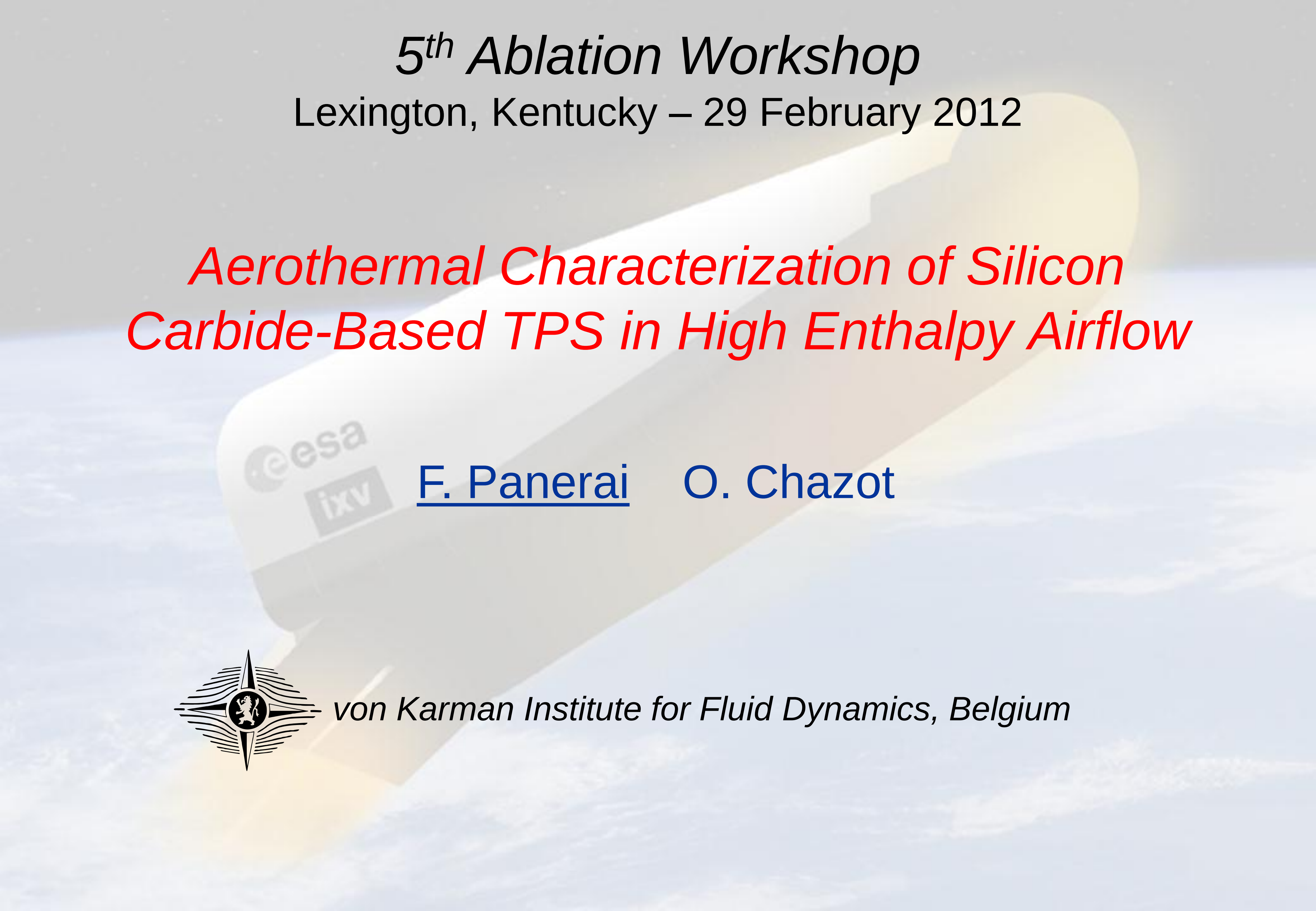


5th Ablation Workshop

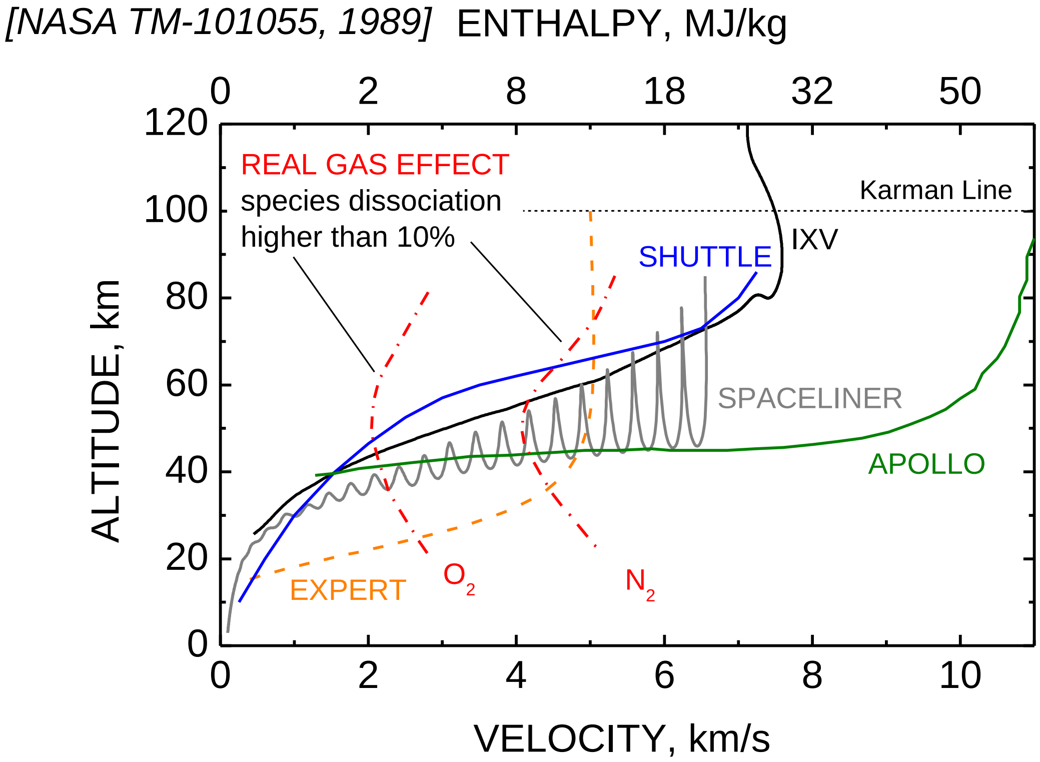
Lexington, Kentucky – 29 February 2012

Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

F. Panerai   O. Chazot

von Karman Institute for Fluid Dynamics, Belgium

Atmospheric Reentry and Gas-Surface Interaction



Gas-surface interaction is characterized by highly exothermic chemistry which impose the use of a Thermal Protection System.

For reusable TPS we need to account for:

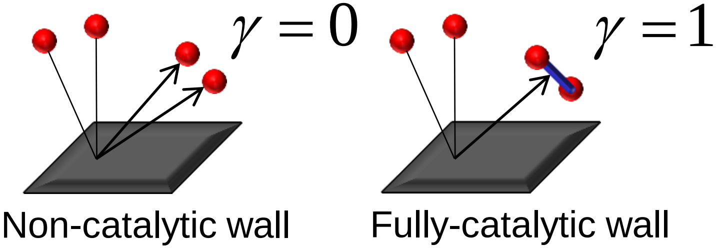
1. recombination reactions (catalysis)
2. oxidation
3. radiative heat transfer

Intermediate eXperimental Vehicle (IXV)

Gas Surface Interaction Phenomena

Catalycity

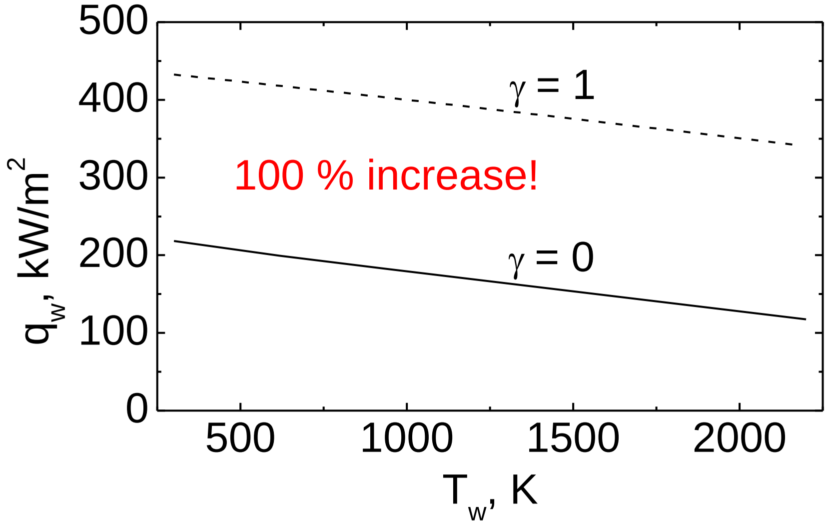
$$\gamma = \frac{\dot{m}_r}{\dot{m}_{\downarrow}}$$



Oxidation

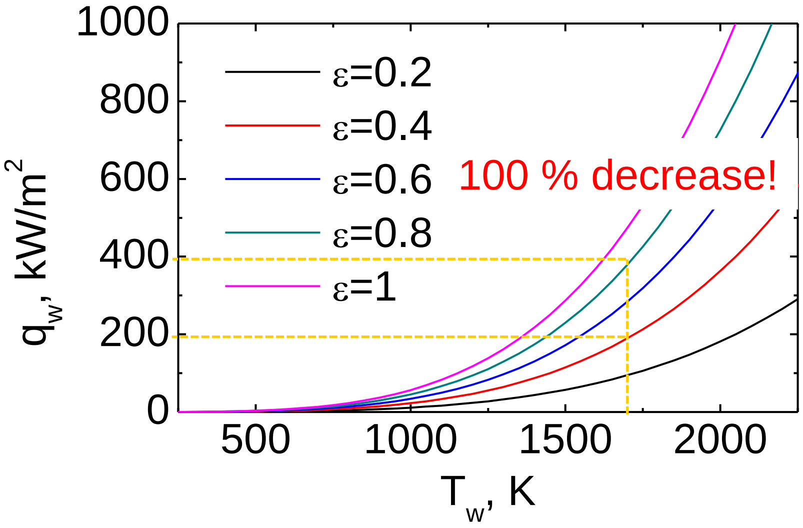
PASSIVE: formation of protective silica layer $SiC_{(s)}+3/2O_{2(g)} \rightarrow SiO_{2(s)}+CO_{(g)}$

ACTIVE: formation of gaseous silicon products $SiC_{(s)}+O_{2(g)} \rightarrow SiO_{(g)}+CO_{2(g)}$

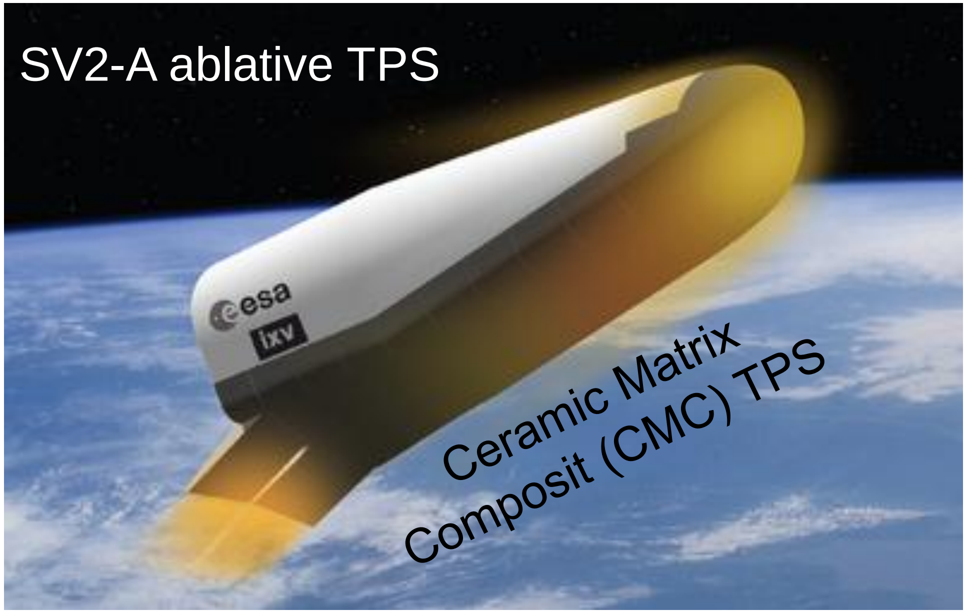


Emissivity

$$\varepsilon = \frac{M}{M^0}$$



Background and Objectives



ESA project for a LEO lifting reentry demonstrator

Main mission objectives are:

- advancement on TPS technologies
- study aerothermodynamic phenomena during the reentry

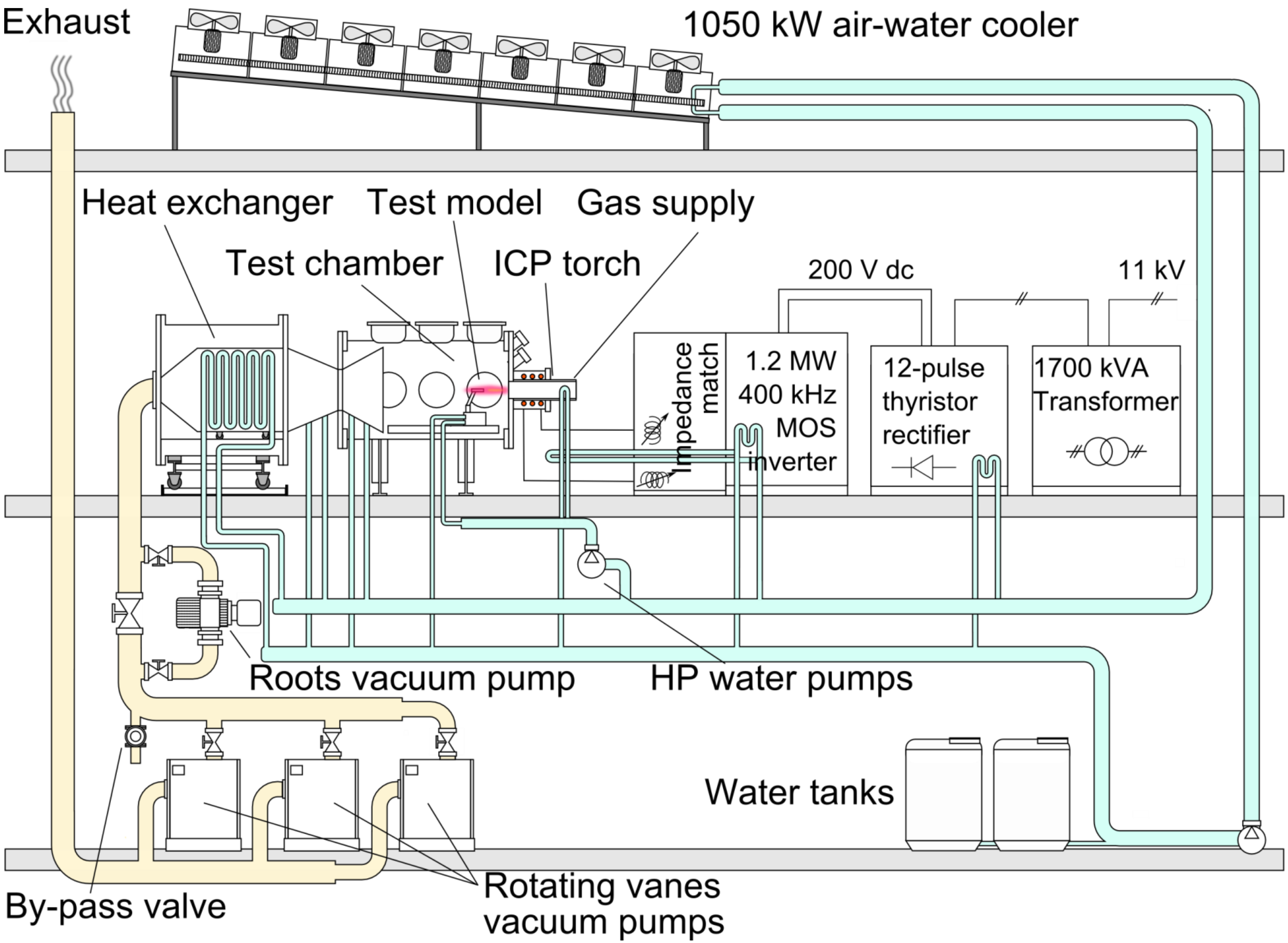
Our Goal

Contribute, through ground testing, to the Aerothermal Database of the IXV mission proving assessment of the oxidative, catalytic and radiative behavior of the CMC Thermal Protection System

Outline

- The VKI Plasmatron facility
- Methodology and Instrumentation
- Test overview and operating conditions
- Results:
    - In-situ emissivity measurements
    - Room temperature reflectivity measurements
    - Oxidation assessment
    - Catalycity determination
    - Gas phase radiative signature
- Summary and outlook

The VKI Plasmatron Facility



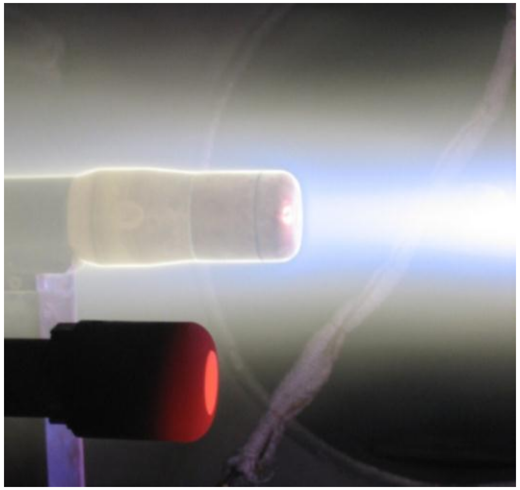
Characteristics

- ICP generation
- Gas: Air, CO2, Ar
- Power: 1.2 MW
- Heat flux:

0.1 - 10 MW/m2

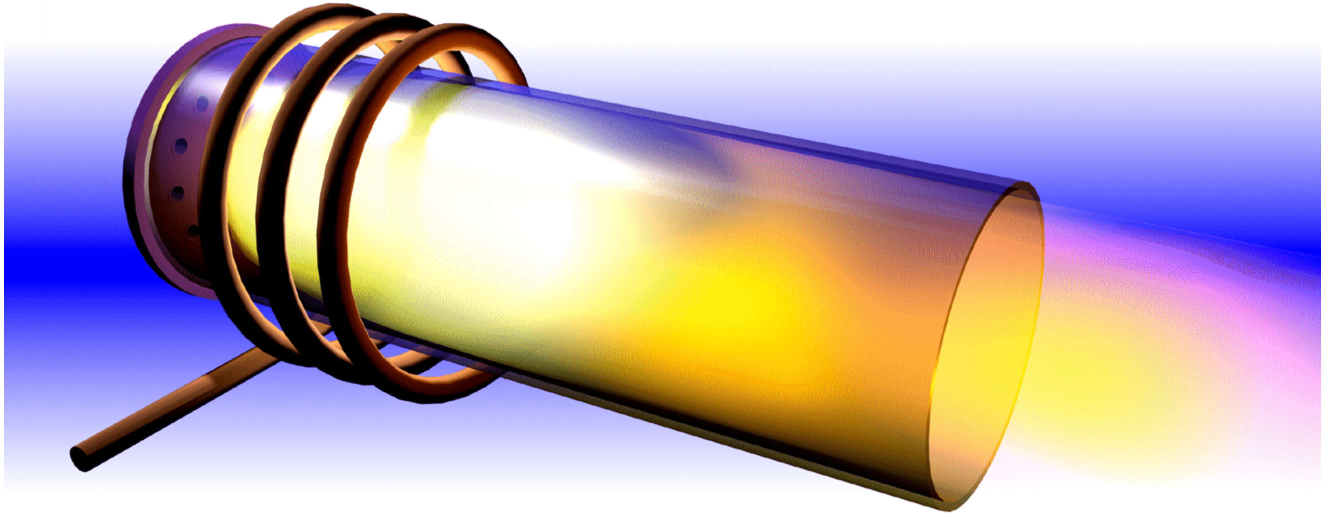
- Pressure:

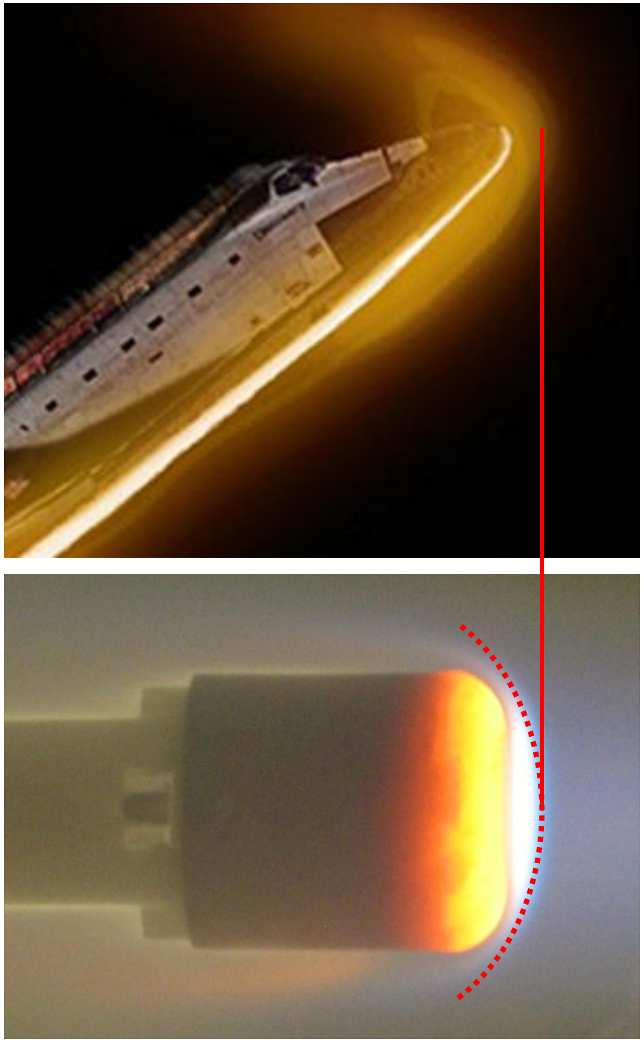
10 mbar - 200 mbar



The VKI Plasmatron Facility, contd.

How it works: electromagnetic induction





Local Heat Transfer Simulation (LHTS):

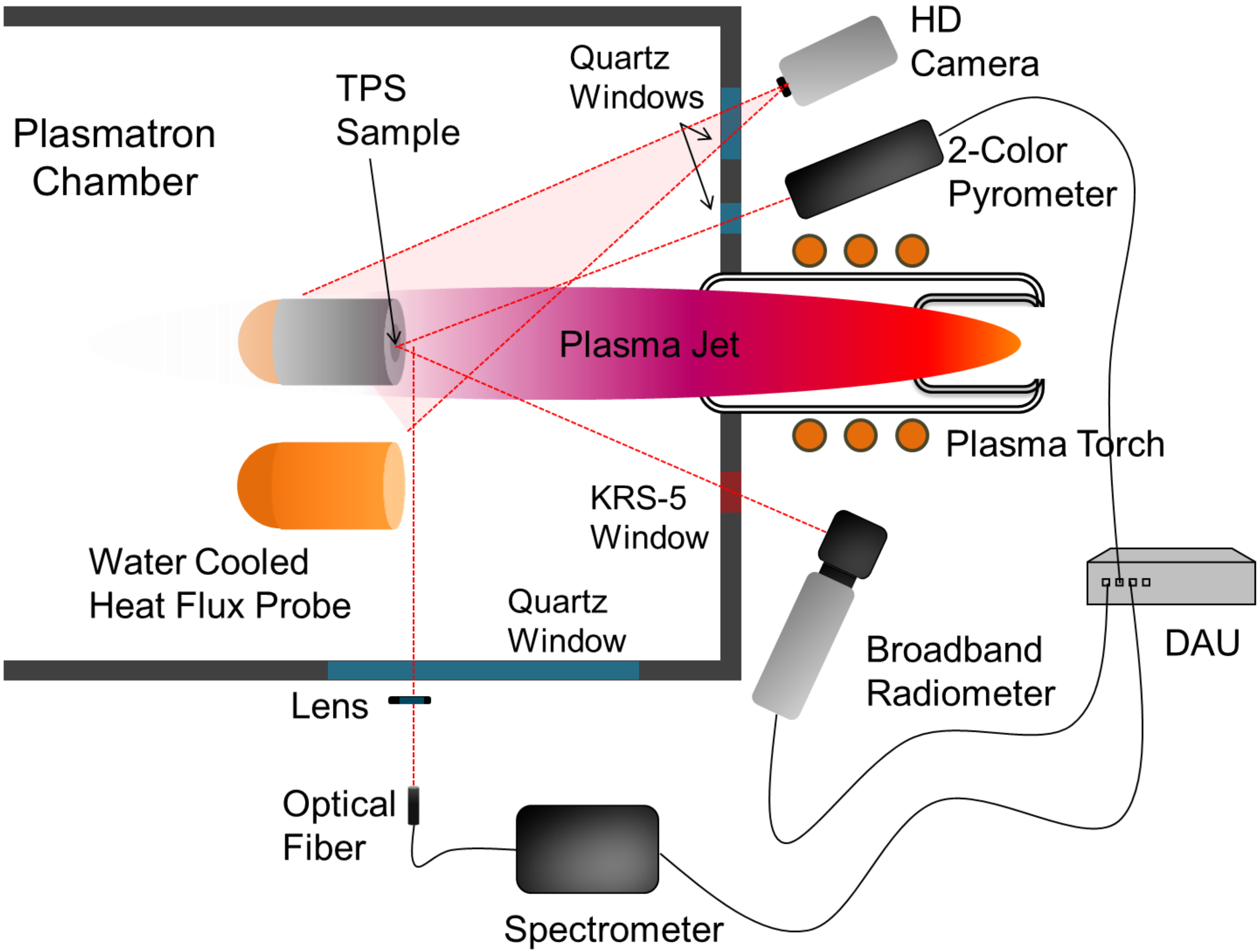
$$H_e^f = H_e^t \quad p_e^f = p_e^t \quad \beta_e^f = \beta_e^t$$

under thermochemical equilibrium

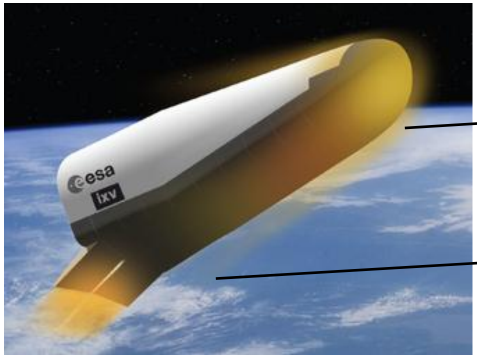
Kolesnikov, Fluid Dynamics 28 (1) (1993) 131-137

Barbante and Chazot, JTHT 20 (3) (2006) 493–499

Instrumentation

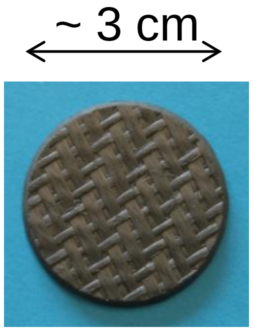


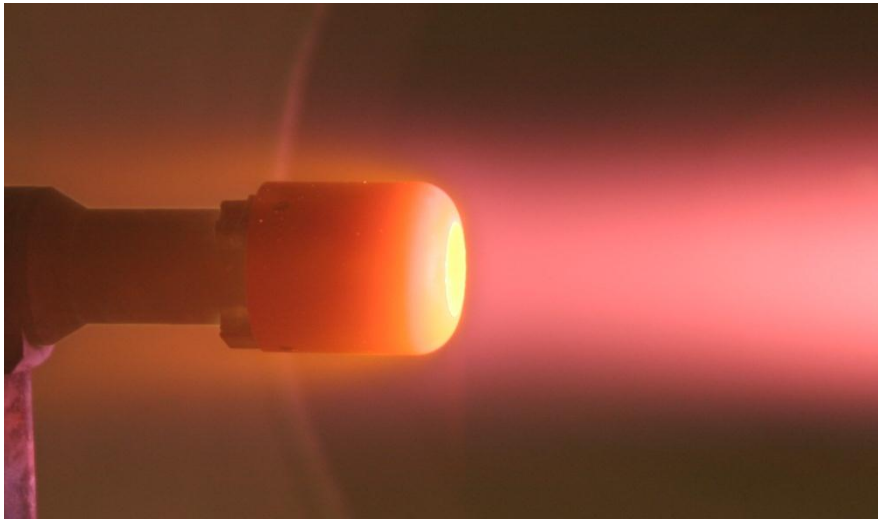
Plasmatron Experiments Overview

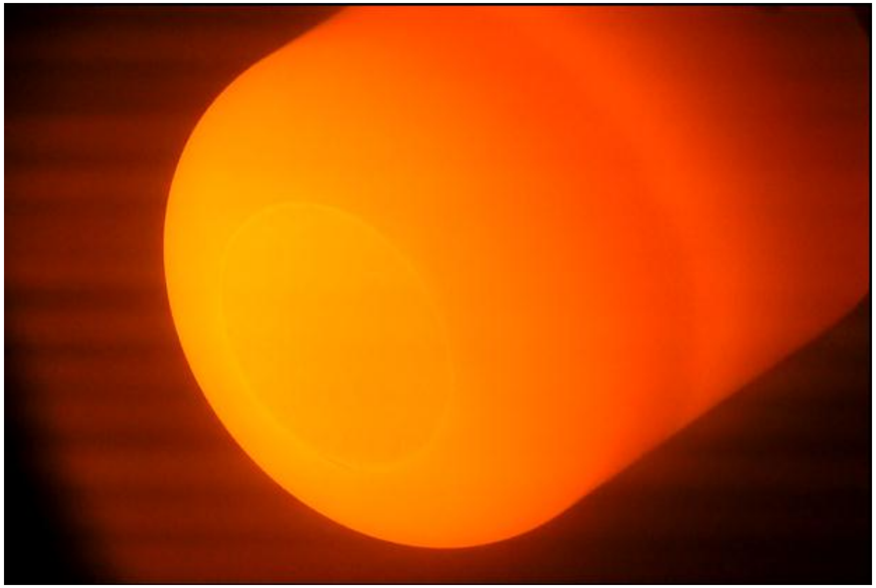


SPS C/SiC

MTA C/SiC







25 SPS C/SiC and 6 MTA C/SiC samples tested at different temperatures and pressures

Procedures:

- Sample exposure to plasma stream at target steady state conditions
- Sample ejection and flow calibration (heat flux and dynamic pressure measurements)

Test Conditions

Target conditions:

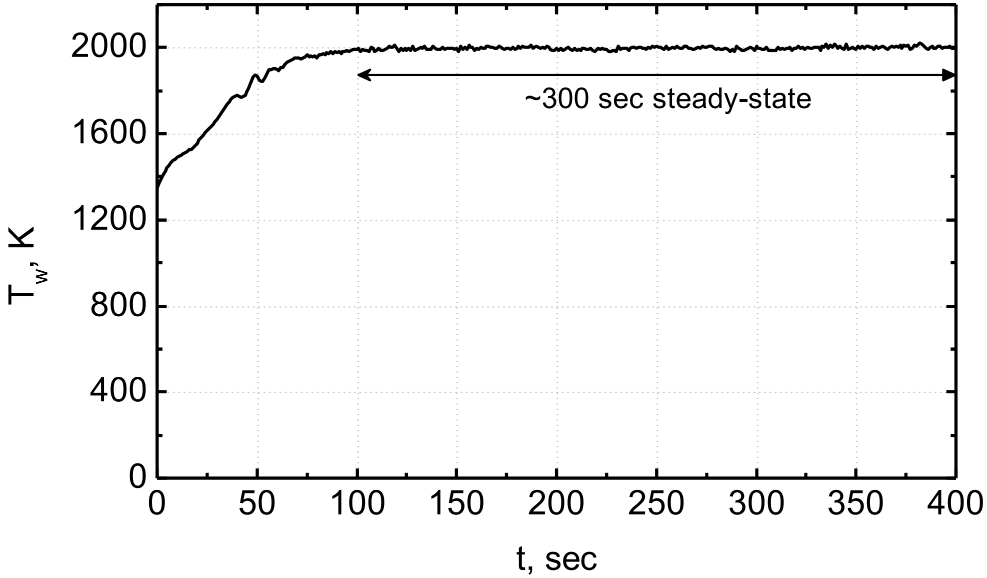
- Static pressure: 1300 – 5000 Pa
- Wall temperature: 1200 – 2000 K
- Test time: 300 sec at steady state

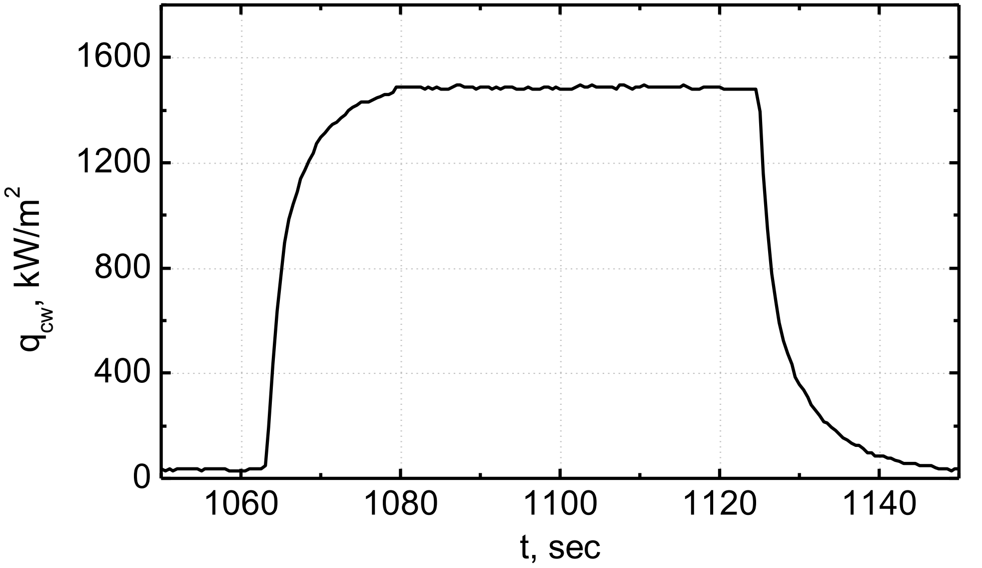
Flow Measurements:

- Cold wall heat flux: 160 – 1600 kW/m^2
- Dynamics pressure: 25 – 300 Pa

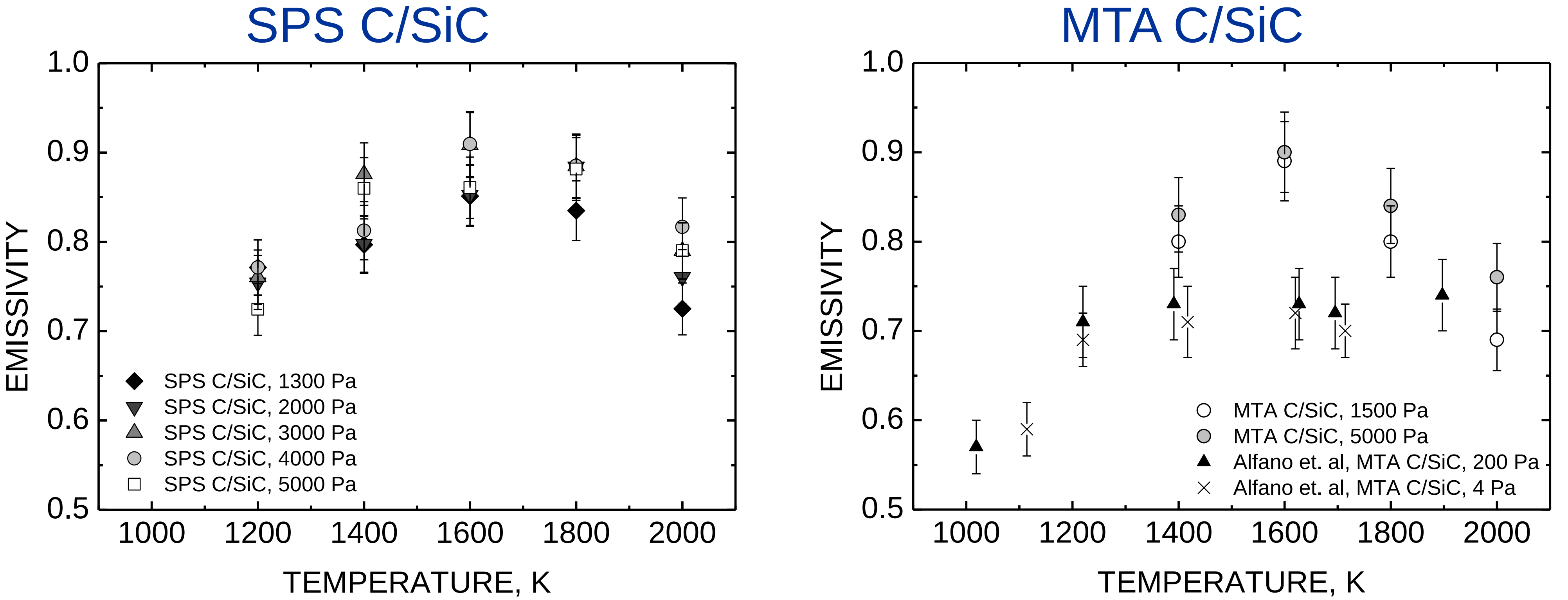
Rebuilding (BL edge conditions):

- Enthalpy: 5 – 35 MJ/kg
- Temperature: 3000 – 6000 K





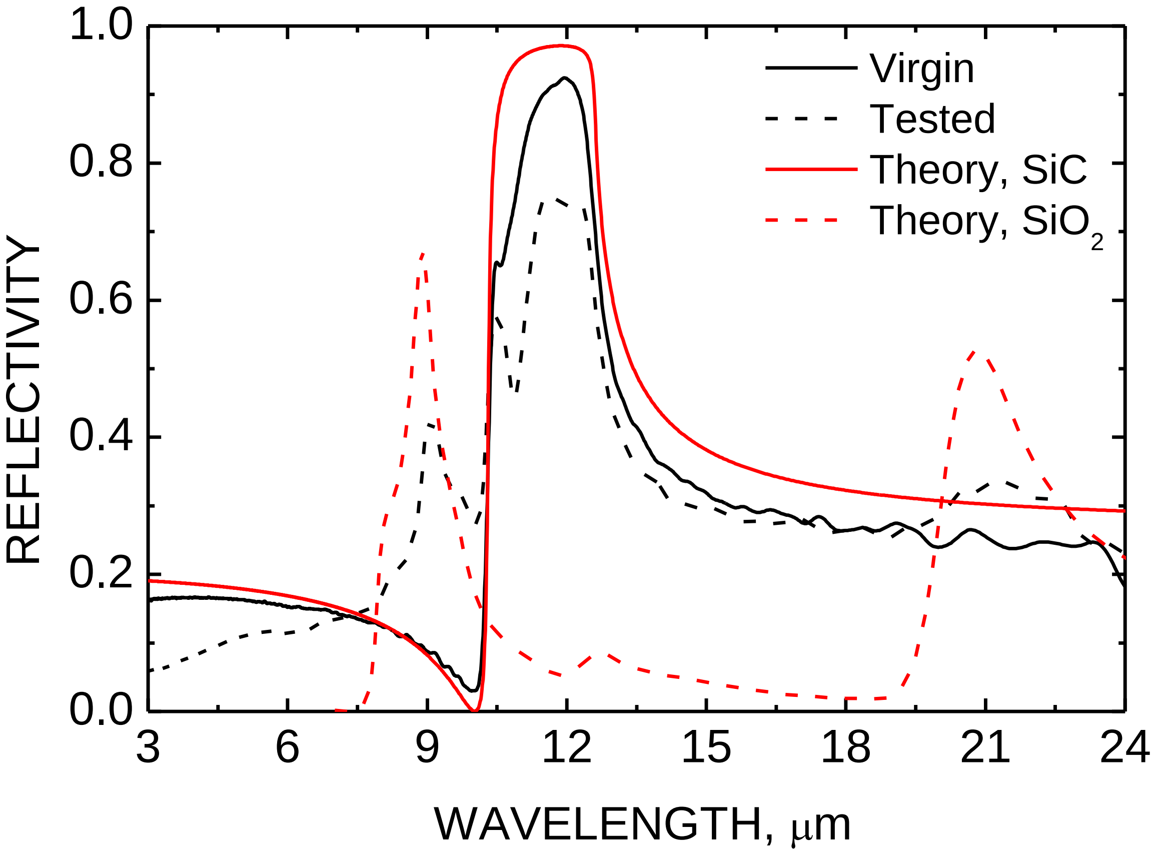
In-situ Emissivity Measurements



[Alfano et al., JECS, 29 (2009) 2045-2051]

- Good radiative behavior (ε > 0.7)
- Emissivity increases up to T_w=1600 K and decreases at higher T
- Good comparison with literature data

Room Temperature Reflectivity Measurements



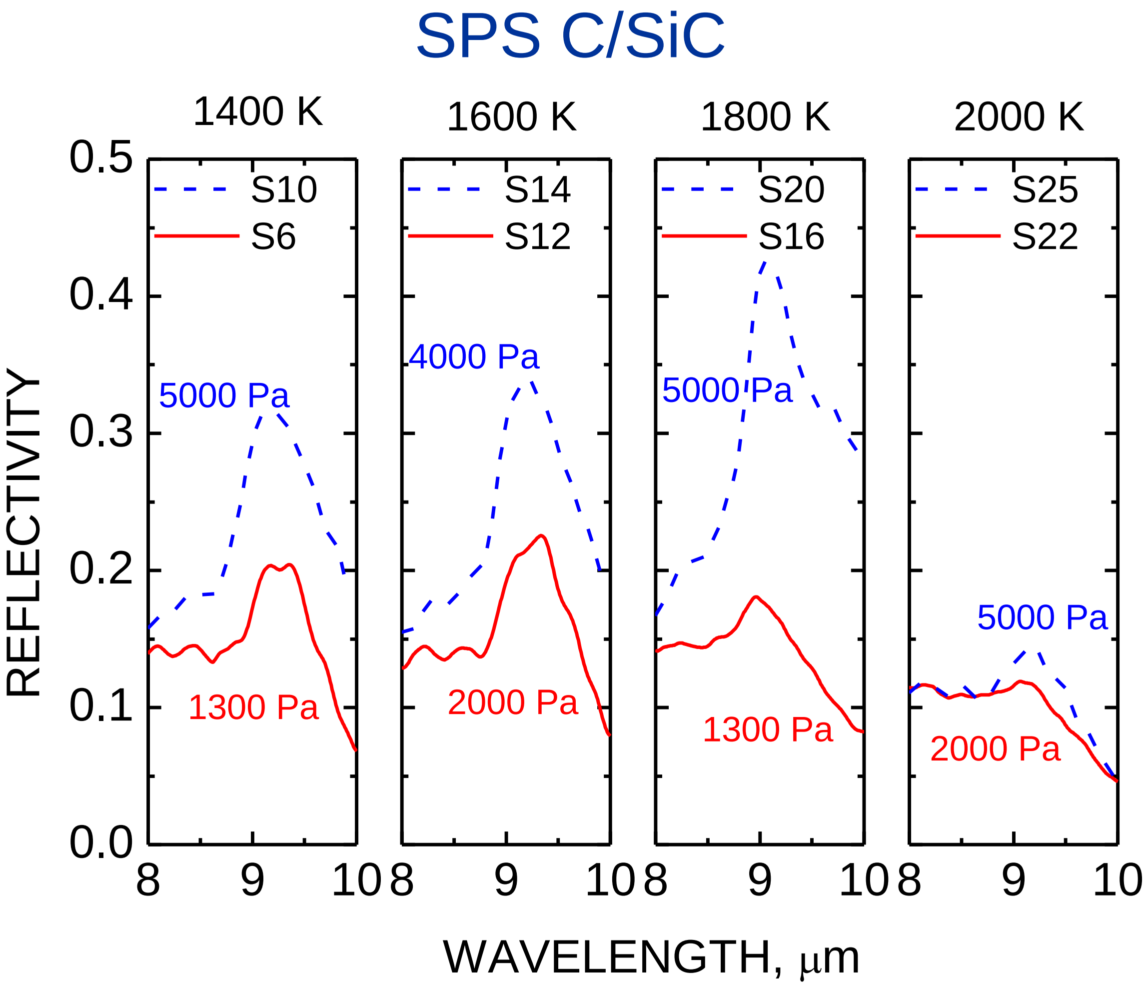
- Virgin specimens follow SiC global behavior
- SiO_2 features appear on the tested samples

Observed for SiC based UHTC *[Marschall et al., JTHT 23 (2009) 267-278]*

Relative strengths of the SiO_2 and SiC spectral features can be used as markers for passive/active oxidation of ceramics

[Marschall and Fletcher, JECS 30 (2010) 2323-2336]

Variation of the 9 µm SiO_2 Feature with P and T

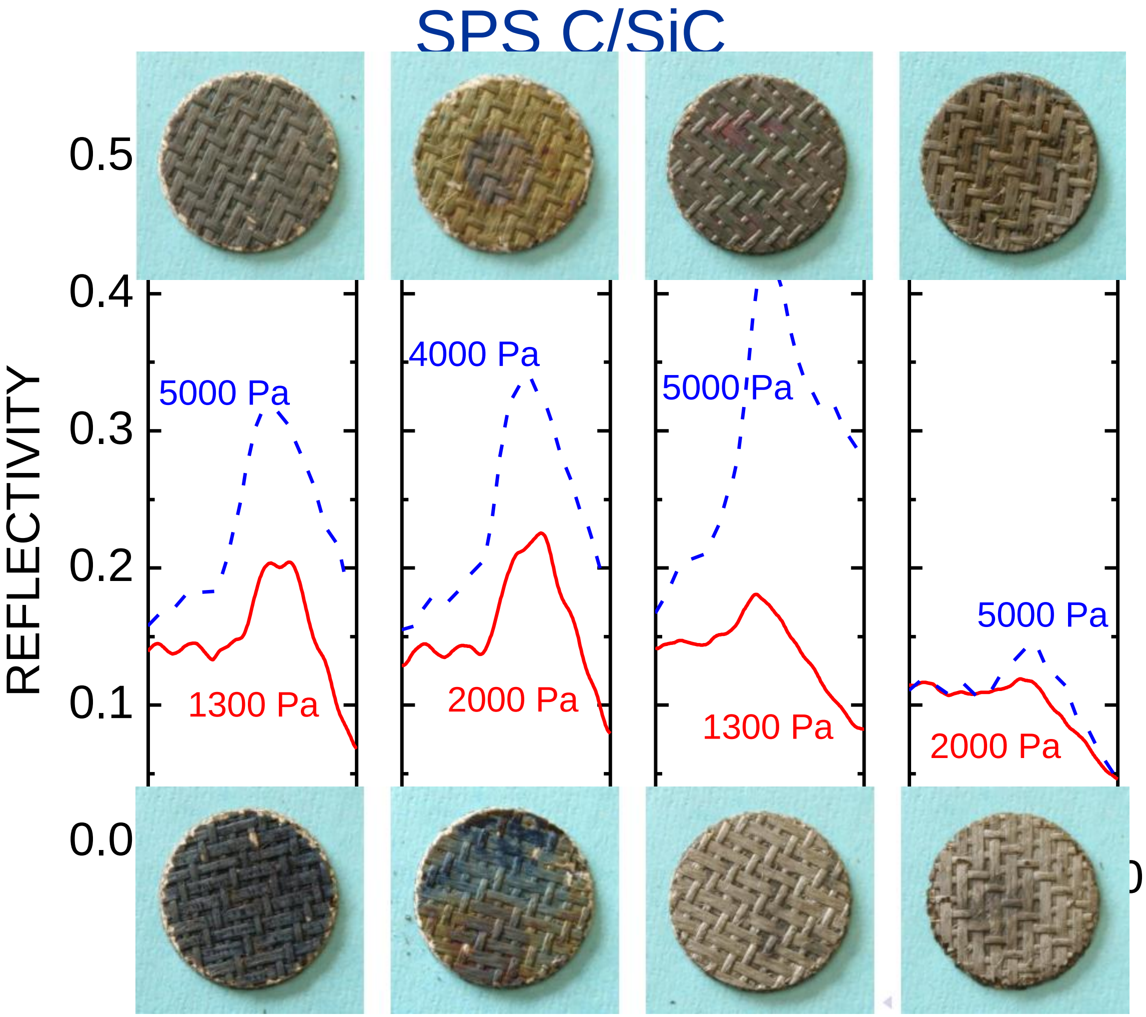


Passive ox. (formation of glassy silica): high P, low T
Active ox. (volatilization of silica): low P, high T

The 9 µm feature correlates the predicted oxidation behavior of a SiC surface:

- SiO_2 thickness increases with pressure and temperature up to 1800 K
- At 1800 K and low pressure SiO_2 starts to volatilize
- At 2000 K only few SiO_2 at high pressure

Variation of the 9 µm SiO_2 Feature with P and T



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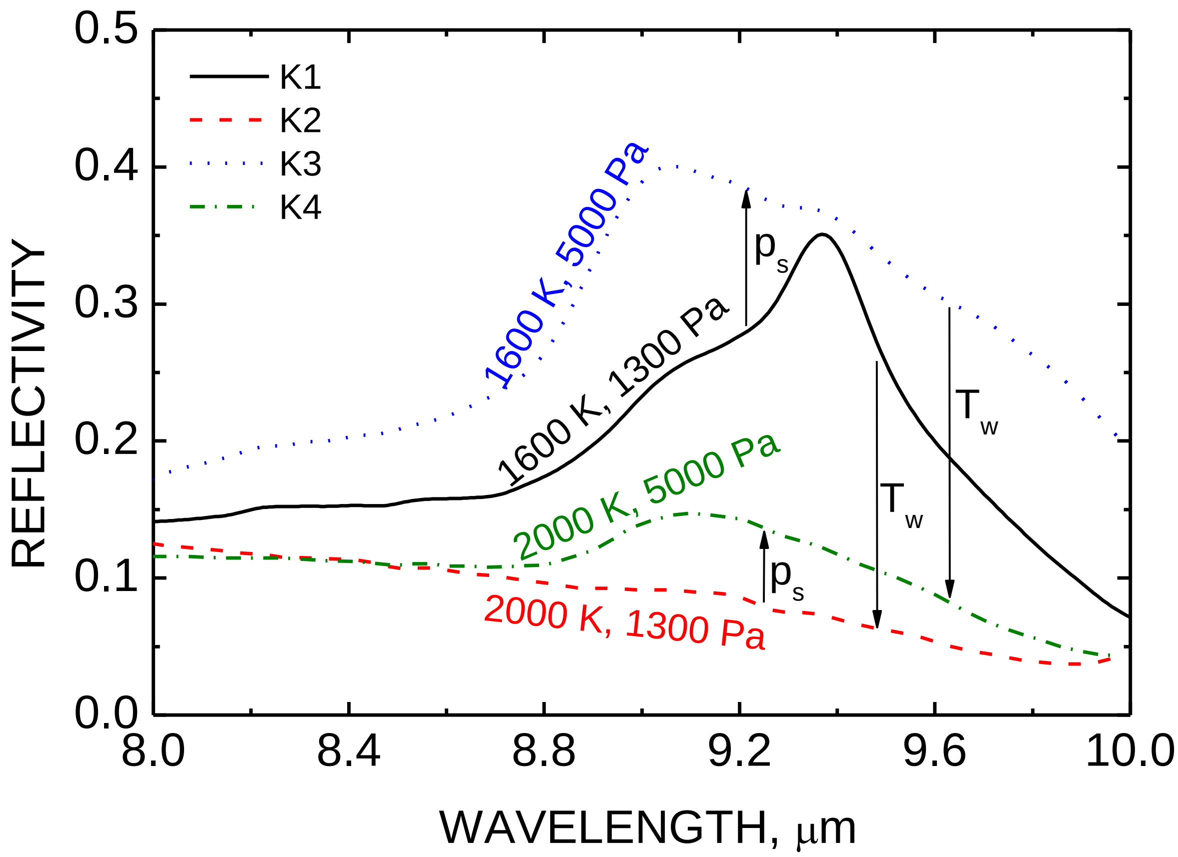
- At 2000 K only few SiO_2 at high pressure

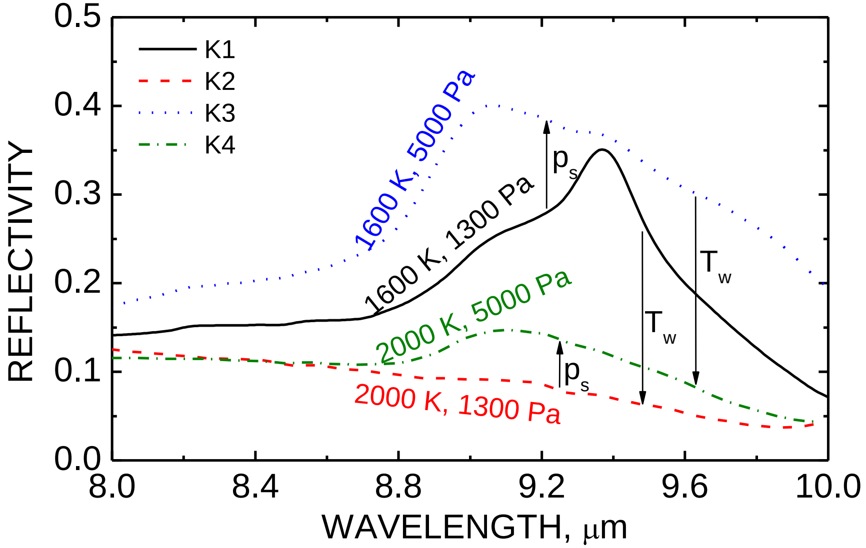
Variation of the 9 µm SiO_2 Feature with T and P, contd.

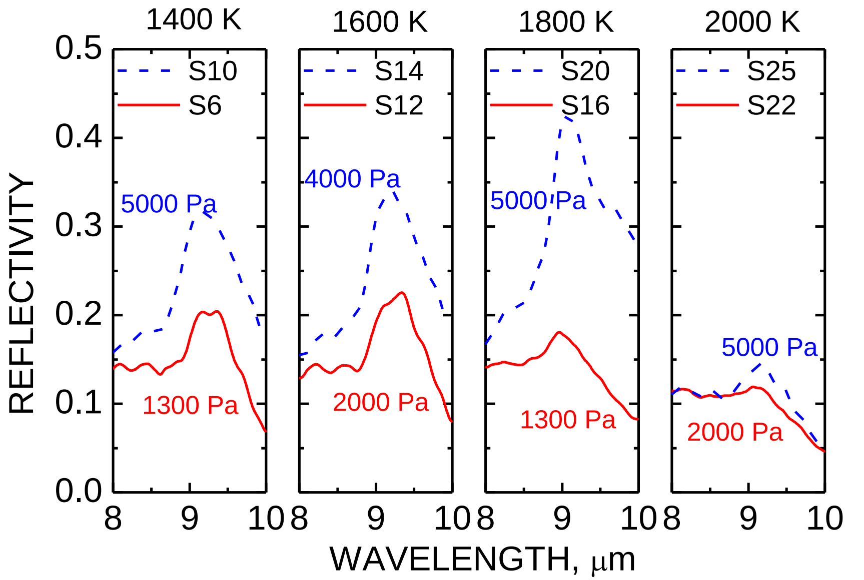
MTA C/SiC



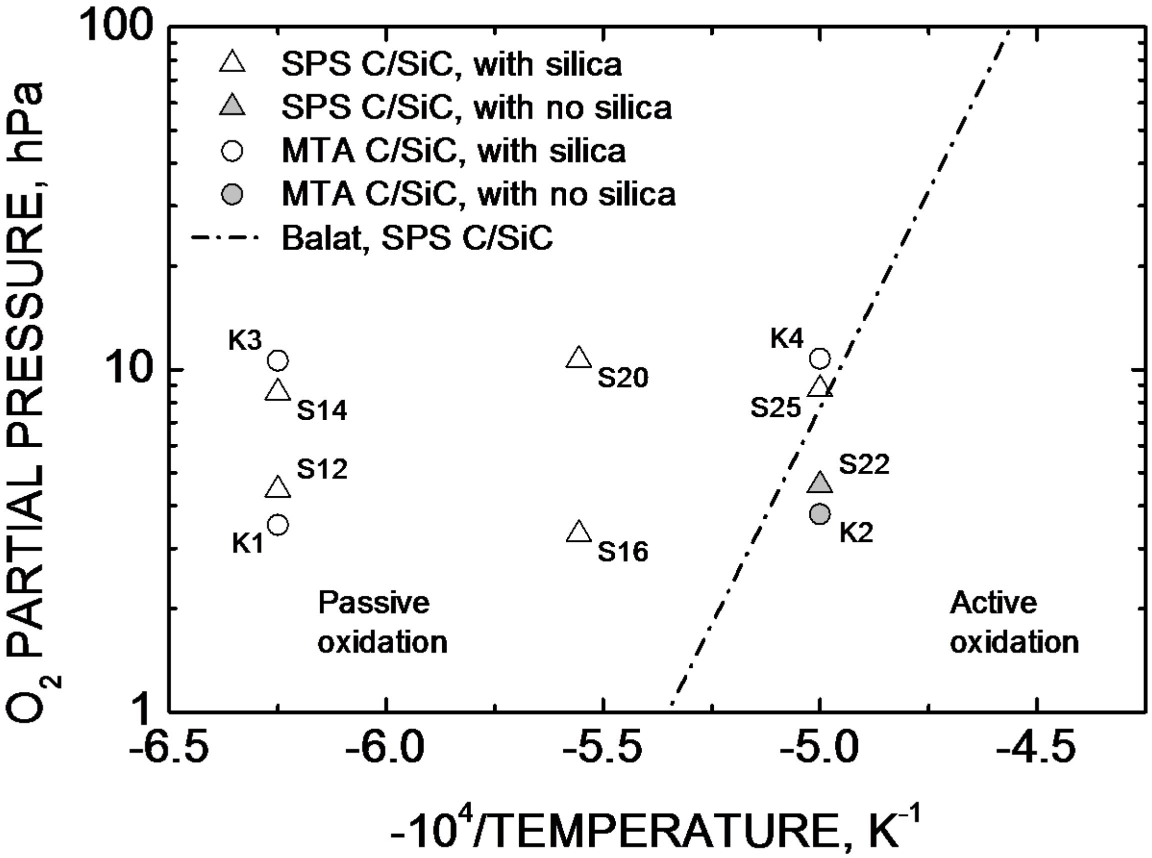
- SiO_2 features grow with decreasing temperature and increasing pressure

Passive/Active Oxidation Assessment



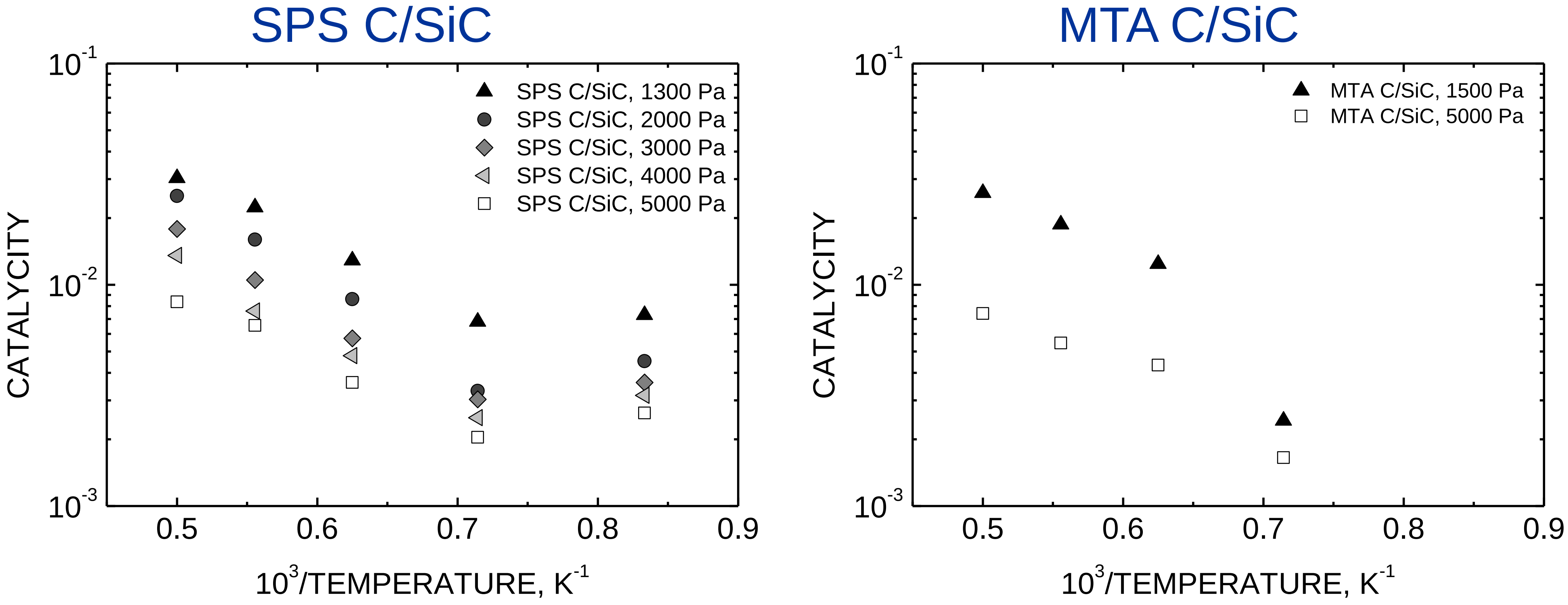


[Balat, JECS 16 (1996) 55-62]



- Plasmatron data agree with Balat PA oxidation transition law for SPS C/SiC

Catalycity Coefficients

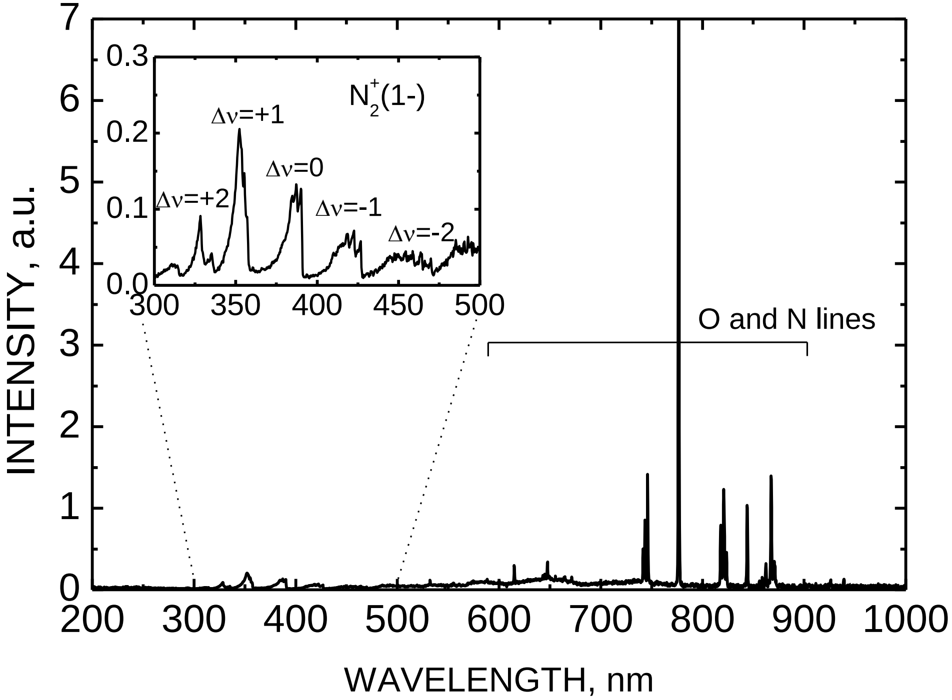


- Catalycity coefficients between 10^{-3} and 10^{-1}
- ~50% reduction with respect to the fully catalytic condition
- γ increases with in increasing surface temperature and decreasing pressure

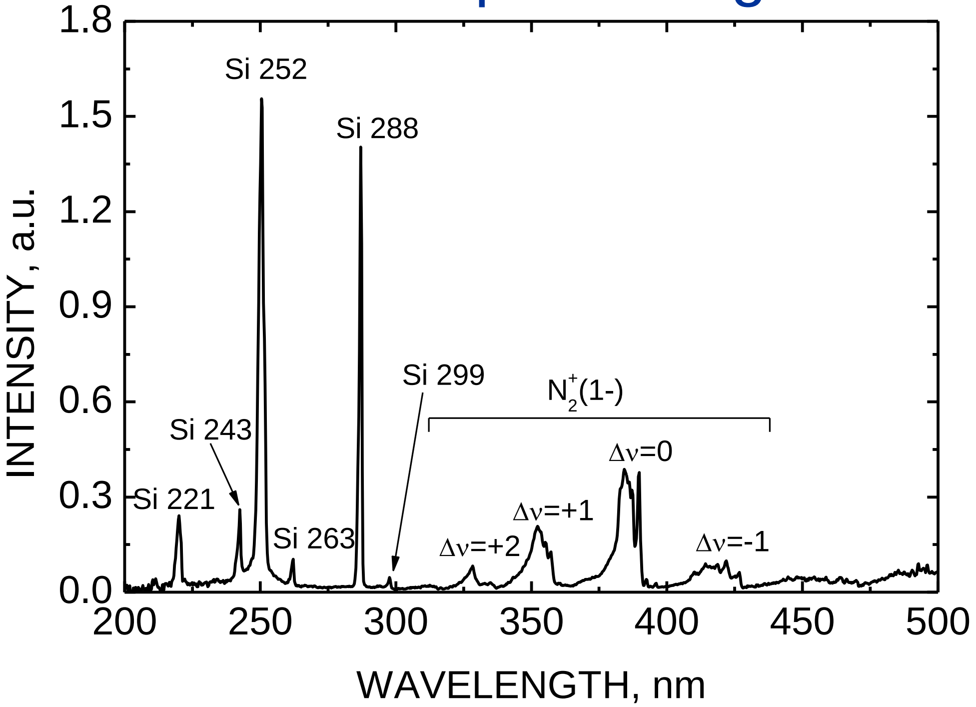
[Balat and Bêche., ASS. 256 (2010) 4906–4914]

Gas Phase Radiative Signature by OES

Freestream



C/SiC sample testing

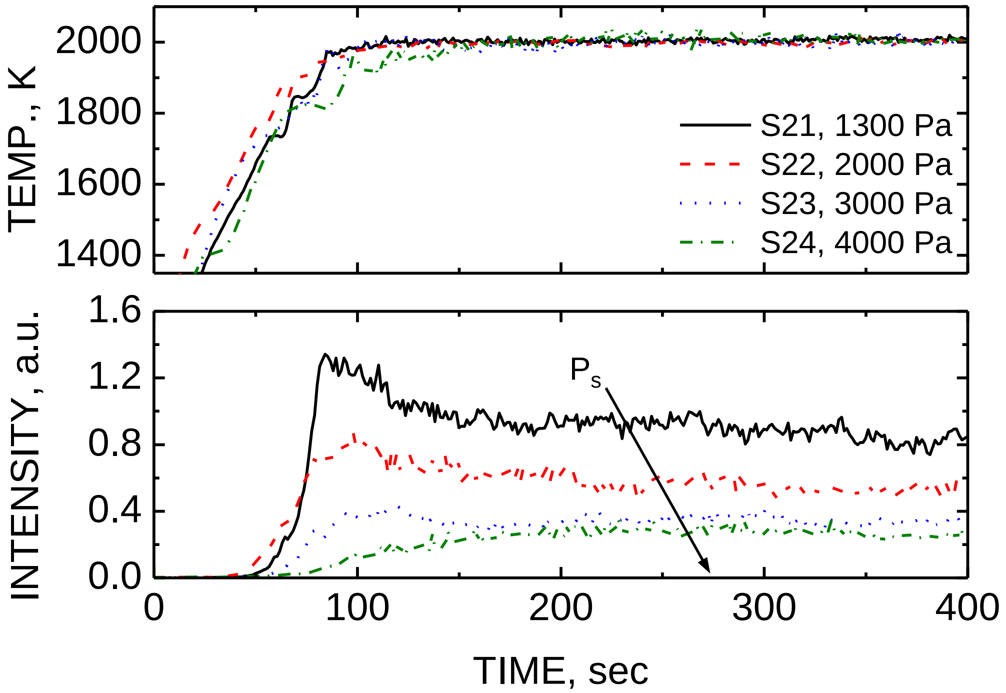


- Si emission appears during C/SiC testing
- Si at 252 and 288 nm observed by several authors
- Si as indicator of PAT (SiO_2 volatilization)

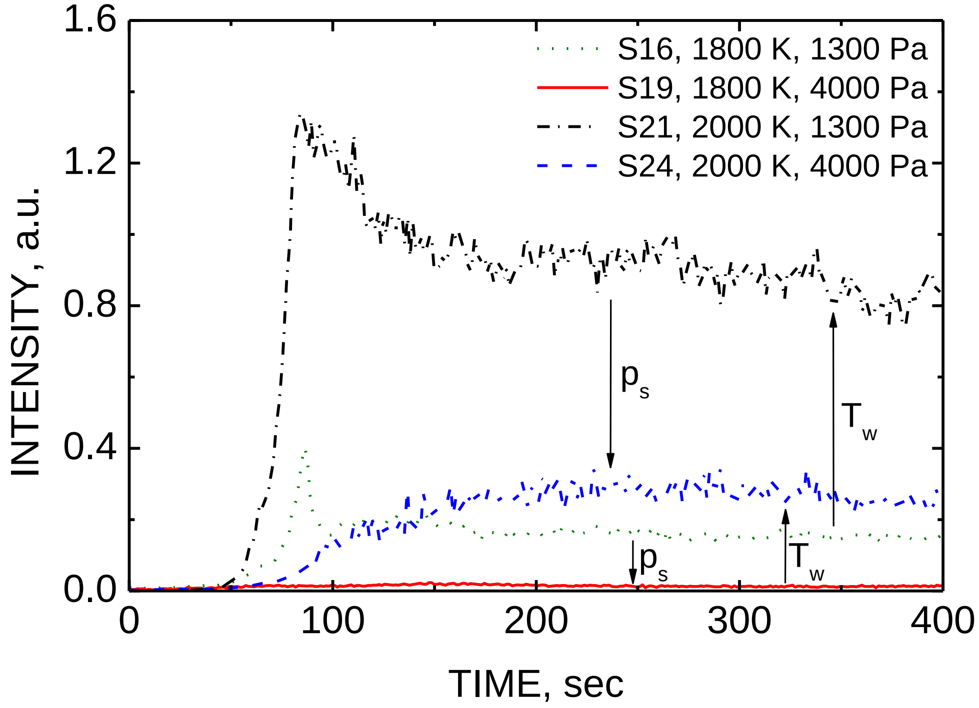
[Hirsch et al., HTHP. 31 (1999) 455–465]
[Altmann et.al., HTHP. 32 (2000) 573–579]
[Jentschke et al., RSI 70 (1999) 336–339]
[Herdrich et al., JSR, 42 (2005) 817–824.]

Si (λ=252 nm) Emission History

Pressure dependency



Pressure/temperature dependency



- Si emission correlates the passive/active oxidation behavior found by reflectivity measurements:

SiO$_2$ volatilization decreases with pressure and increases with temperature

Summary and Outlook

1. Characterization of the the catalytic, radiative and oxidation behavior of the IXV TPS materials
2. Silica features found on the reflectivity spectra of plasma exposed specimens
3. Silica features intensity varies with P and T according to the predicted passive/active oxidation behavior for SiC
4. Si emission in front of the test specimens well correlates the predicted SiO_2 volatilization due to oxidation

- Extrapolation to flight…
- Uncertainty quantification…
- Very high heat fluxes…
- GSI models validation benchmark

Thanks for your attention...

… questions?

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von Karman Institute for Fluid Dynamics

Thanks to:

DASSAULT AVIATION

SAFRAN
Snecma Propulsion Solide

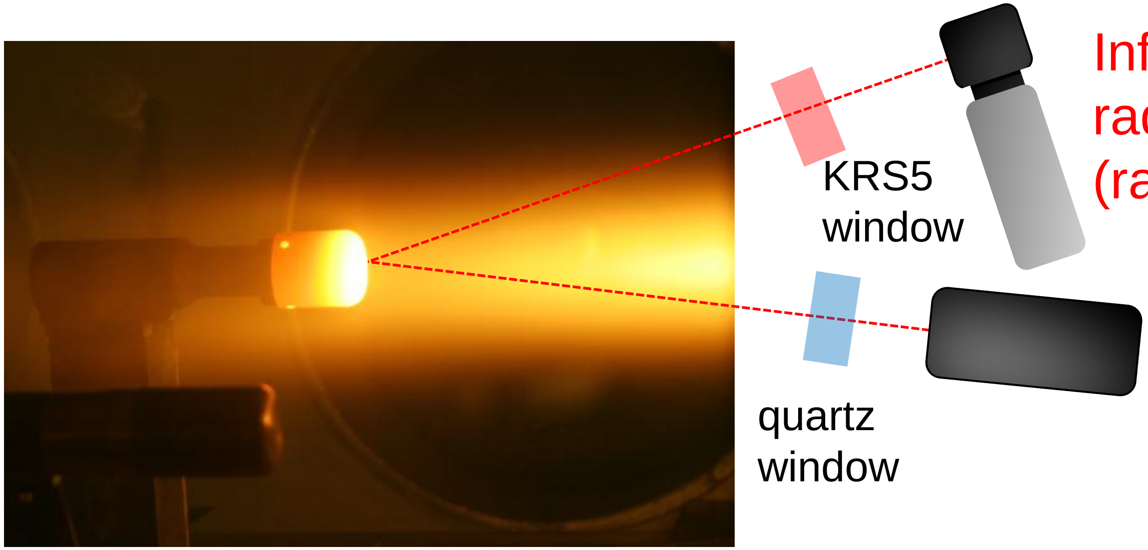
MT AEROSPACE
An OHB Company

ThalesAlenia Space
A Thales / Finmeccanica Company

esa

Emissivity Measurement Techniques

In-situ measurements



Infrared broadband radiometer (radiance)

$$\varepsilon'_{0.6-39\mu m} = \frac{L'_{0.6-39\mu m}}{L^{0}_{0.6-39\mu m}}$$

2-color pyrometer (temperature)

Room temperature measurements*

$r(\lambda)$ is measured by:

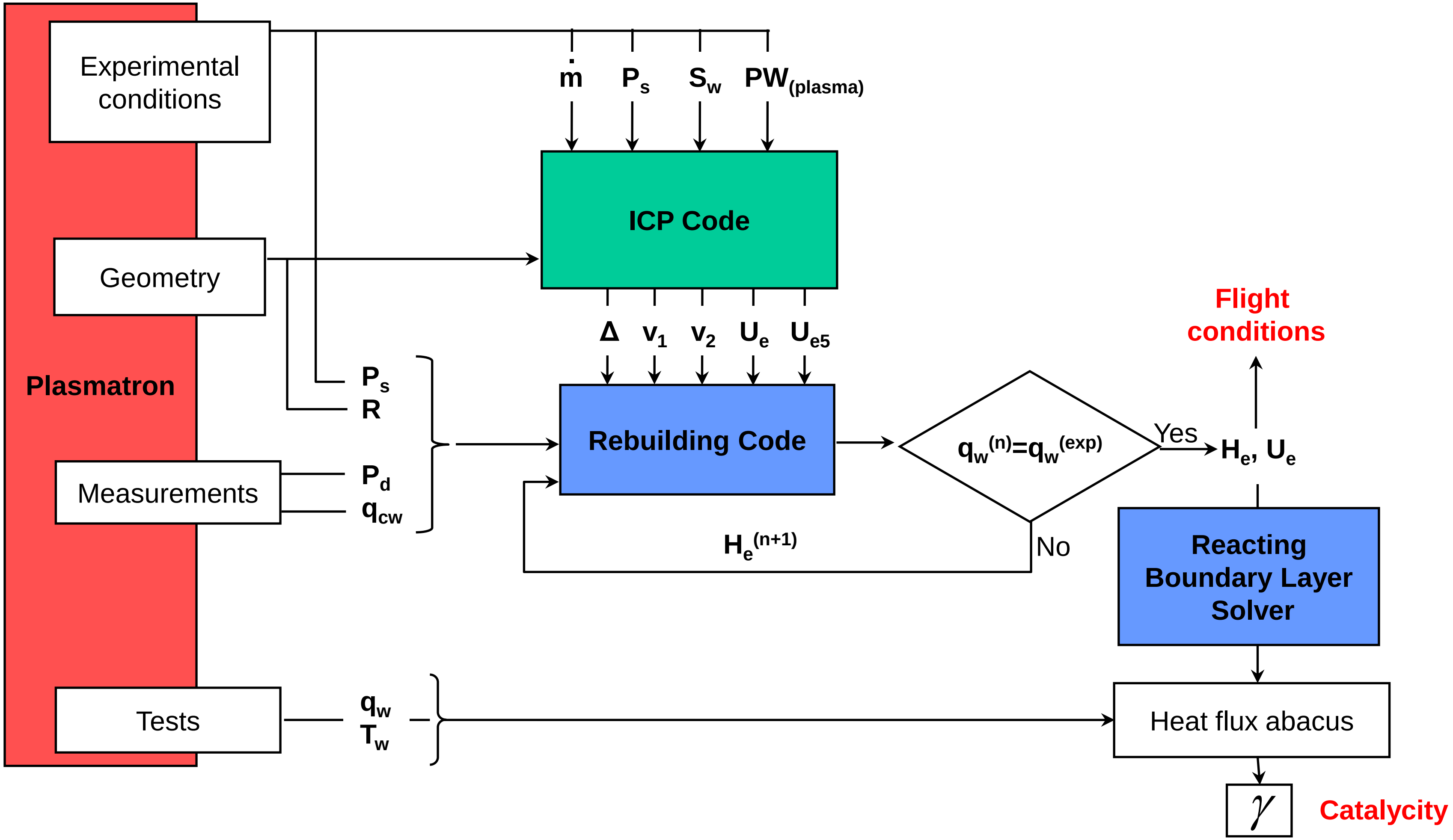
MIR spectrometer (2.1 μm – 40 μm)

UV/VIS/NIR spectrometer (0.25 μm – 2.5 μm)

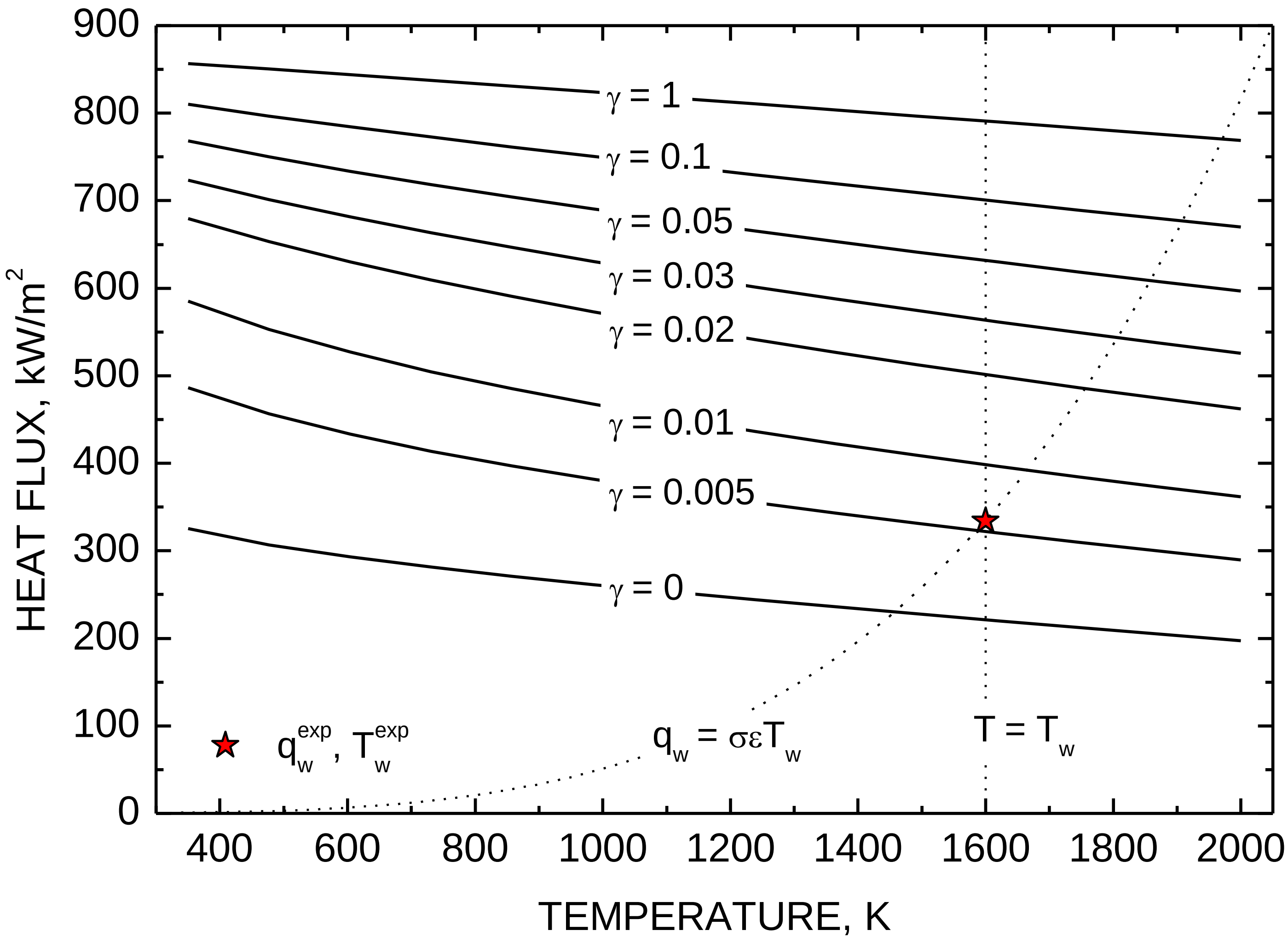
$$\varepsilon(T) = \frac{\int_{0.25\mu m}^{40\mu m} (1 - r(\lambda)) E(\lambda, T) d\lambda}{\int_{0.25\mu m}^{40\mu m} E(\lambda, T) d\lambda}$$

*performed at ESA ESTEC, Noordwijk, The Netherlands

Catalycity Determination Procedure



Catalycity Determination Procedure, contd.



We Determine an Effective, Apparent Catalycity

Effective catalycity:

$$\gamma_{eff} = \gamma\beta$$

where:

$\beta = \frac{q_{rec}}{D}$	Energy accommodation coefficient
$\gamma = \frac{M_r}{M_\downarrow}$	Recombination efficiency

Apparent catalycity:

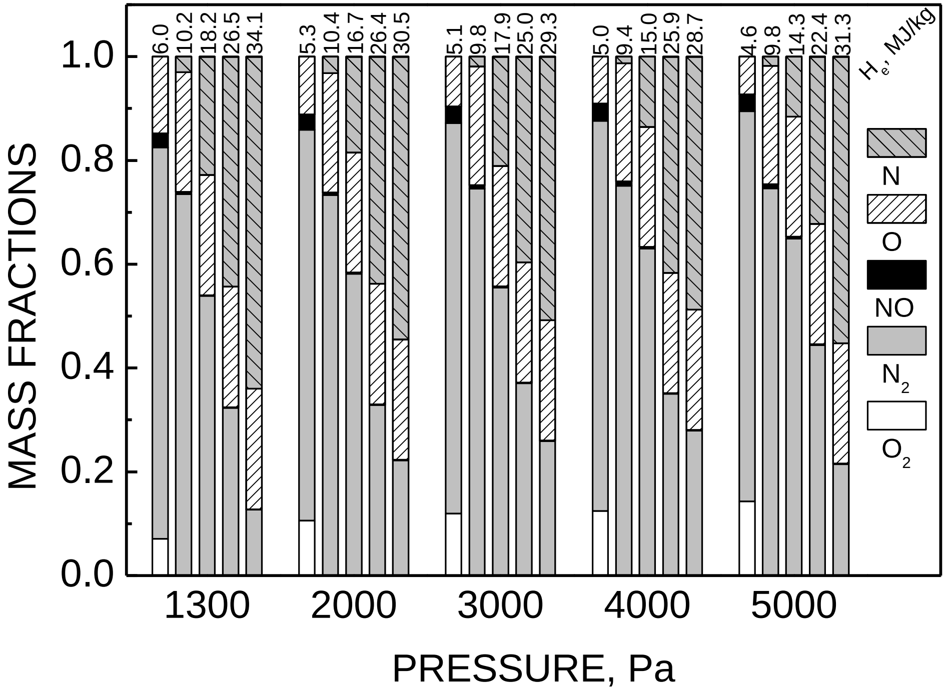
$$\gamma_{app} = \frac{S_{wet}}{S_{geom}} \gamma_{intrinsic}$$

where:

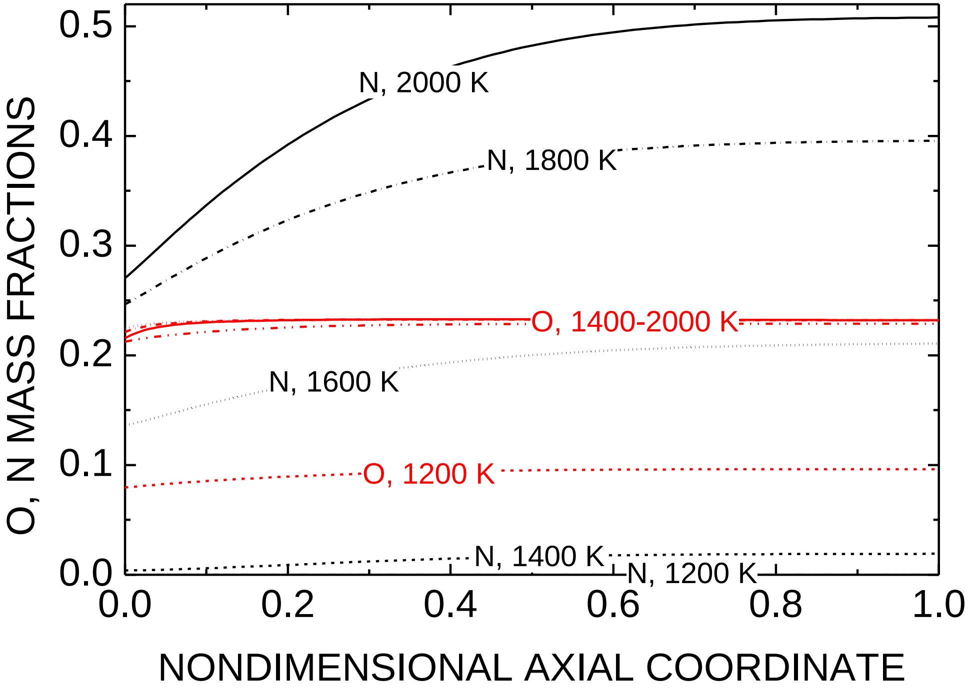
$\frac{S_{wet}}{S_{geom}}$	Roughness
$\gamma_{intrinsic}$	True catalycity

Boundary Layer Rebuilding

Edge mass fractions



Stagnation line species at 3000 Pa



Extrapolation to Flight

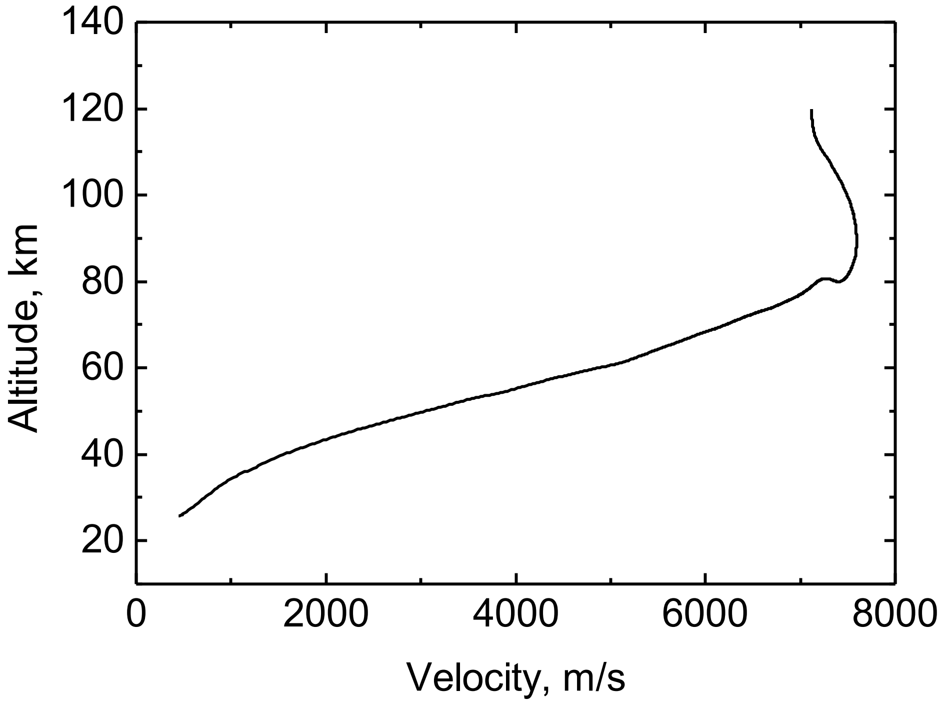
LHTS is valid if:

$$H_e^f = H_e^t \longrightarrow \cancel{h_\infty^f} + \frac{1}{2}V_\infty^{f\,2} = H_e^t$$

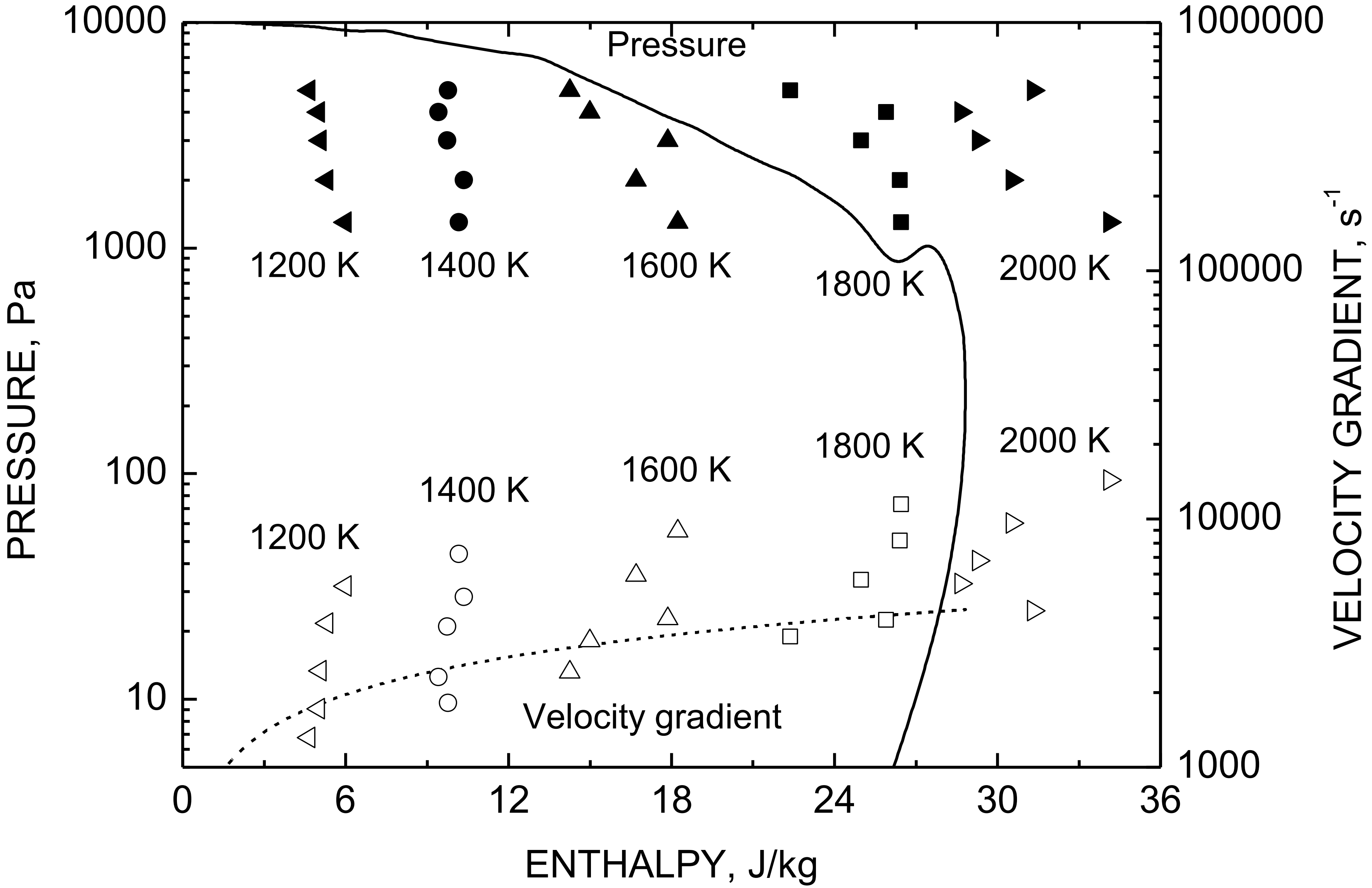
$$p_e^f = p_e^t \longrightarrow \cancel{p_\infty^f} + \rho_\infty V_\infty^{f\,2} = p_e^t$$

$$\beta_e^f = \beta_e^t \longrightarrow \frac{1}{R}\sqrt{\frac{2(p_e - p_\infty)}{\rho_e}} = \beta_e^t$$

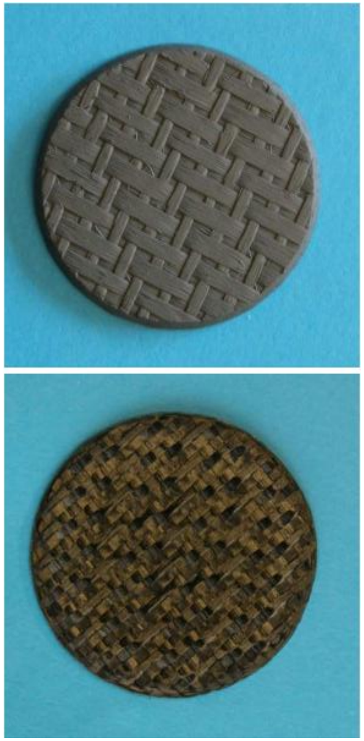
IXV flight trajectory

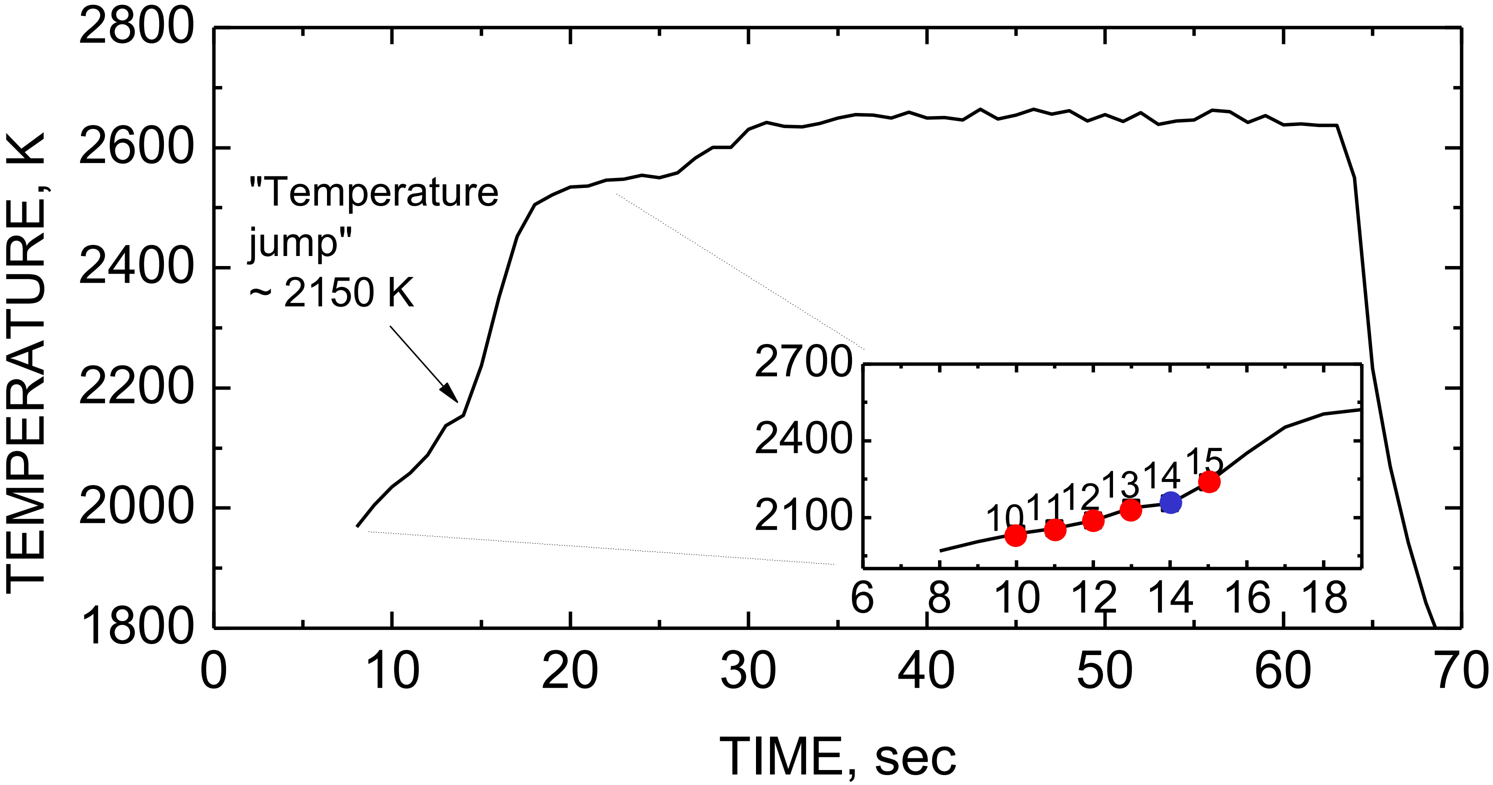


Extrapolation to Flight, contd.

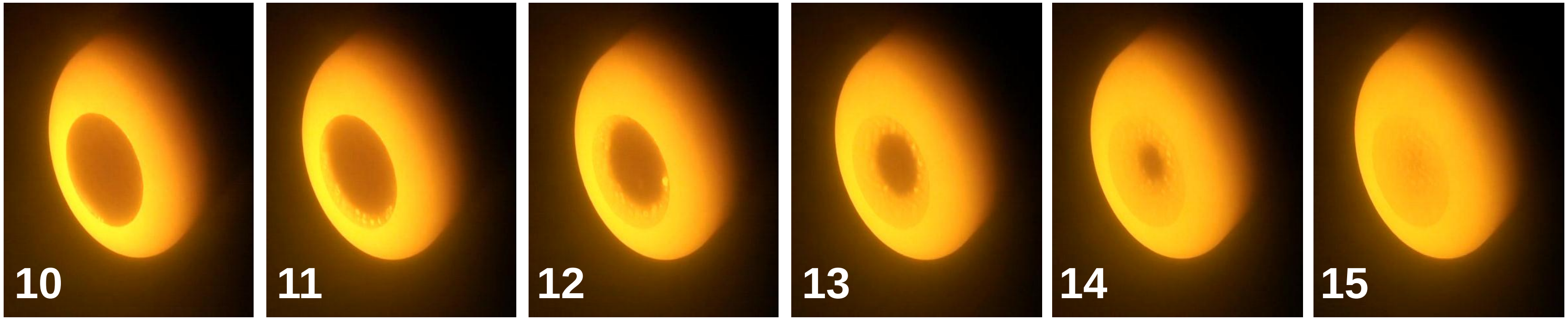


1.8 MW/m^2 Heat Flux Test





[Herdrich et al., JSR, 42 (2005) 817–824.]



1.8 MW/m^2 Heat Flux Test - Gas Phase Radiative Signature