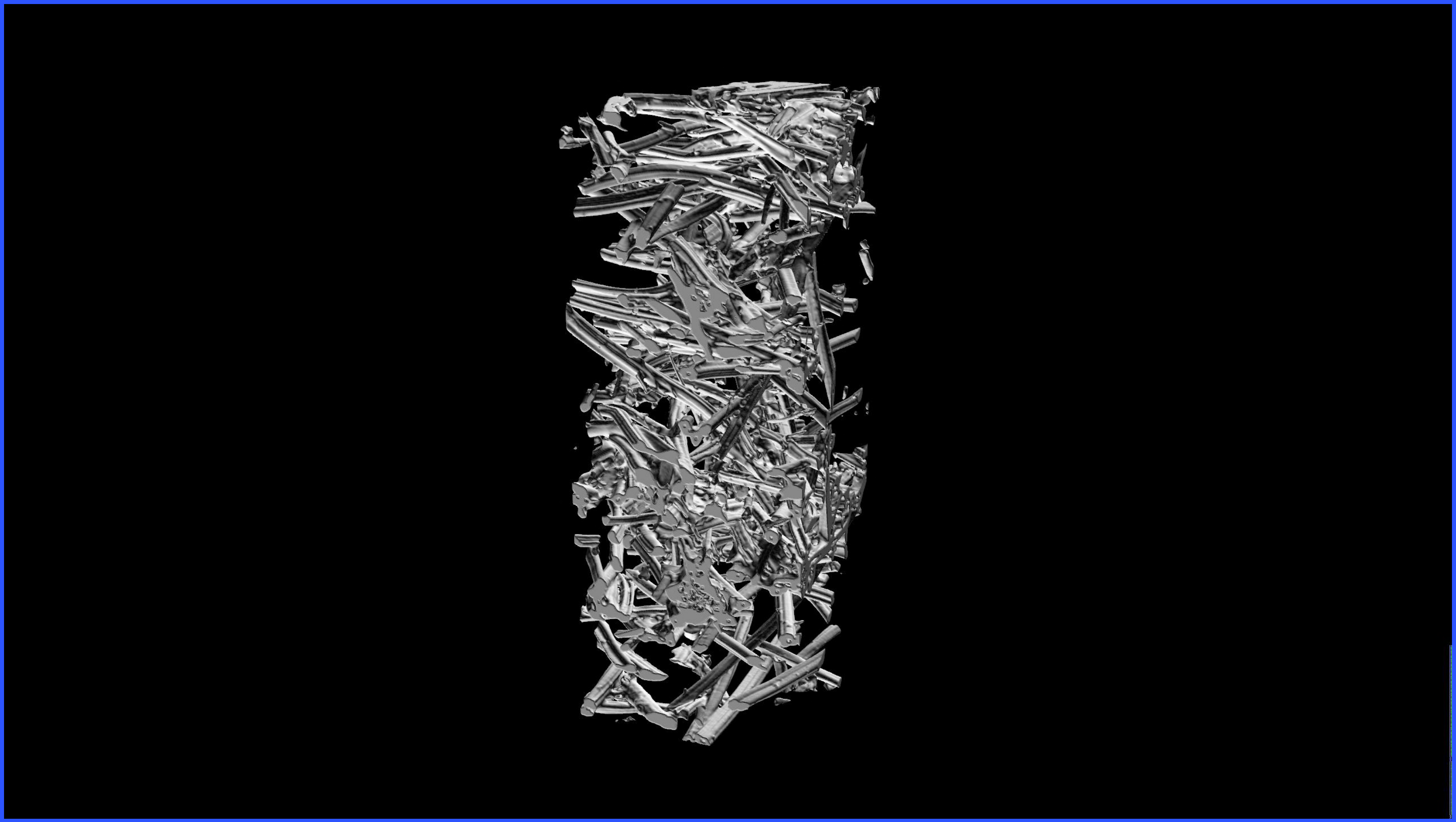


A = 10 Sh = 0.1



A = 2 Sh = 0.2

PuMA

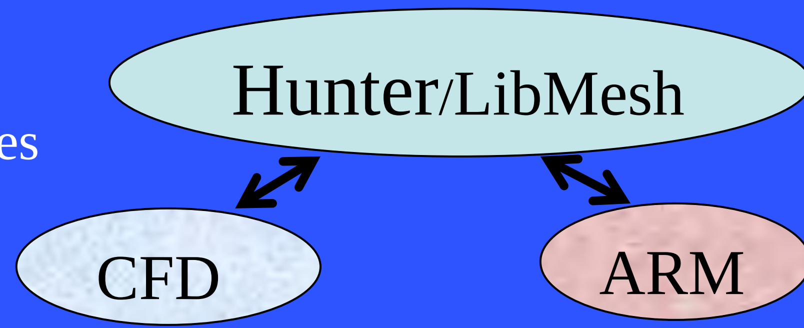


DPLR/Ablator Response Model coupling

DPLR and Material response model:

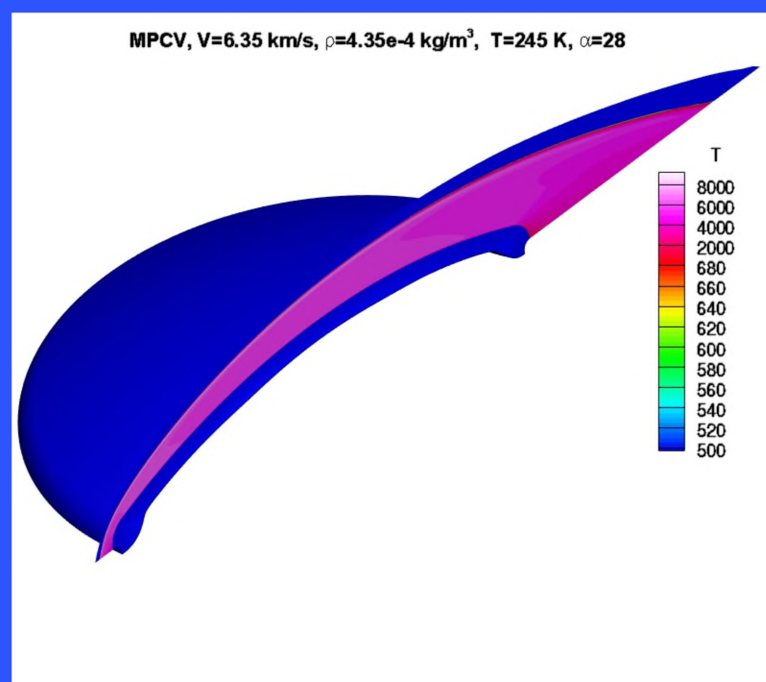
– Communication between the two codes

– Parallelization strategy



Hunter negotiates between:

- DPLR
- Material response
- Grid generation



Time dependent energy soak into a simplified capsule structure for the MPCV.

Summary

- Material performance tests (ICP, ArcJets, Flight data, etc.) as well as basic laboratory testing campaigns are needed to advance material response models to match advancements in our ability to model the flow physics (i.e. the environment).

Team + Collaborators

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- C. Henze
- A. Omidy
- J. Ferguson
- A. Wray