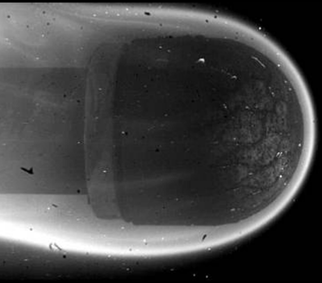

Material Response Characterization of Low Density Carbon-Phenolic Ablators in High-Enthalpy Plasma Flows

10th International Planetary Probe Workshop

von KARMAN INSTITUTE FOR FLUID DYNAMICS

San Jose, CA, USA
June 20, 2013

Vrije Universiteit Brussel

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Outline

Outline

Ablative Thermal Protection Systems (TPS)

Start of space flight
High-speed reentries

$\rightarrow$ until today

All European missions:
ablative heat shields

Apollo 10 capsule
(May 26, 1969)

Soyuz capsule
(1967-today)

Atm. Reentry Demonstrator
(1998)

Ablative Thermal Protection Systems (TPS)

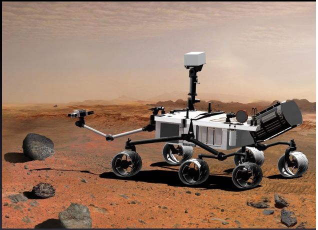
Start of space flight
High-speed reentries

→ until today

Future: Sample returns
High-speed reentries

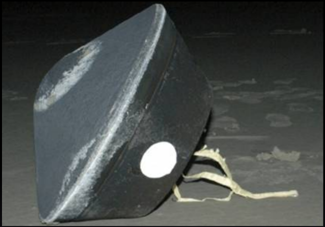
Apollo 10 capsule
(May 26, 1969)

Soyuz capsule
(1967-today)



Mars Science Laboratory (2012)
Courtesy: NASA

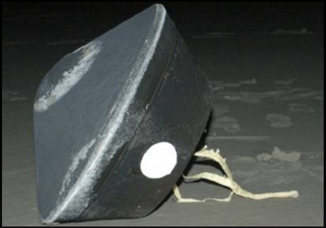
New Porous, Lightweight Ablators



Stardust probe (2006, 12.9 km/s, [1])

- New low weight materials (PICA, ASTERM) [2, 3]
- New missions (Asteroid / Mars sample return)

New Porous, Lightweight Ablators



Stardust probe (2006, 12.9 km/s, [1])

- New low weight materials (PICA, ASTERM) [2, 3]
- New missions (Asteroid / Mars sample return)

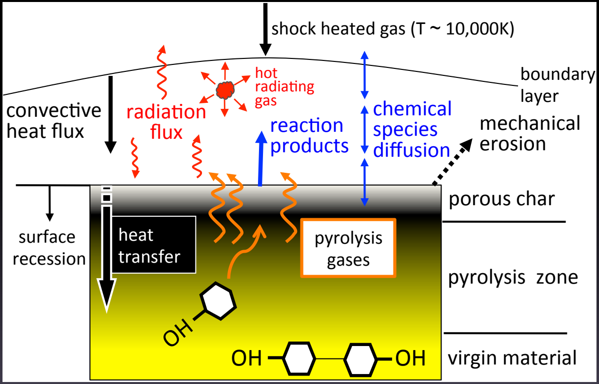
Modeling tools inherited from Apollo program (1960s) [4]

→ new material response models [5]

→ qualification of materials & validation of models required [6]

Complex Multiphysics - Multiscale Problem

Radiative and convective heating $\Rightarrow$ Pyrolysis of phenolic resin $C_6H_5{-}OH$ ($>200°C$)



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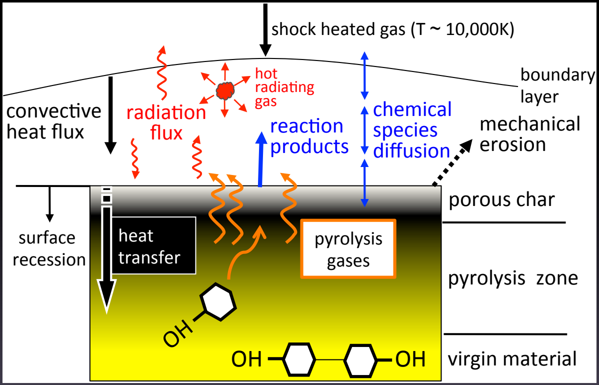


Ablation

Chemical mechanisms

oxidation (CO, CO_2), nitridation (CN)

Phase changes

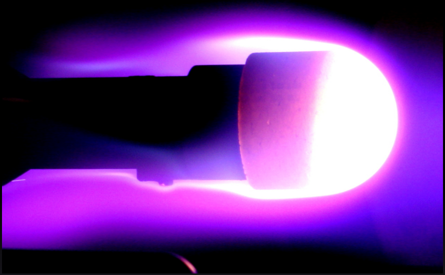
melting, sublimation (C, C_2, C_3)

Mechanical removal

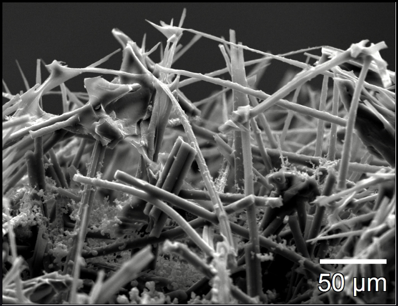
spallation, shear stress, melt removal

Complex Multiphysics - Multiscale Problem

Research Strategy and Objectives



VKI: Analysis in High-Enthalpy Plasma Flows



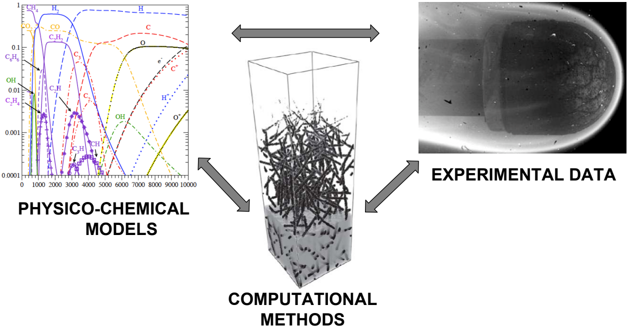
VUB: Multiscale Characterization

→ Gas phase:
- pyrolysis gas chemistry
- transport phenomena & radiation in the boundary layer

→ Material:
- thermal performance and internal degradation
- char ablation zone and degradation of carbon fibers

Research Frame and Goals

- ⇒ Methodology to characterize material response & gas-gas / gas-surface interaction of innovative ablators
- ⇒ Model validation and flight extrapolation



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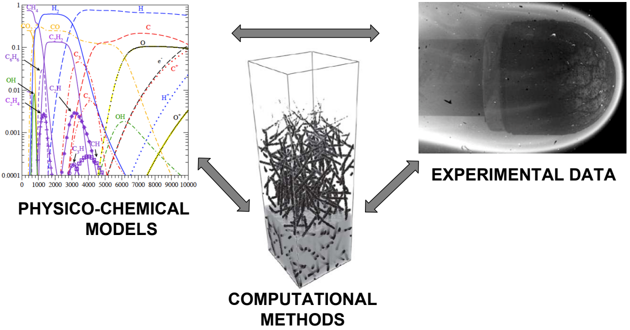
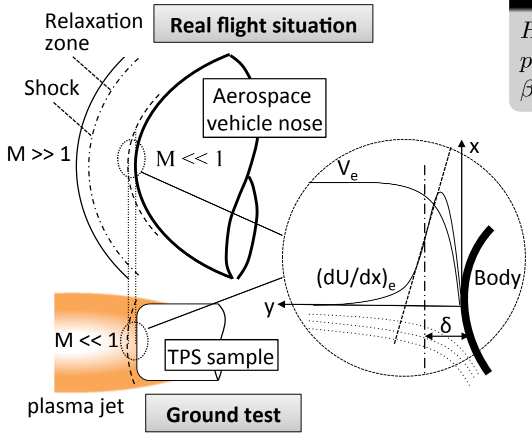


⇒ **Combining basic ingredients for prediction in aerospace science**

Outline

Local Heat Transfer Simulation (LHTS)

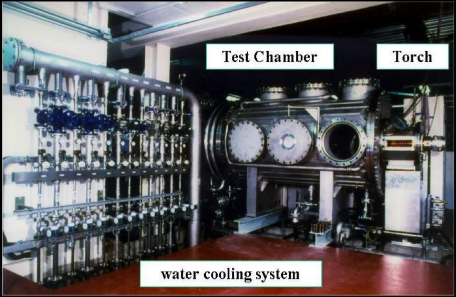
→ Plasmatron design based on LHTS methodology
→ Well characterized plasma flow through numerical-experimental procedure

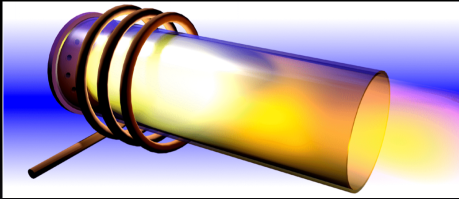


Stgn.pt. heat flux similarity[7]:

$H_f = H_{exp},$
$p_f = p_{exp},$
$\beta_f = \beta_{exp},\ \beta = (dU/dx)_e$

1.2 MW Inductively Coupled Plasmatron





Plasmatron facility and artistic impression of plasma torch

- Originally designed for Hermes project (Ceramic Matrix Composites (CMC) $\rightarrow$ ablation)
- Gas: Air, N_2, CO_2, Ar
- Power: 1.2 MW (most powerful ICP in the world)
- Heat-flux: up to $10\,\mathrm{MW/m^2}$ (superorbital re-entry)
- Pressure: 10 mbar - 1 atm

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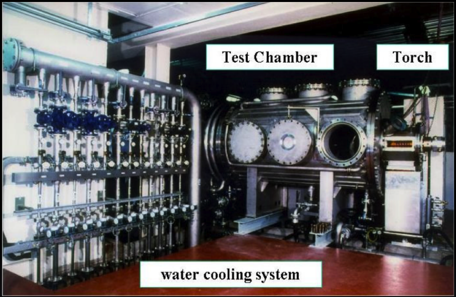

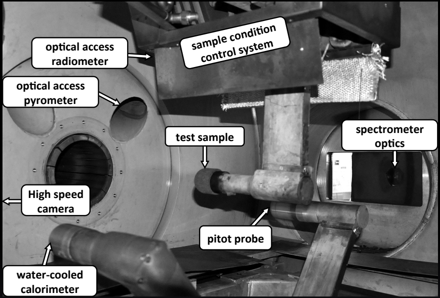

Plasmatron test chamber showing experimental setup and torch exit

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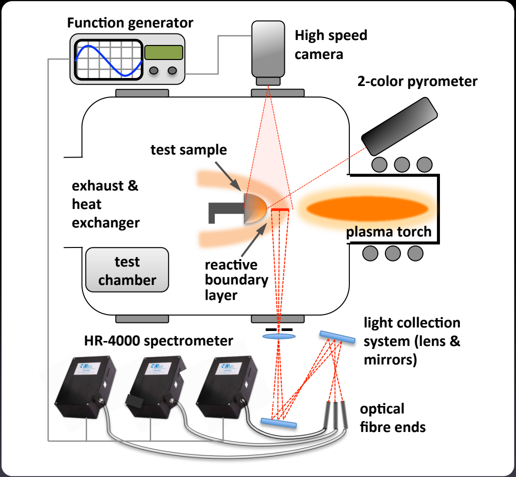
1.2 MW Inductively Coupled Plasmatron

movie loading...

Experimental Techniques for Ablation Characterization



- Radiometry
  surface temperatures & emissivity
- Thermocouples
  internal temperature histories
- High-speed-camera
  - → in-situ recession analysis
  - → in-situ determination of spectrometer probing locations
- Optical emission spectroscopy
  temporally and spatially resolved radiation profiles in the boundary layer
  - → chemical composition
  - → temperature estimation

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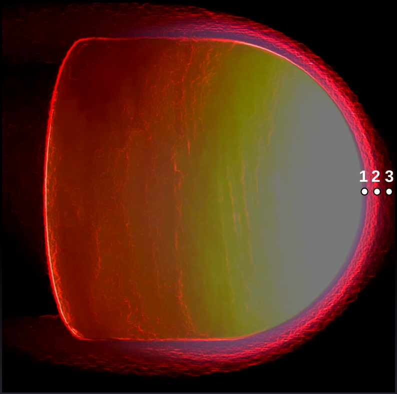

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  → temperature estimation

Materials of Investigation

<u>Carbon fiber preform (Mersen Scotland Holytown Ltd.)</u>

- chopped carbon fibers, fully carbonized **no phenol content**
- density: 180-210 kg/m3, porosity: 90%

<u>AQ61 (EADS Astrium ST)</u>

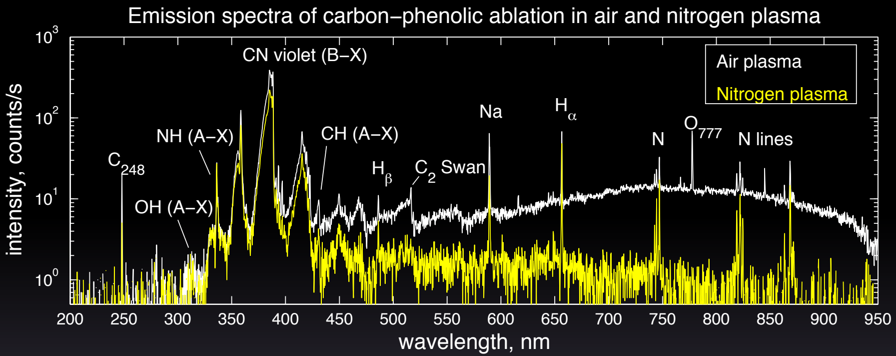
- low density carbon-phenolic
- made of short carbon fibers impregnated **with phenolic resin** → compacted & pyrolysed
- low resin content

<u>ASTERM (EADS Astrium ST)</u>

- low density carbon-phenolic
- rigid graphite felt impregnated **with phenolic resin** → polymerization
- precursor similar to carbon fiber reform

Outline

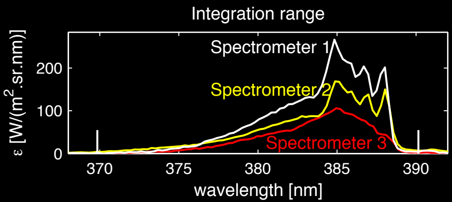
Contaminated Boundary Layer



Detection of contamination products originating from phenol (C_6H_5-OH)

1. pyrolysis $\Rightarrow$ C, C_2, CH, NH, OH
2. ablation $\Rightarrow$ C, C_2, CN

CN Spatial Radiation Profiles in Boundary Layer



$$I_{CN}^{(t)} = \int_{370nm}^{390nm} \epsilon(\lambda) d\lambda \qquad (1)$$

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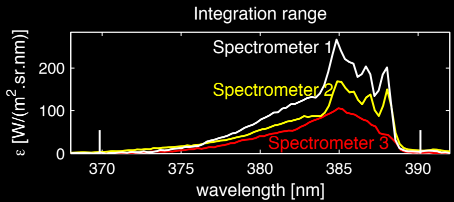

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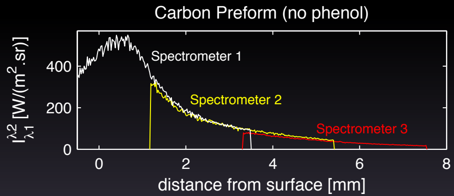

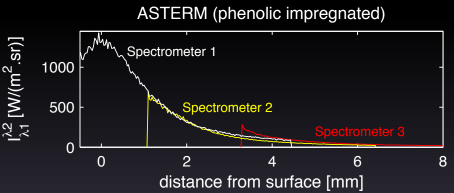

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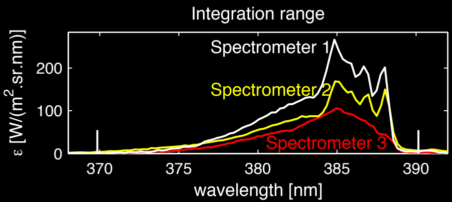

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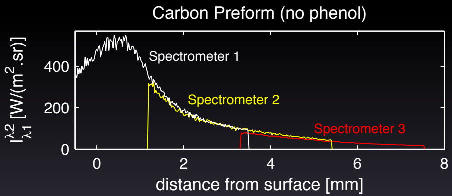
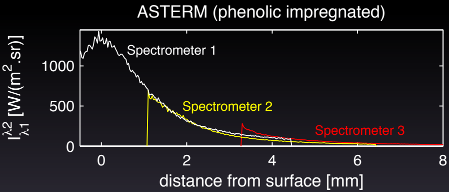
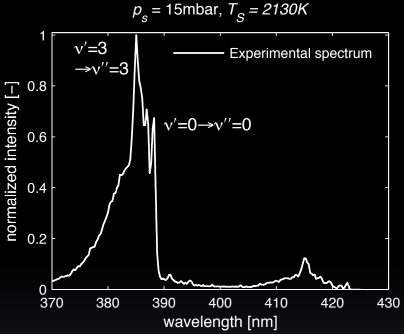




We are interested in temperature and concentration profiles in the boundary layer
→ molecular radiative signature of CN violet system

CN Radiation Simulation for Temperature Estimation



- Vibrational levels variations for different chamber pressures (close to wall) $\rightarrow$ temperature estimation using simulation tool SPECAIR [8]

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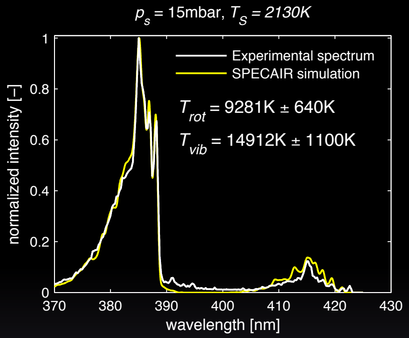

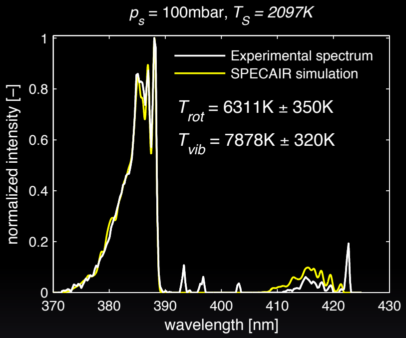

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- Deviation from thermal EQ w.r.t. T_{rot} and T_{vib} (Boltzmann distribution!)
- Evident for all three materials (Preform, AQ61, ASTERM)
- Only electrically excited states are probed (CN B-X)

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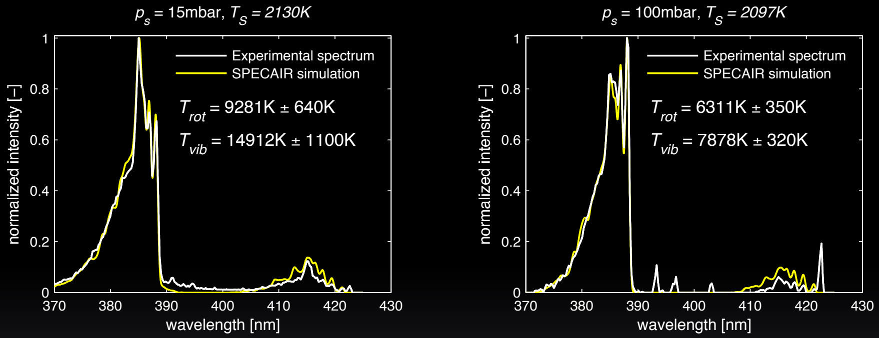

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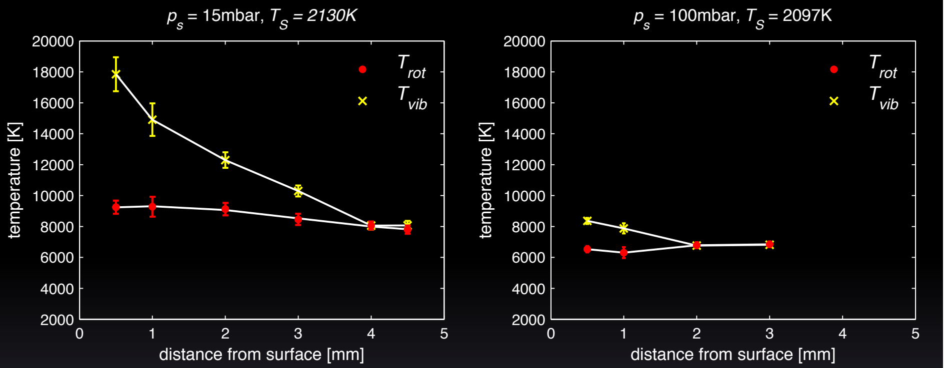
→ Check for various distances off the surface

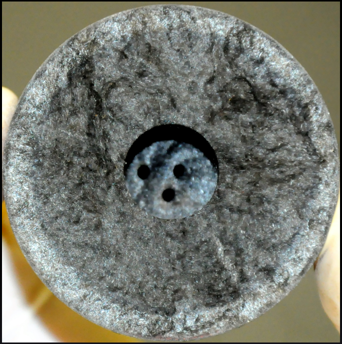
Boundary Layer Temperature Profile



- Deviation from thermal EQ close to the wall (low pressures)
- Equilibrating effect throughout BL
- Mainly equilibrium condition at high pressure (right)

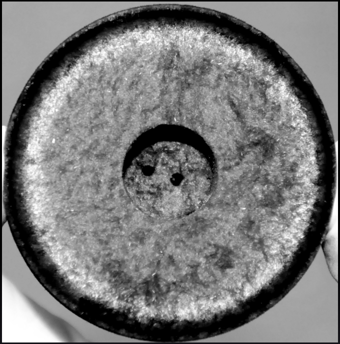
⇒ AIAA-2013-2770

Post-Test Visual Inspection



after ablation in air

- Macroscopic char identification
- Symmetric charring of AQ61



after ablation in N_2

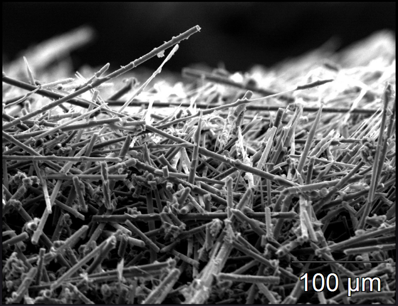
- Black char over whole surface
- Symmetric charring of AQ61

SEM Inspection: Stagnation Point (Air Ablation)

Carbon Preform

- icicle shaped fibers after ablation in air
- icicle angle and depth of ablation depend on oxygen diffusion [9]

AQ61



- icicle shaped fibers & high porosity (charred resin sparely identified)

SEM Inspection: Stagnation Point (Air Ablation)

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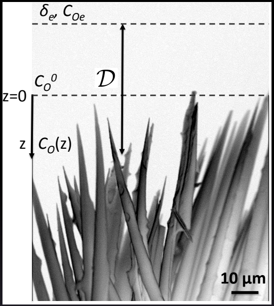

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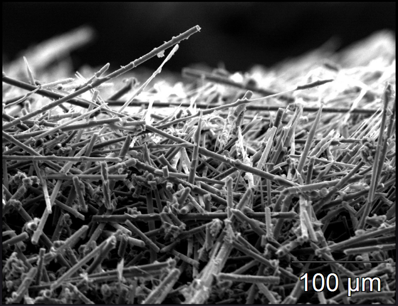

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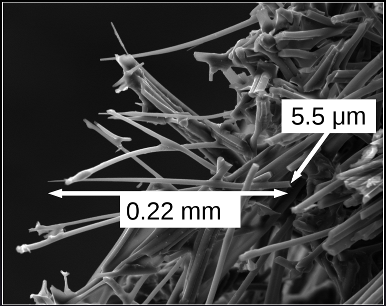

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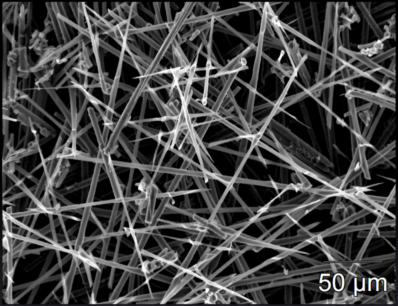

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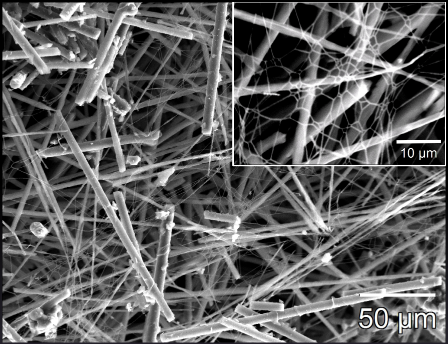
SEM Inspection: Ablation in Nitrogen

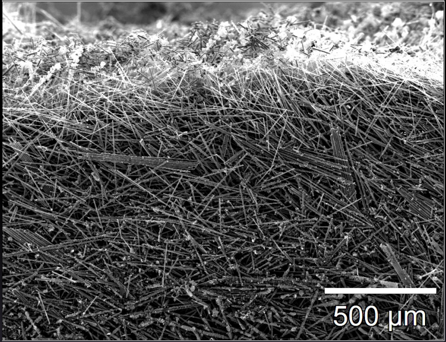
Stagnation Point



- 'cross filaments' found on the surface after ablation in N

→ production of strong & stable C-C bonds (catenation?)

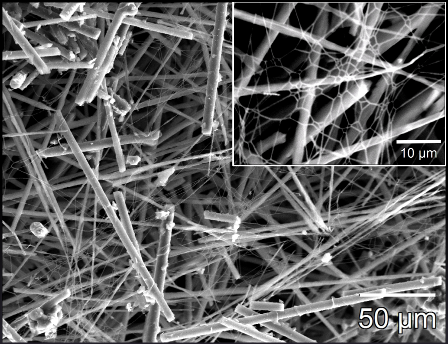
Side- & Backface



- black carbon (similar to soot) deposited at surface

SEM Inspection: Ablation in Nitrogen

Stagnation Point



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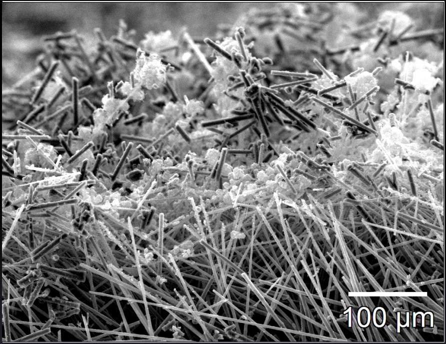

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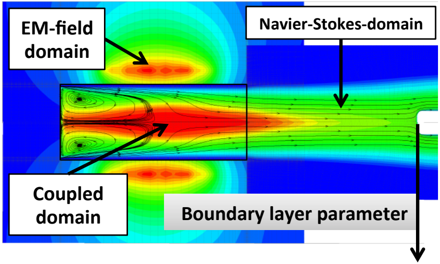
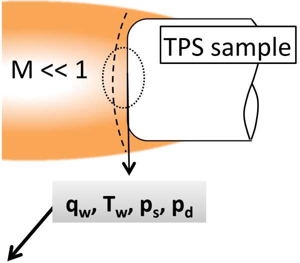
Outline

Combined Numerical/Experimental rebuilding Procedure

CFD simulation (VKI ICP code)



Experiments

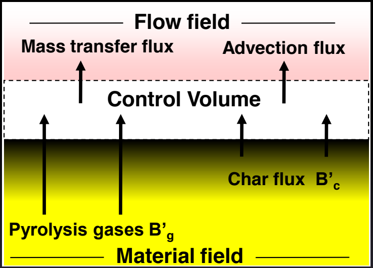


Boundary layer solver

- **Input**: Boundary layer parameter (LTE CFD computation) & measurements from experiments
- **Procedure**: Iteration on boundary layer edge temperature T_e:
  $\Rightarrow q_w^n = q_w^{(exp)} = q_w(\gamma, T_w, p_e, h_e, \beta, ...)$
- **Output**: Edge enthalpy H_e, boundary layer chemistry, (catalycity)

State of the Art Ablation Modeling

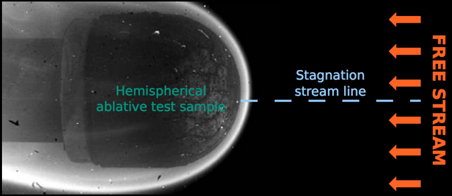
Common strategy (Kendall et al.[4]):



Assumptions:

- Material and flow decoupled
  → **Control volume approach**
- Chemically active surface
  → carbon char reacts with oxygen
- Chemically active species from
  → pyrolysis of decomposing material
  → edge of boundary layer (equilibrium chemistry)

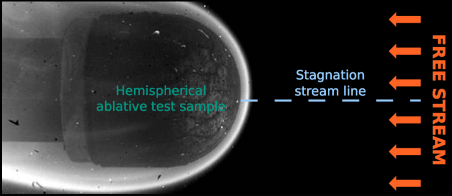
1D Stagnation Line Description w/ Surface Ablation (Poster: A. Turchi)



Approach:

- SPECIES SURFACE MASS BALANCE (SMB)
- SURFACE ENERGY BALANCE (SEB)

1D Stagnation Line Description w/ Surface Ablation (Poster: A. Turchi)



- Reconstruction of experiments
- Gas mixture properties: Thermo-chemistry library MUTATION++ (**Poster: J.B. Scoggins**)
- 1D stagnation-line formulation with SMB & SEB

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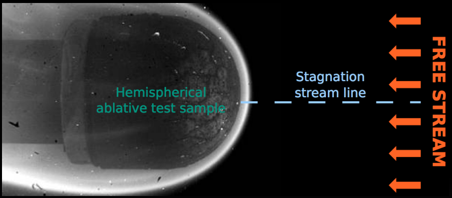

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- 1D stagnation-line formulation with SMB & SEB

Table: Preliminary results on a Carbon Preform (no phenol content)

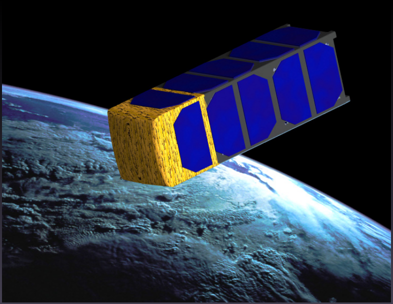
	T_w, K	$\dot{m}_c, \mathrm{kg.m^{-2}.s^{-1}}$
Experiment ($\dot{q}_{cw} = 3\,\mathrm{MW/m^2}, p_s = 20\,\mathrm{kPa}$)	2783	$0.0155^{\,0.0175}_{\,0.0111}$
Isothermal ablation w/ nitridation	2783 (imposed)	0.0202
SEB ablation w/ nitridation	2198	0.0201
SEB ablation w/o nitridation	2174	0.0152

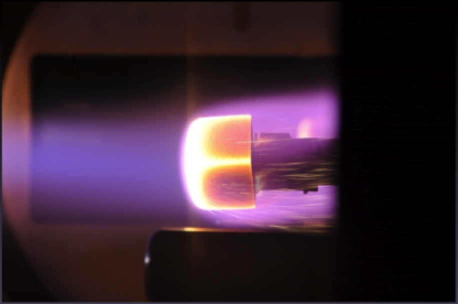
Outline

Application to Mission Design (Presentation: I. Sakraker, G. Baillet)

QARMAN: QubeSat for Aerothermodynamic Research and Measurements on AblatioN (Re-entry cube-sat as part of the VKI QB50 project)

⇒ TPM selection campaign (heat load reproduction)





Outline

Conclusions and Perspectives

In-situ observation: Recession rates, sample temperature response, boundary layer thermo-chemistry (AIAA-2013-2770)

Post-test Analysis Char layer examination at carbon fiber length scale:
Mechanisms of fiber oxidation in diffusion-limited regime
Carbon deposition on surface in N_2 environment

1D-Code Comparison: Stagnation line description matches experimental results within uncertainty

→ More conditions for additional comparison / validation
→ Extend to carbon-phenolic ablator (loose coupling with material code)
→ Goal: Comparison of BL chemistry and spectroscopy data (profiles, mole fractions) for code validation

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