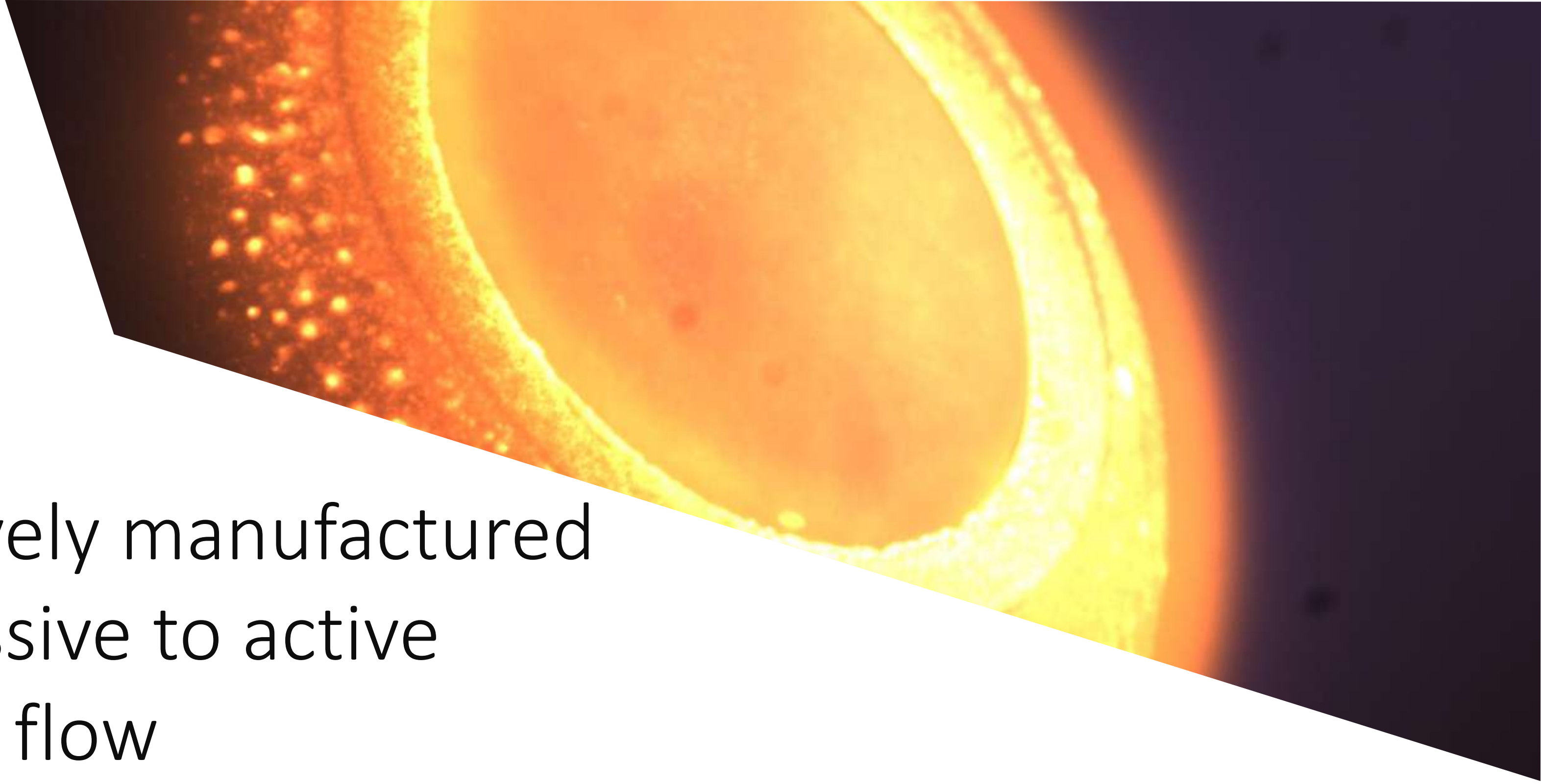

Testimony presentation

Characterization of additively manufactured ceramic composite for passive to active oxidation in high-enthalpy flow

Dr. B. Helber, Dr. J. El Rassi, Prof. T. E. Magin, (VKI)

Dr. S. Meyers, Prof. B. Van Hooreweder, Prof. J. Vleugels (KUL)

Cooperative agreement
Number W911NF-21-2-0228.

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DEVCOM

Acknowledgements

VKI research team

Alan Viladegut
Joseph El Rassi
Pierre Schrooyen
Sander Holum
Thierry Magin
Olivier Chazot

Funding

U.S. Army *material characterization* grant
A. Napier, K. Risko, P. Sparks

Visiting Scientist Program, U.S. Army
J. Brame, A. Napier, K. Risko, P. Sparks

AFOSR *Plasmut* grant
I. Leyva, D. Smith

Background and award initiative

First contact through AFOSR PLASMUT grant
Program officer: Dr. Douglas R. Smith
Aeronautical Sciences (AFOSR/EOARD)

AMETEE workshop (A. Napier, International Programs Lead DEVCOM)
(Advanced Materials & Enabling Technologies for Extreme Environments)

U.S. Army DEVCOM grant

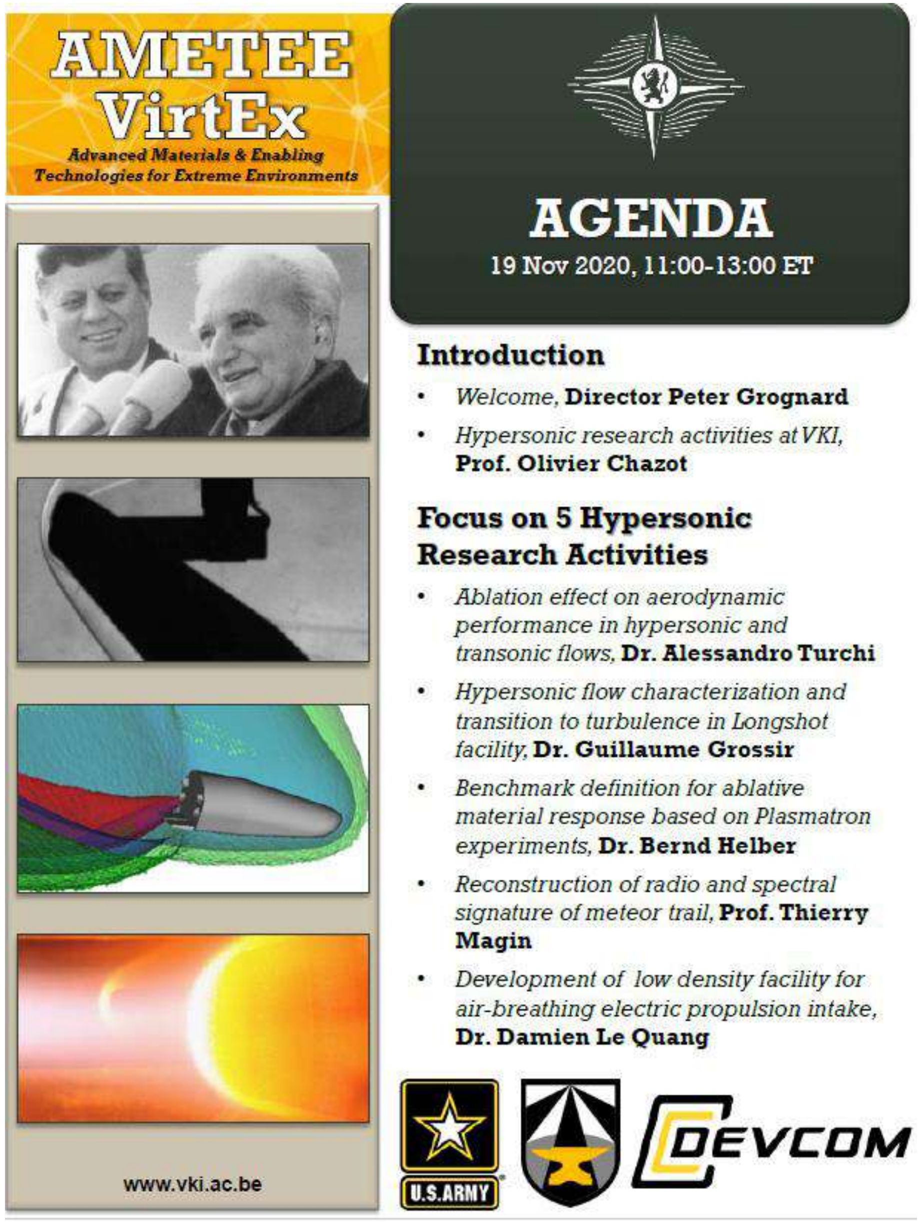
Ceramic-Matrix-Composite high-enthalpy characterization testing in the VKI Plasmatron

Aug 2021 – Aug 2024

Two site visits and presentations through Visiting Scientist Program (VSP):

2022 Aviation Missile Center (AvMC, Huntsville)

2023 Army Research Laboratory (ARL, Aberdeen Proving Ground)



von Karman Institute for Fluid Dynamics

Founded in 1956, renamed in 1963

Non-profit international educational and scientific organization

Experimental and numerical R&D

Three departments:

- Aeronautics and Aerospace
- Environmental and applied fluid dynamics
- Turbomachinery & propulsion

Staff, Post-Doc, PhD, bachelor/master thesis, internship

EDUCATION

Training in Research through Active Research

RESEARCH AND CONSULTING

LECTURE SERIES

Aeronautics and Aerospace Department

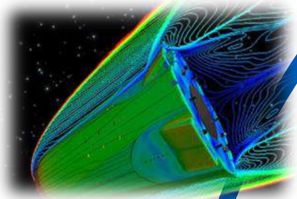
Research expertise groups at VKI

Rarefied and Plasma flows

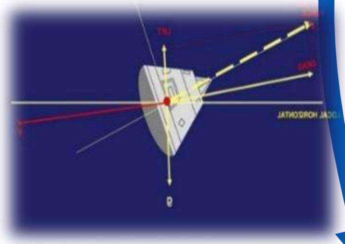
- TPS characterization
- Space debris demise
- Multi-physics modelling
- Non-equilibrium flows
- Uncertainty Quantification

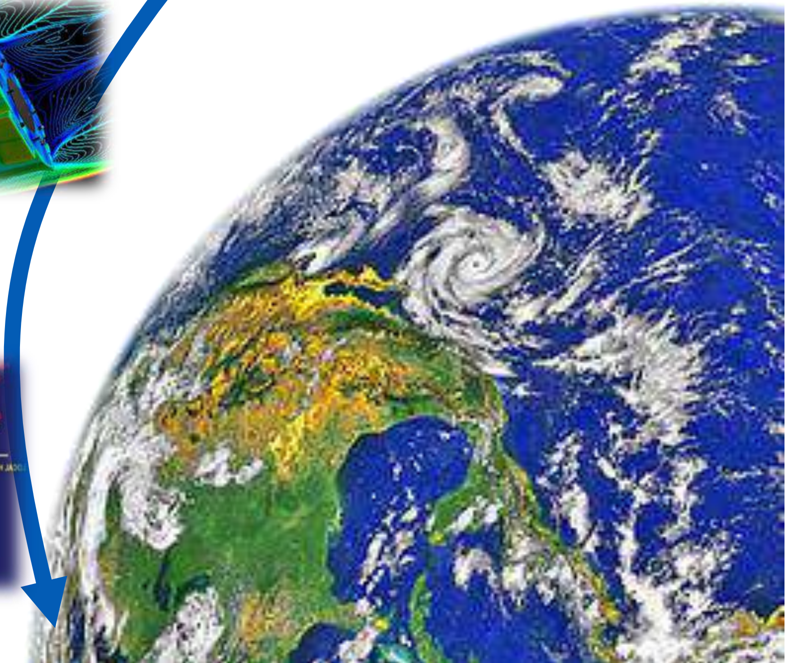
Aerothermochemistry

Aerothermodynamics



Aeronautics & Aerodynamics

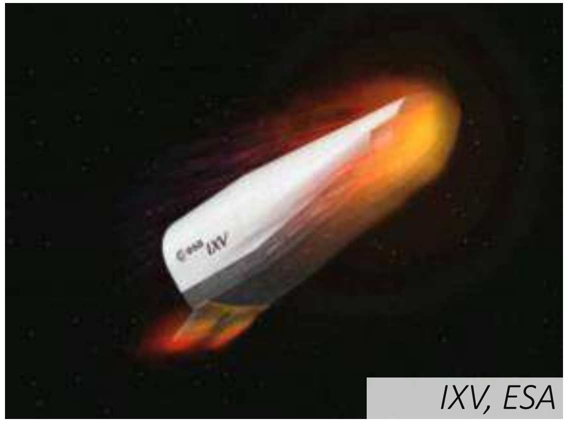




Aeronautics and Aerospace Department

Aerothermochemistry research expertise group

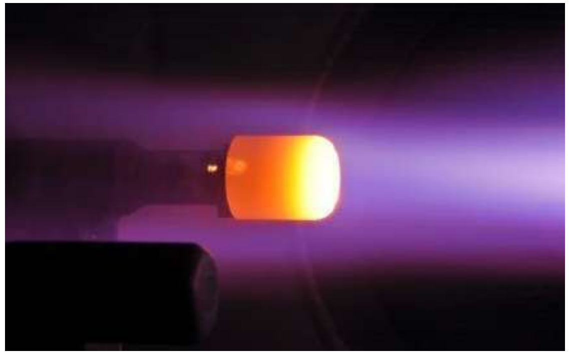
Reusable	Ablative	ETC	Demise

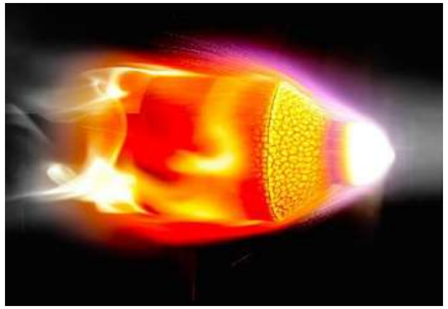

IXV, ESA

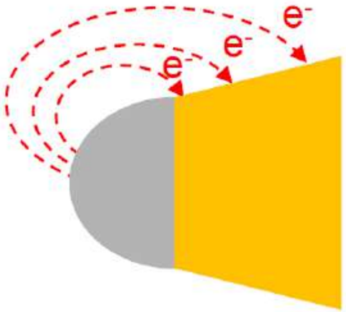

ARD, ESA


HTV-2, DARPA

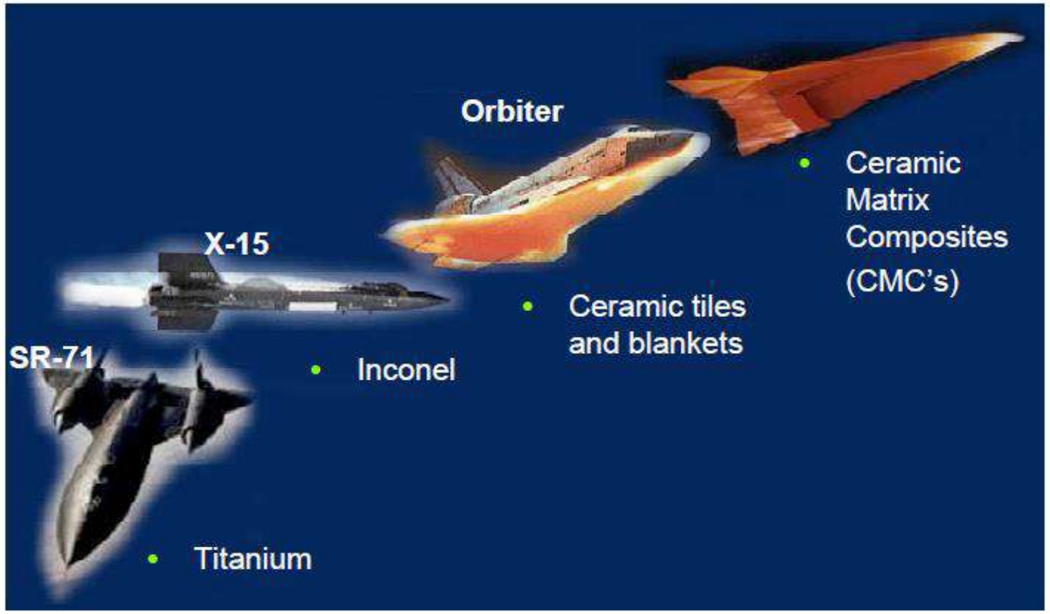

Virgili 2017

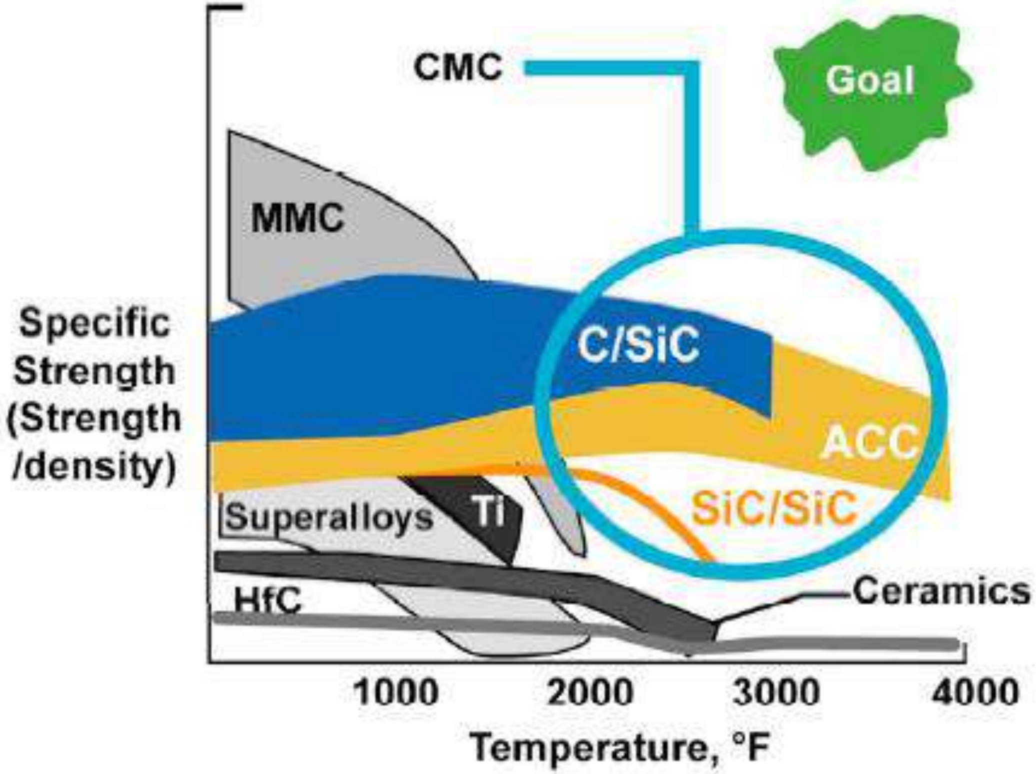






Future challenges for thermal structures on hypersonic glide and cruise vehicles



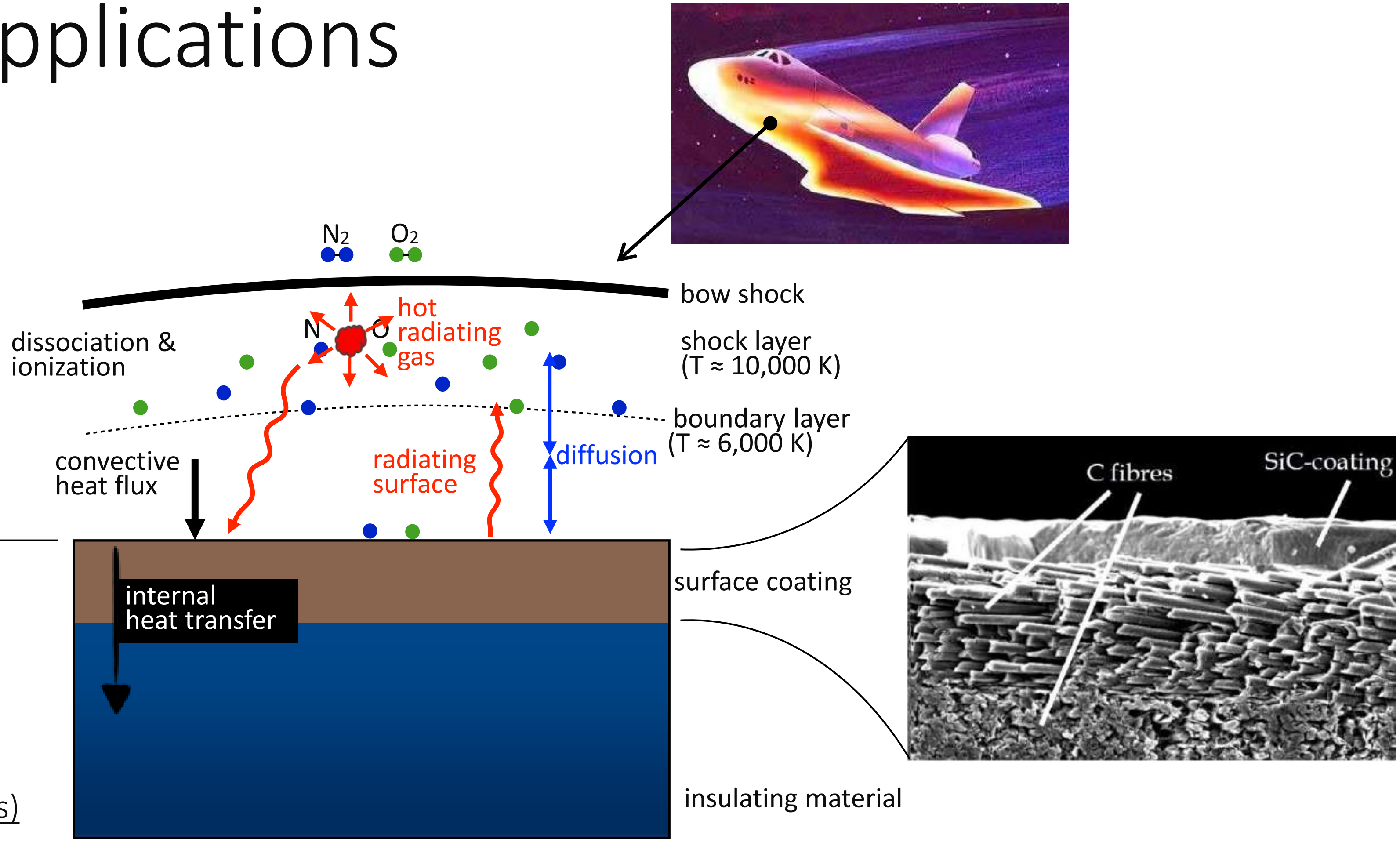


Thermo-structural challenges

New material systems have helped enable new vehicles

Requirements: high strength, high temperature, light weight, durability etc.

Background: Oxidation of ceramics for high temperature applications



Gas-surface interaction

<u>passive oxidation</u> (desired)

$SiC_{(s)} + 3O \rightarrow SiO_{2(s)} + CO$

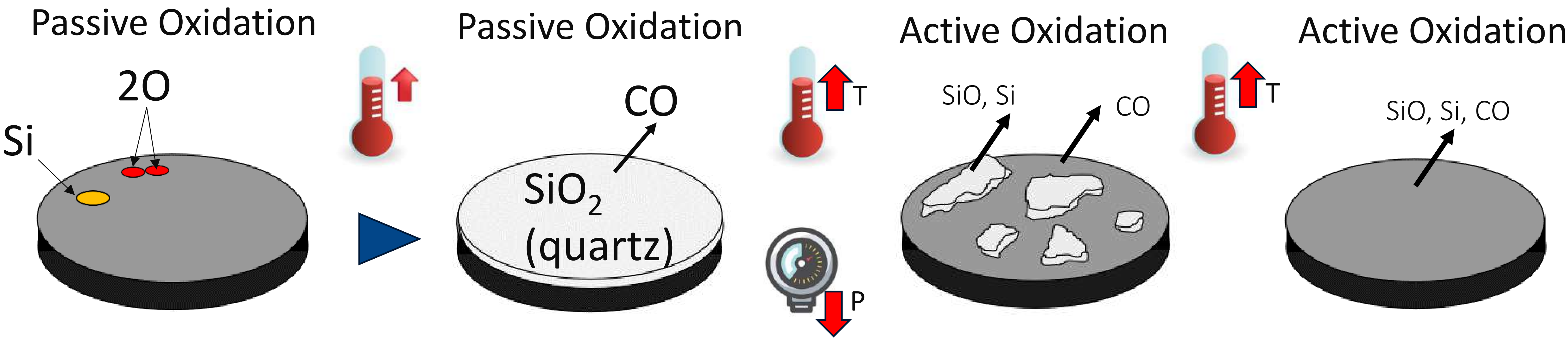
<u>active oxidation</u> (destruction)

$SiO_{2(s)} + O \rightarrow SiO + O_2$
$SiC_{(s)} + 2O \rightarrow SiO + CO$

<u>Catalysis (recombination reactions)</u>

$O + O \rightarrow O_2$ + heat
$N + N \rightarrow N_2$ + heat
$N + O \rightarrow NO$ + heat

Background: Oxidation of ceramics for high temperature applications



Passive oxidation (desired)

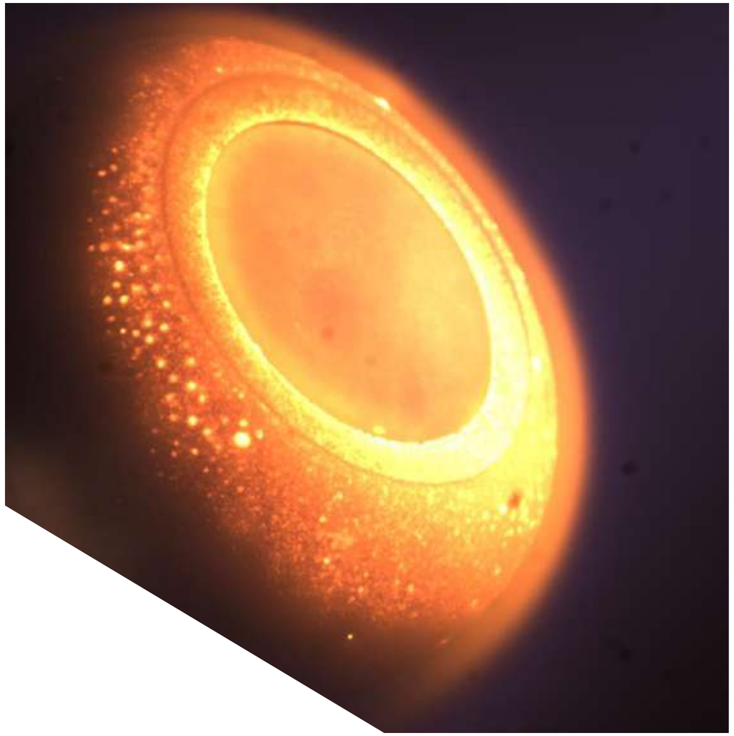
$SiC(s) + 3O \rightarrow SiO_2(s) + CO$

Active oxidation (destruction)

$SiO_2(s) + O \rightarrow SiO + O_2$

$SiC(s) + 2O \rightarrow SiO + CO$

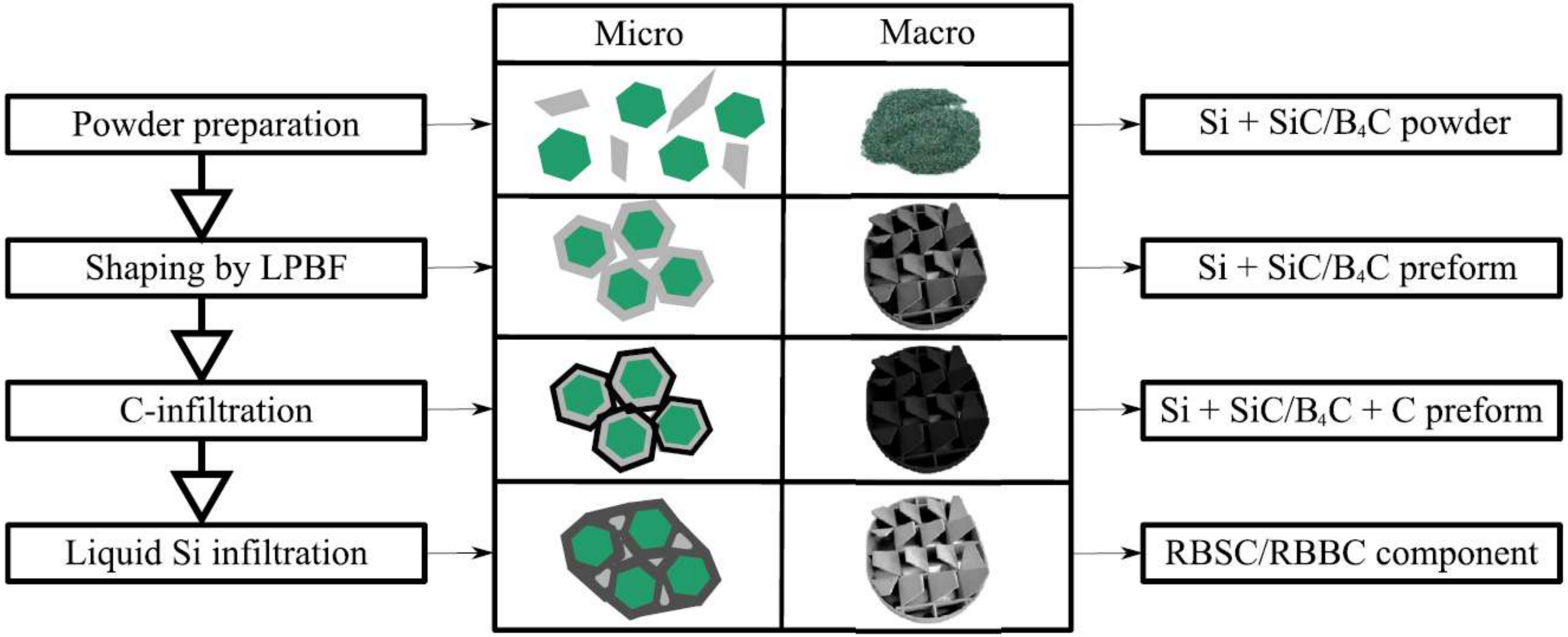
Objectives and motivation



Material response characterization of additively manufactured ceramics in passively and actively oxidizing atmosphere

Laser Powder Bed Fusion technique for additive manufacturing of silicon-carbide ceramics

Katholieke Universiteit Leuven (KU Leuven)



Gyroid heat sink
*design courtesy of Michel Smet

Meyers, S., et al. "Laser powder bed fusion as a net-shaping method for reaction bonded SiC and B4C." Virtual and Physical Prototyping 17.4 (2022): 854-863.

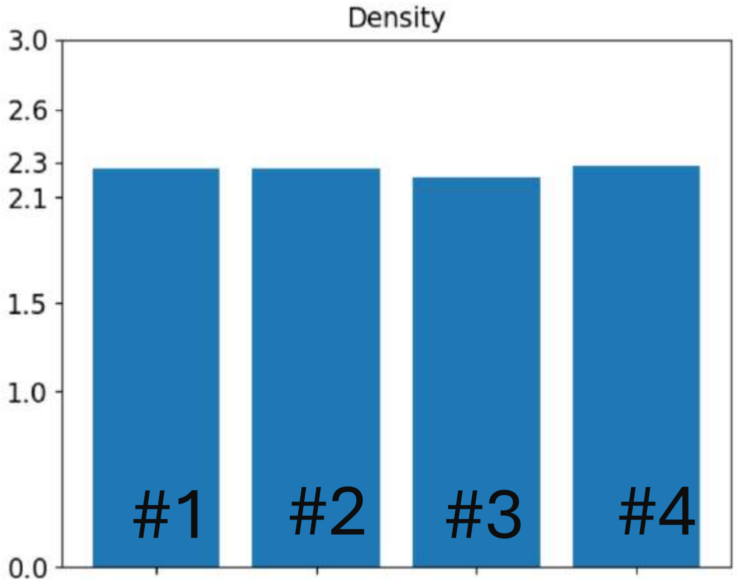
As machined, pristine samples

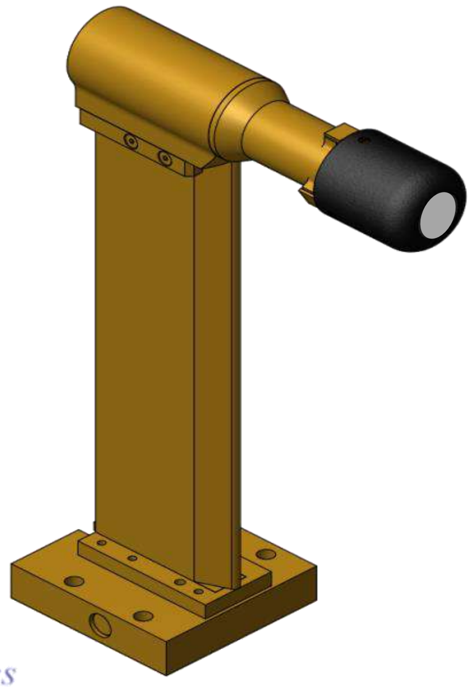
Sample1

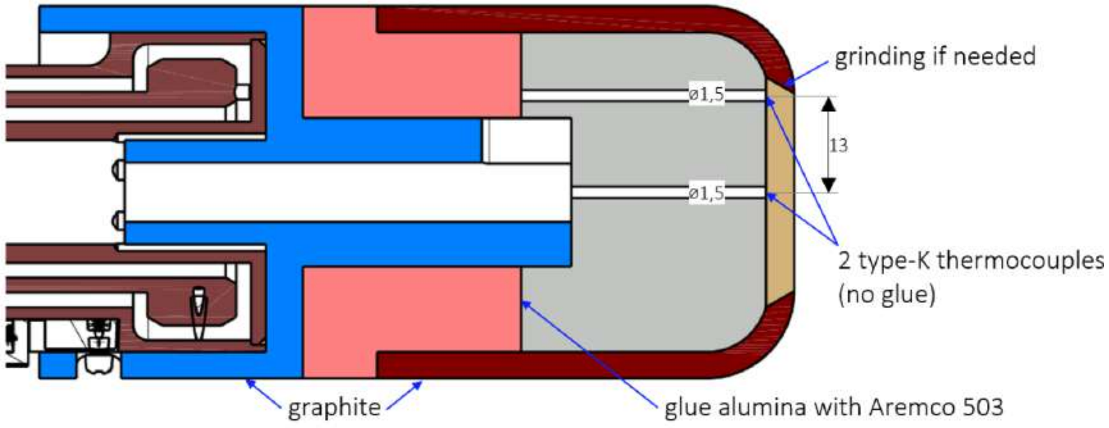
Sample2

Sample3

Sample4

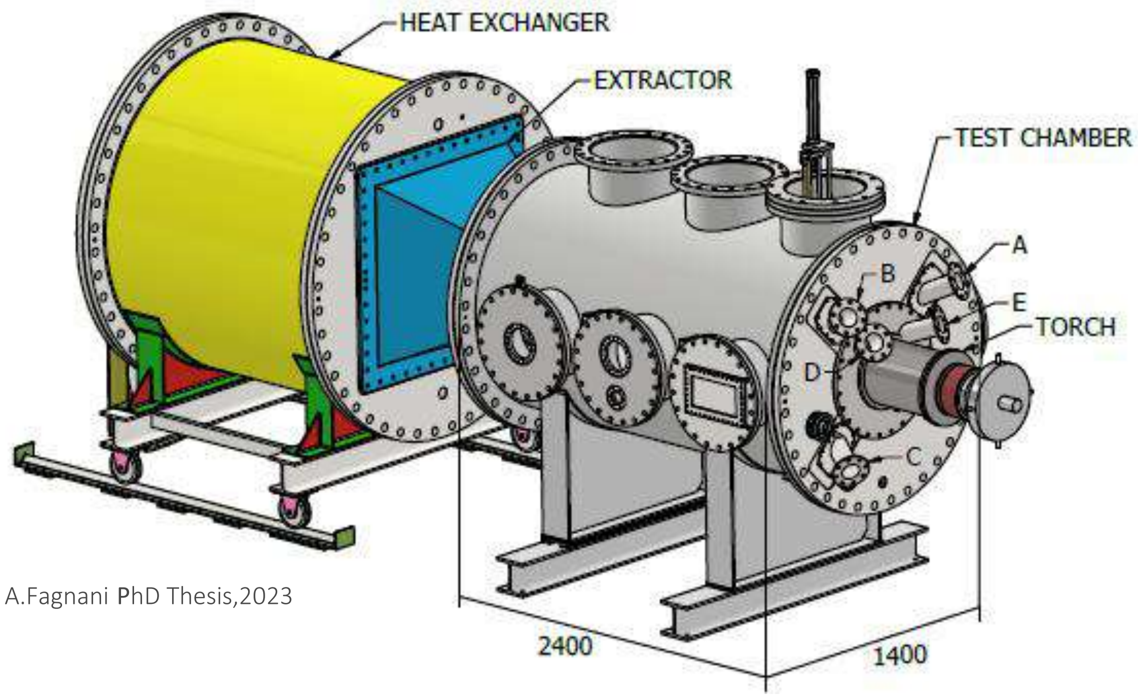




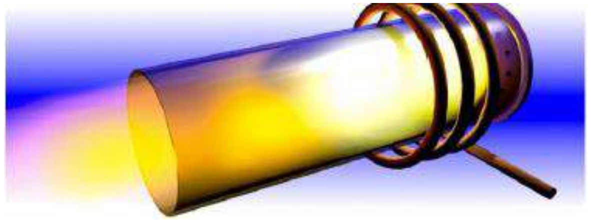


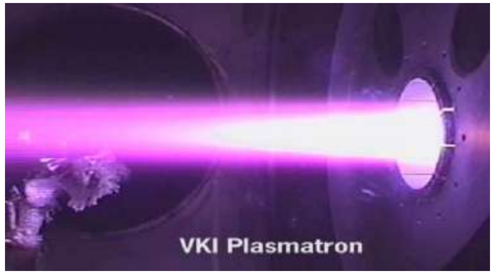
1.2 MW Inductively Coupled Plasmatron

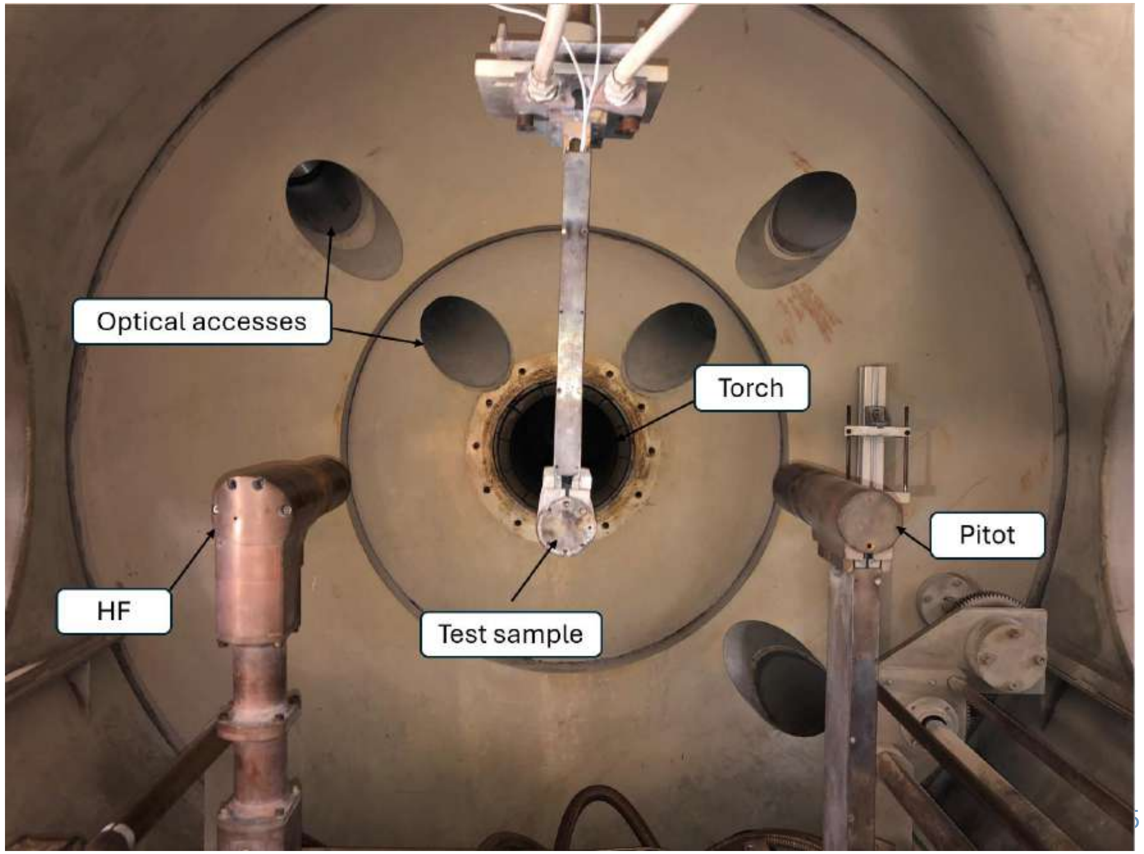
A subsonic test bed for re-entry flow reproduction



A.Fagnani PhD Thesis,2023



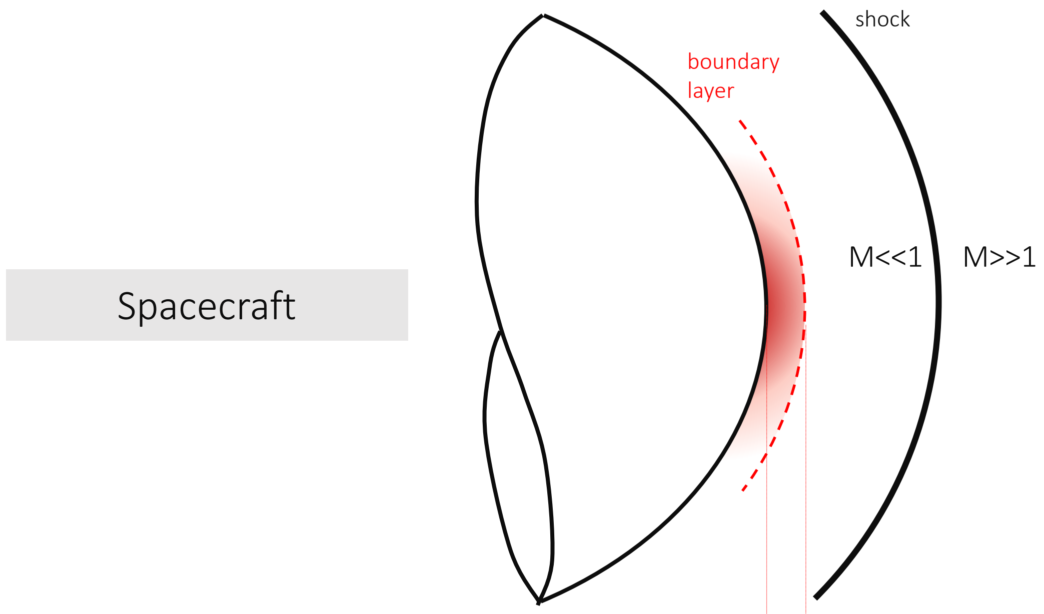




Gas	air, N_2, CO_2, Ar
Power	1.2 MW
Max. heat flux	15 MW/m^2
Pressure	10 hPa - 400 hPa

1.2 MW Inductively Coupled Plasmatron

Subsonic plasma flow to recreate a high temperature, reactive boundary layer

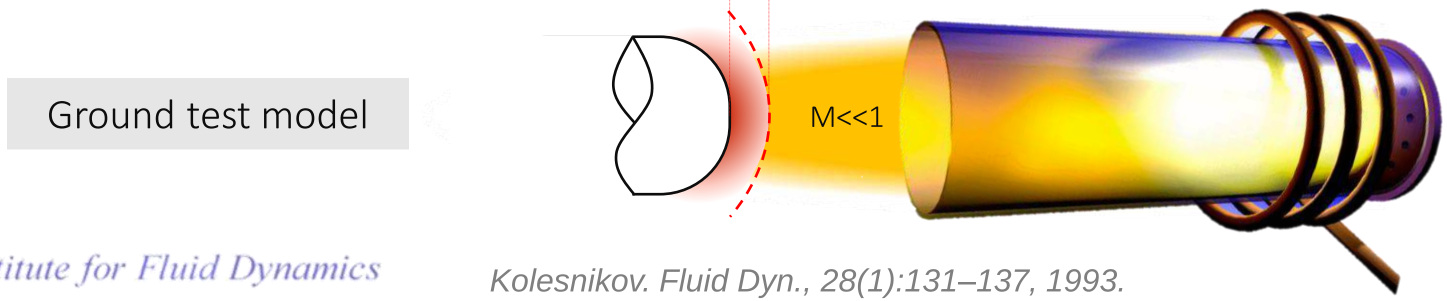


$$H_e^{\text{ground}} = H_e^{\text{flight}} = \cancel{h^{f}_{\infty}} + \frac{1}{2}(v^{f}_{\infty})^2$$

$$p_e^{\text{ground}} = p_e^{\text{flight}} = \cancel{p^{f}_{\infty}} + \rho^{f}_{\infty}(v^{f}_{\infty})^2$$

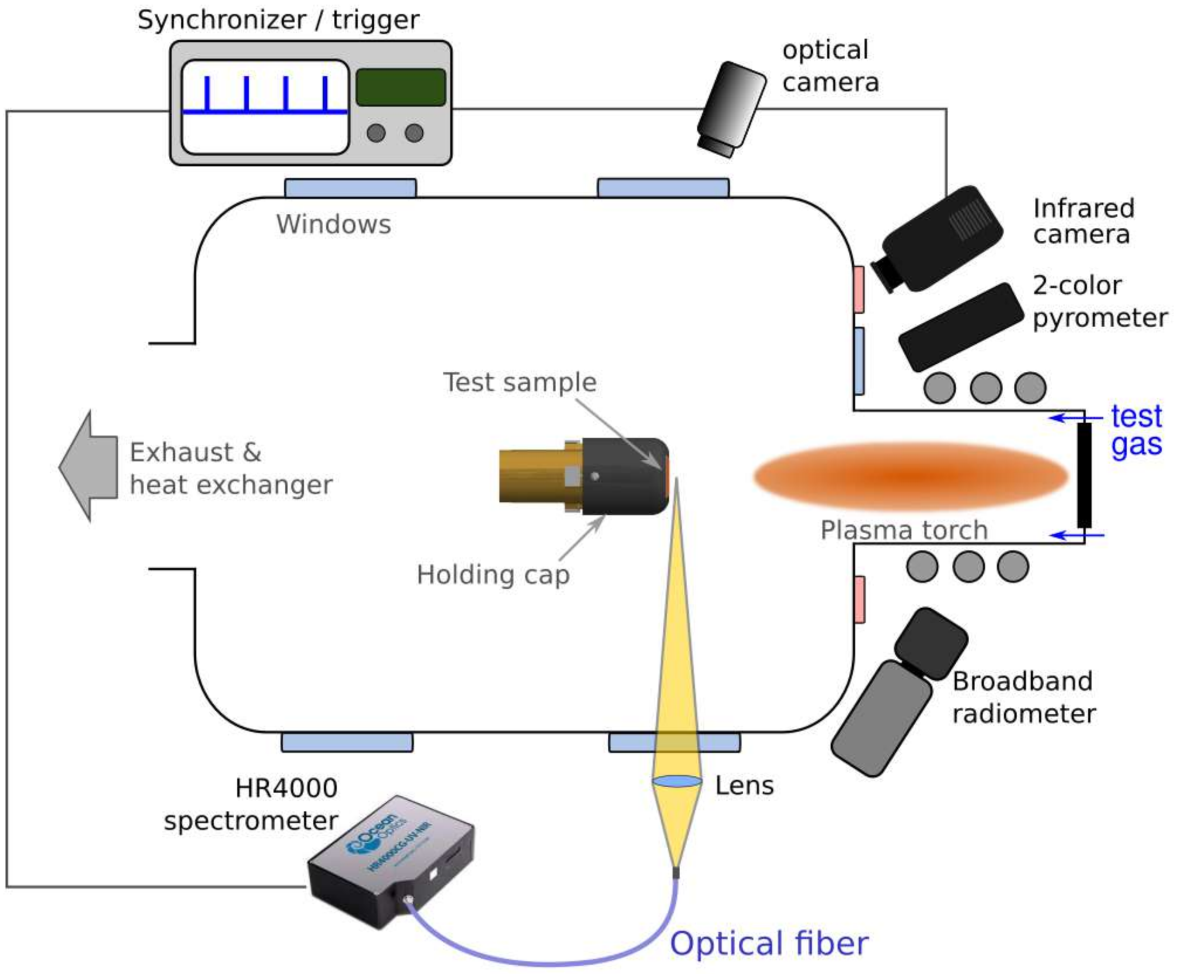
$$\beta_e^{\text{ground}} = \beta_e^{\text{flight}} = \frac{1}{R_{eff}}\left(\frac{2(p_e - p_\infty)}{\rho_e}\right)^{0.5}$$

→ Boundary layer reproduction (h_f, p_f, χ_f)



Kolesnikov. Fluid Dyn., 28(1):131–137, 1993.

Instrumentation in the Plasmatron and test observation



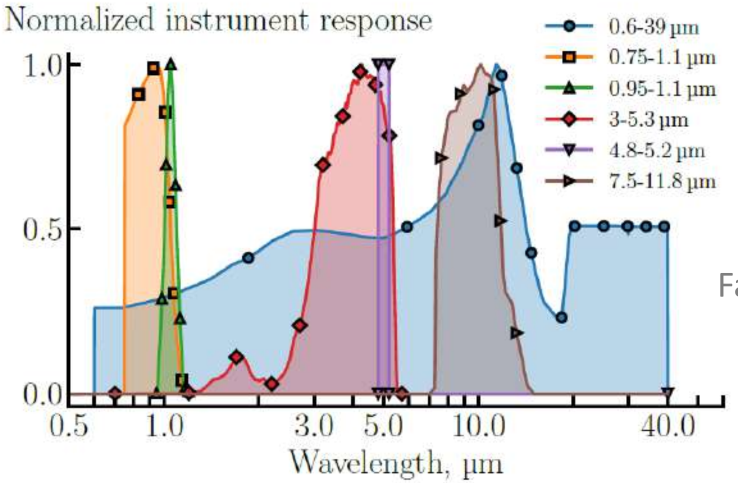
FLIR A6750sc MWIR (3-5µm)
450 - 3270 K calibrated (FLIR)

2-colour pyrometer (0.75-1.1µm, 0.95-1.1)
1300 - 3270 K calibrated (NPL London)

Broadband radiometer (0.65-39µm)
300 - 3270 K calibrated (NPL London)

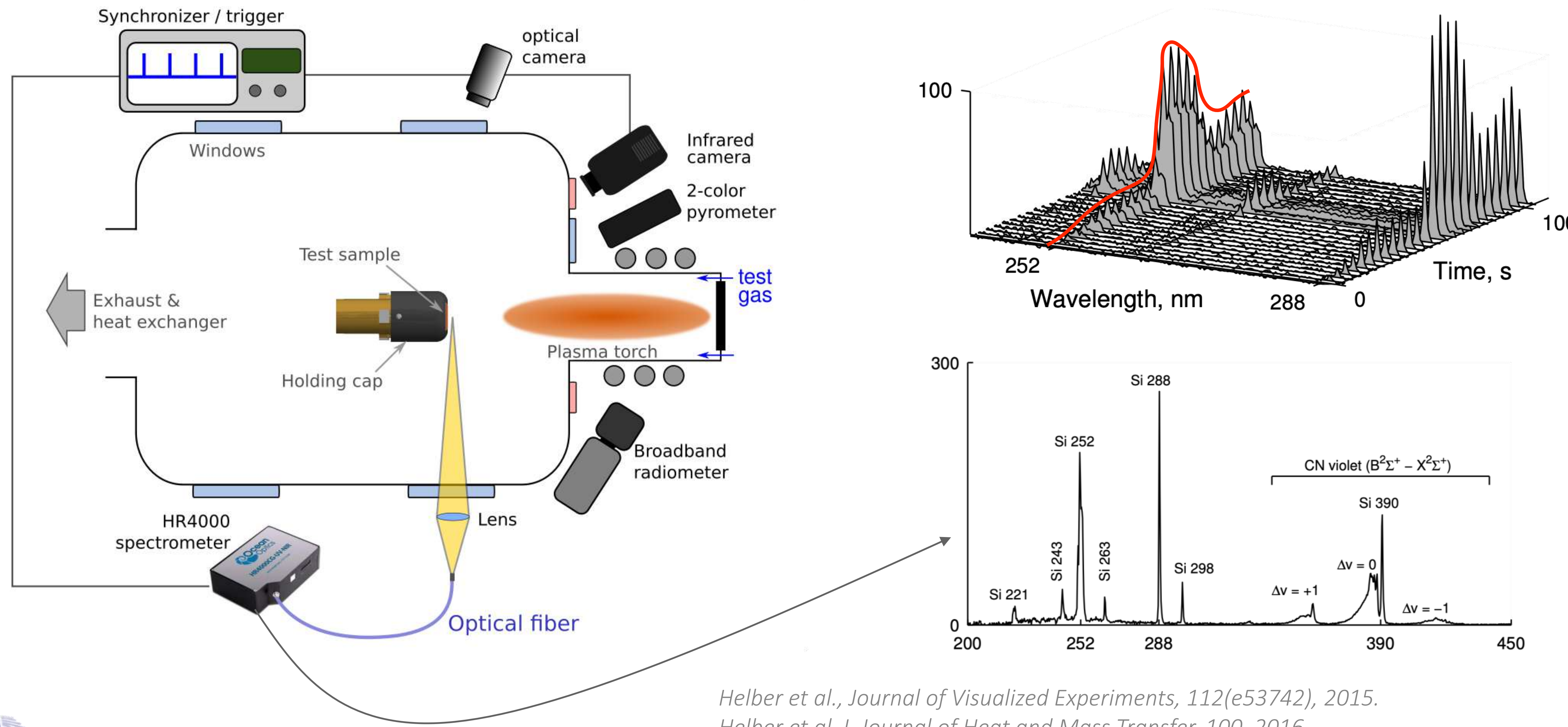
Optris (4.8-5.2µm)
525 – 3270 K calibrated (NPL London)

Type-K thermocouples (Nickel-Chromium/Nickel-Alumel)
300 - 1500 K



Fagnani et al, 2023

Instrumentation in the Plasmatron and test observation



Helber et al., Journal of Visualized Experiments, 112(e53742), 2015.
Helber et al, I. Journal of Heat and Mass Transfer, 100, 2016

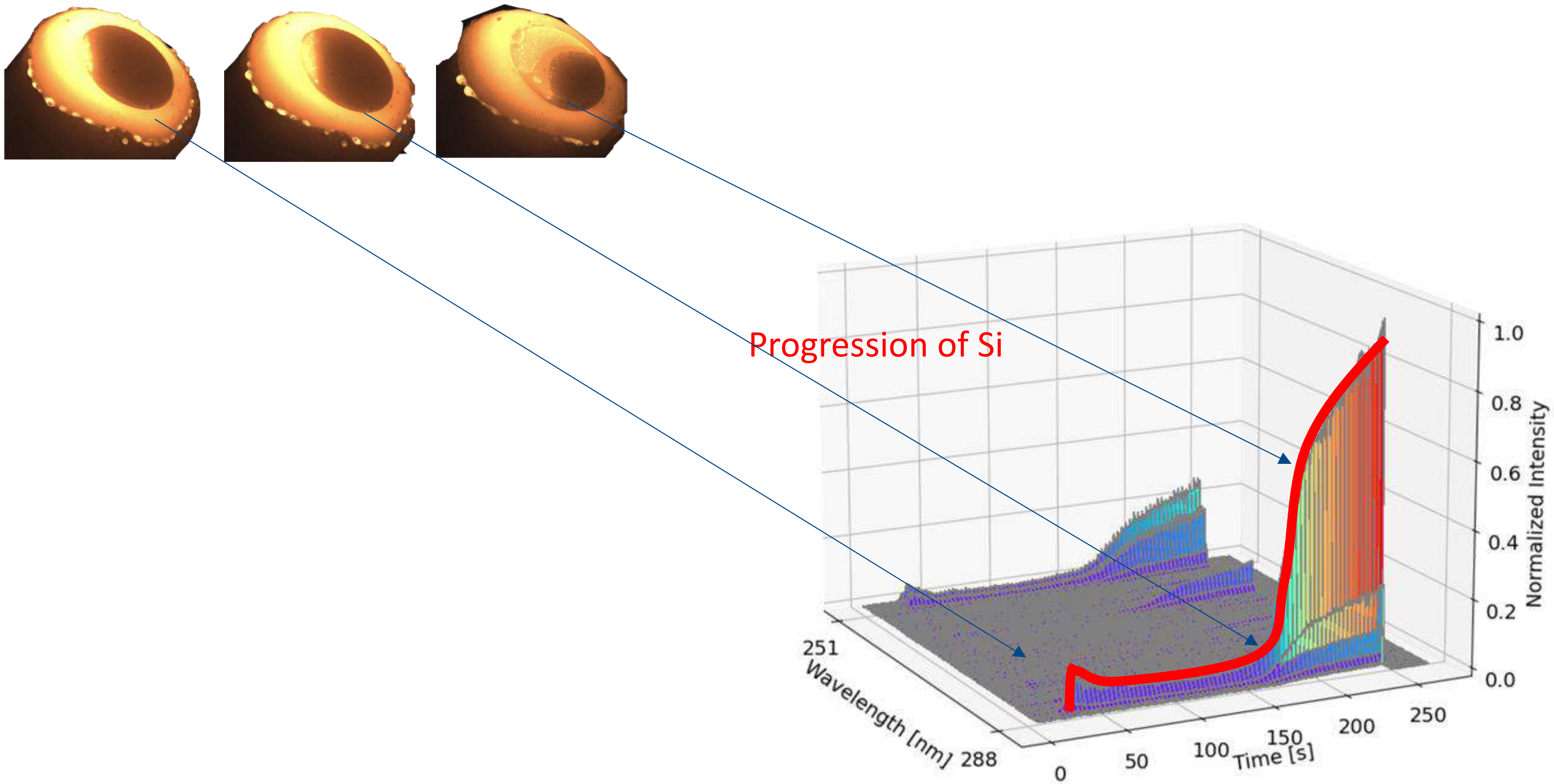
Test matrix overview

Material 1: KUL

	Oxidation Regime	Heat Flux [MW/m²]	Flow Regime	Power [KW]	Static Pressure [hPa]	Time [s]
Test 1	Passive	1	Subsonic	200	100	360
Test 2	Transition	1.3	Subsonic	230	100	240
Test 3	Active	1.6	Subsonic	270	100	360
Test 4a	Passive	0.8	Subsonic	210	20	150
Test 4b	Active	1	Subsonic	245	20	240

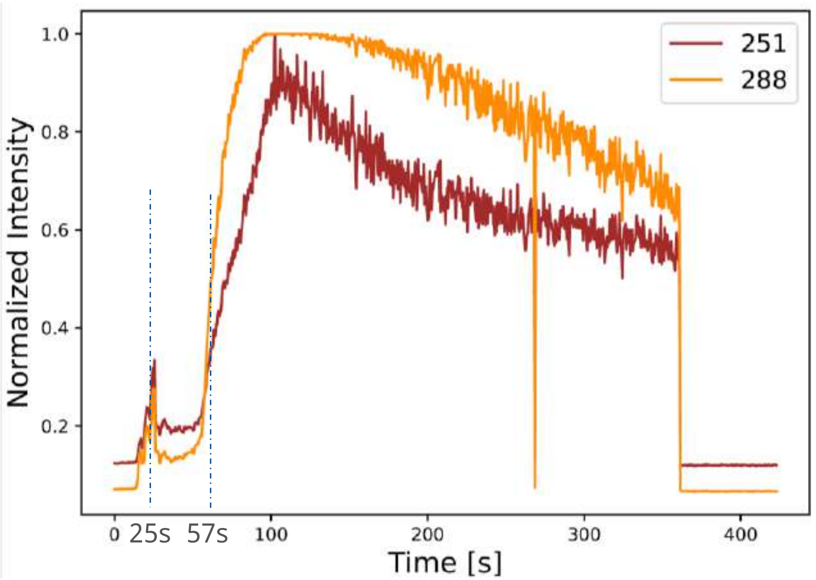
Material 2: Petroceramics, CMC used for SpaceRider (not disclosed here)

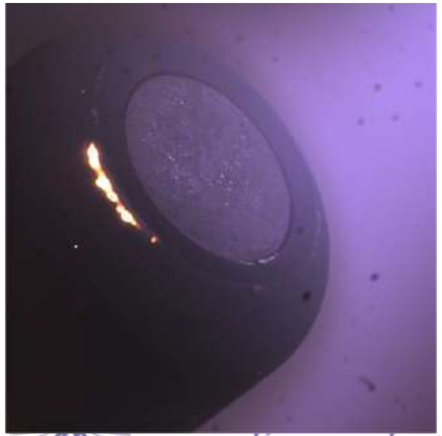
The passive-active transition observed visually and in the emission spectrum



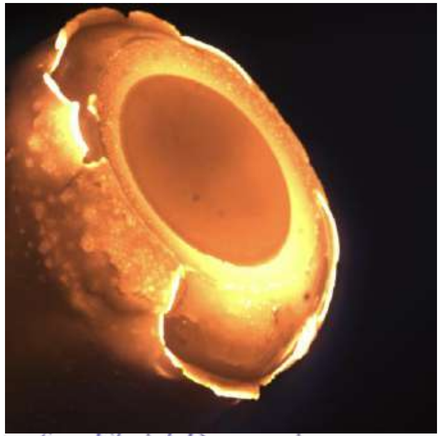
“Temperature jump” observed in the emission spectrum

Test 3

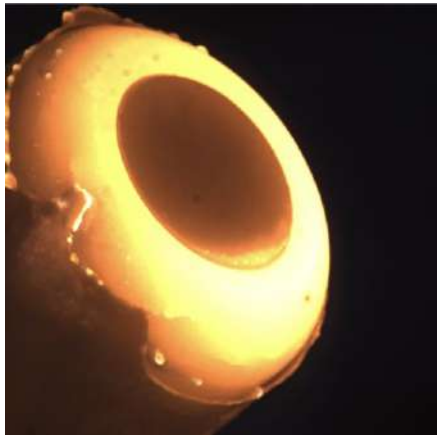




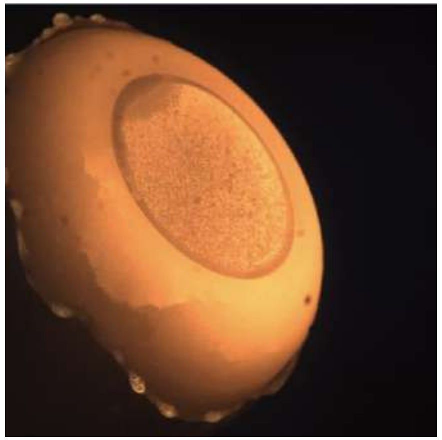
t= 1 s



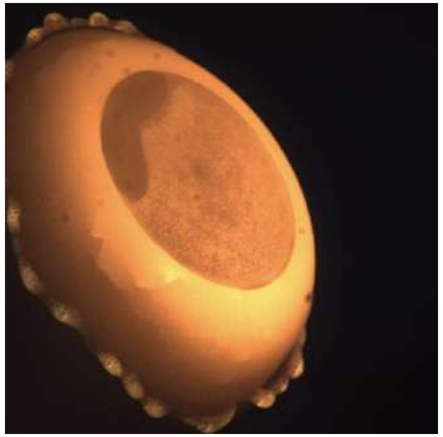
t= 25 s



t= 57 s



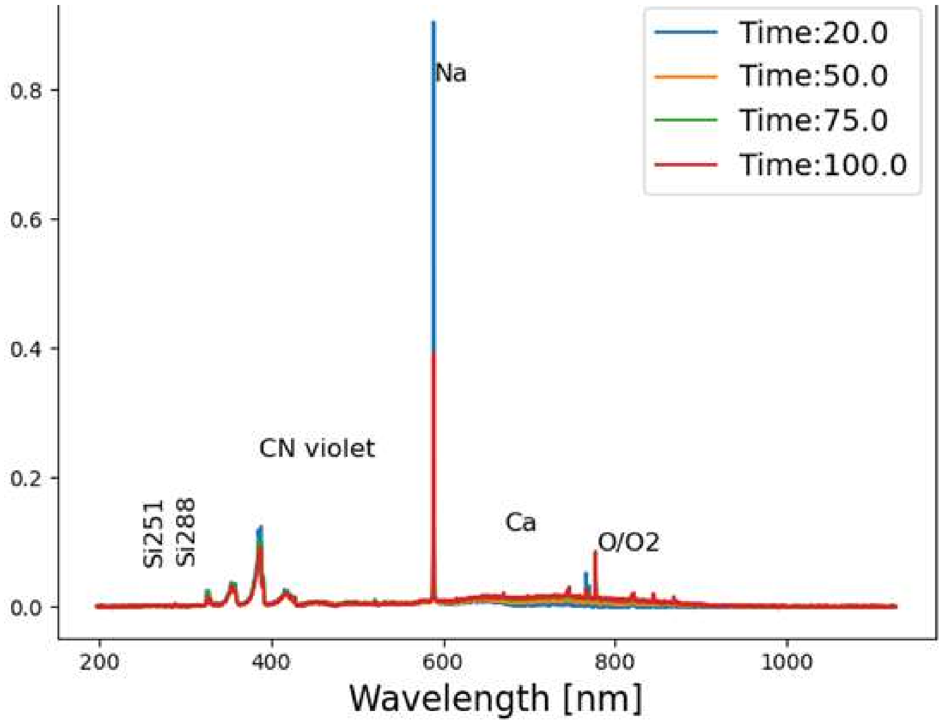
t= 200 s



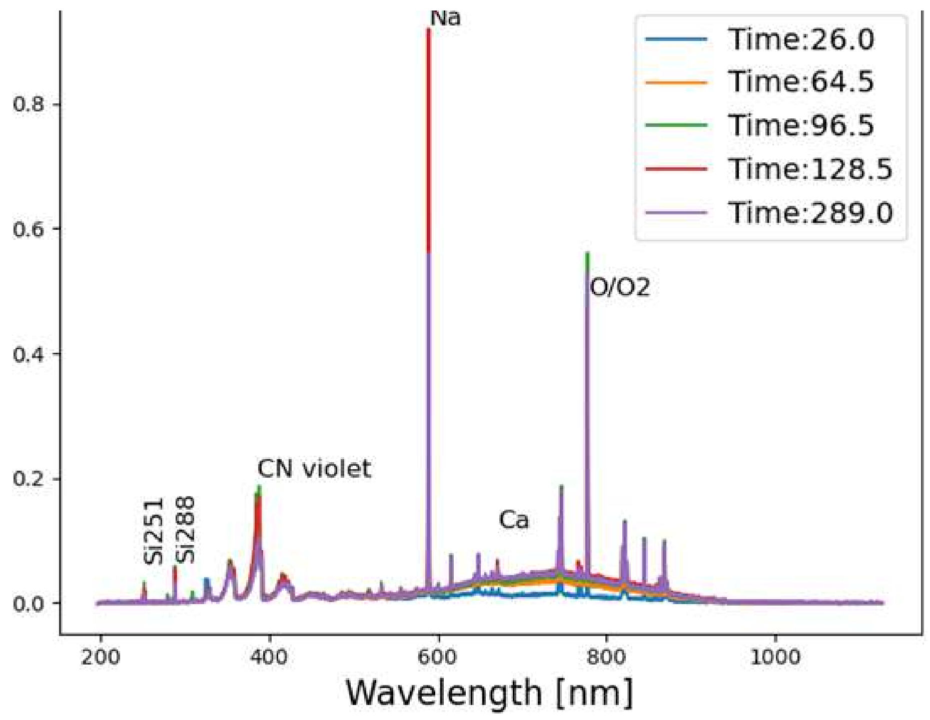
t= 360 s

Comparison at low pressure (20 hPa)
Same test sample tested in two test conditions

Test 4a (0.8 MW/m²) (Passive)



Test 4b (1.0 MW/m²) (Active)

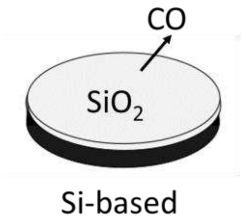


Detailed surface and material analysis

Passive oxidation (desired)

$SiC(s) + 3O \rightarrow SiO_2(s) + CO$

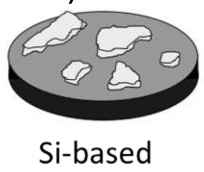
Minimal mass change

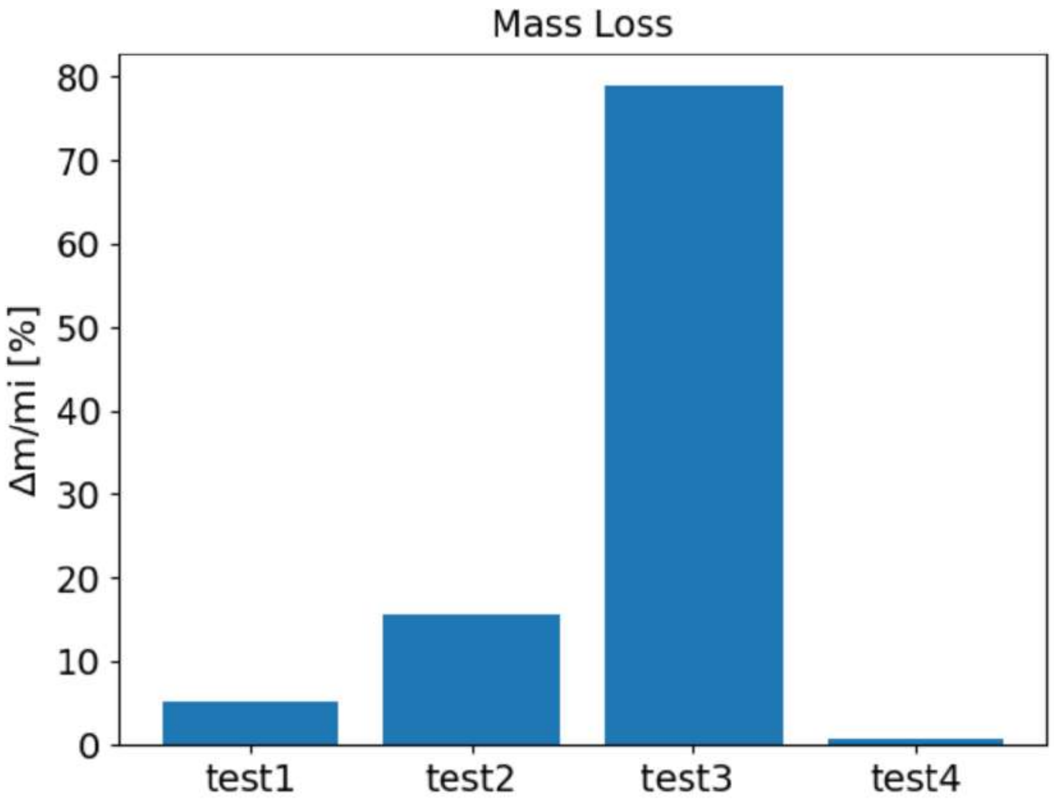


Active oxidation (destruction)

$SiO_2(s) + O \rightarrow SiO + O_2$

$SiC(s) + 2O \rightarrow SiO + CO$

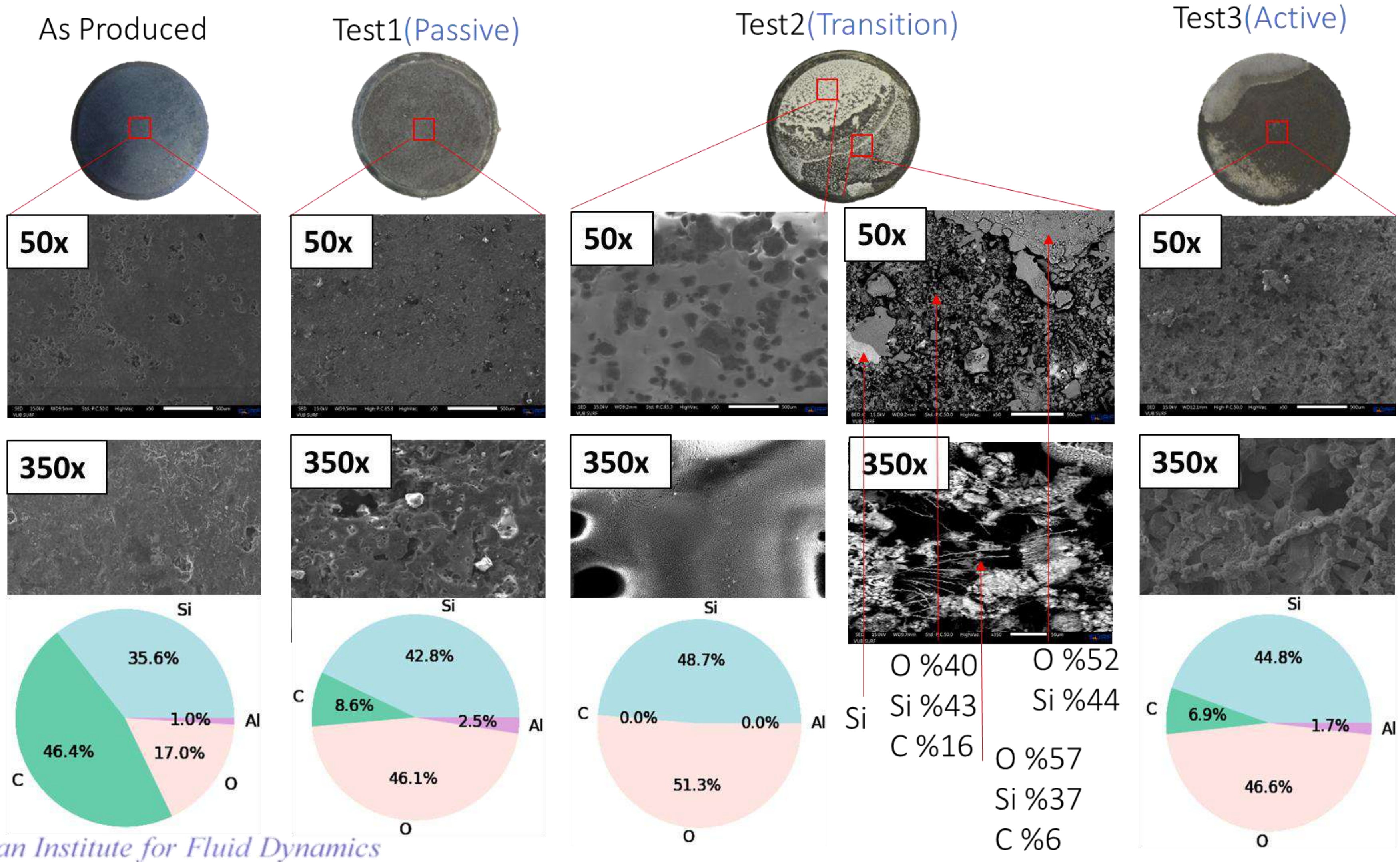




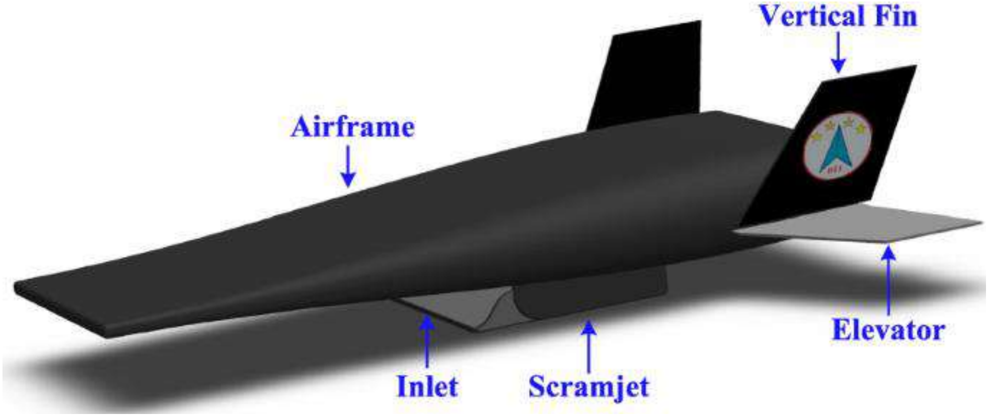
(Passive) (Transition) (Active) (Active)

Detailed surface and material analysis

Free University Brussels (VUB)



Ongoing: ESA GSTP on Morphing of aero-thermally loaded structures (VKI, Cenaero, Sonaca, KU Leuven)

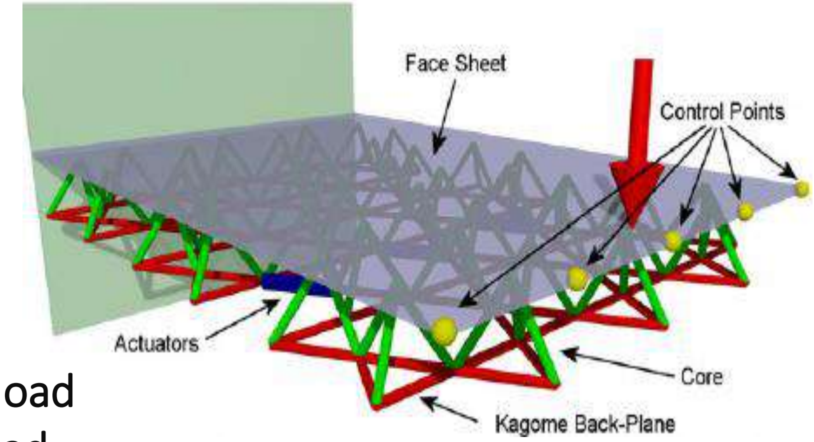


OBJECTIVES

Structure – selection, design, limitation
Hot surface – more than 1000K - flexible

Design and fabrication

Demonstrator for mechanical load
Demonstrator for thermal load

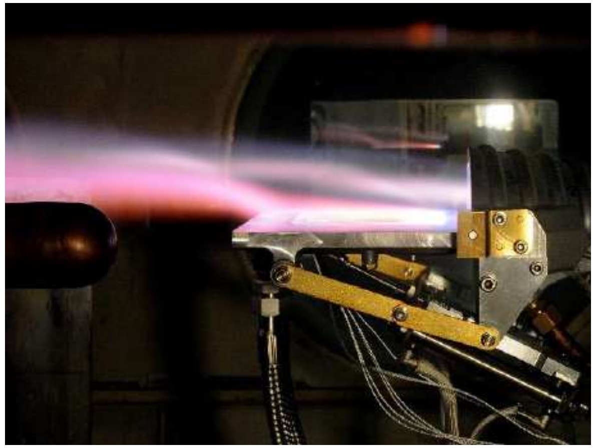


Experimental testing – Validation

Plasmatron for thermal load
Dedicated bench for mechanical load

OUTPUT

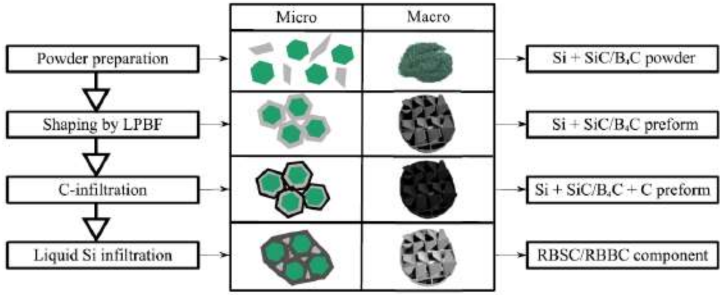
Morphable material validated for **high thermal load**
Morphable material validated for **mechanical load**
Road map for development of the technique **up to TRL6**



Jan 2025: The effect of High-velocity ballistic Impact on the Thermo-mechanical behavior of Space materials (HITS)

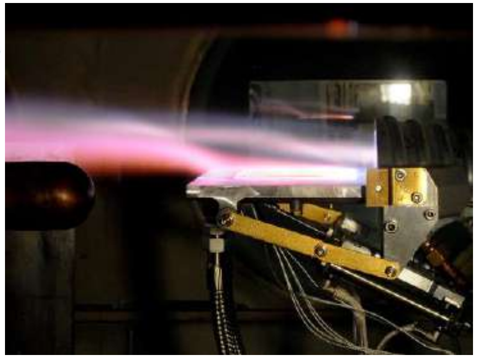
DEfence-related Research Action (DEFRA)
Belgian royal higher institute for defence

KU LEUVEN

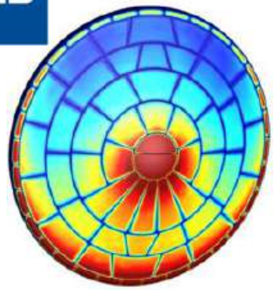


1. High-temperature material
2. Foreign Object Damage
3. Plasma testing
4. Computational modeling

RMA Royal Military Academy Brussels



ULB



Belgian Science Policy Office belspo

sonaca

TELESPAZIO a LEONARDO and THALES company

von Karman Institute for Fluid Dynamics

Summary and perspectives

This research:

Reusability range determined (up to 2000 K), then slow destruction

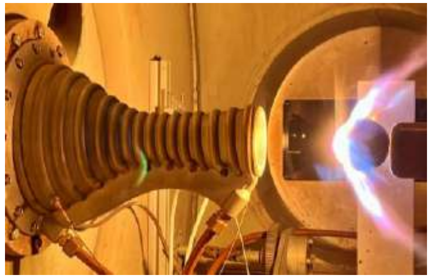
3D material dimensions to be improved for accuracy (±1mm), especially at curvatures

Comparison to real CMC material performance → not disclosed

Additively manufactured materials are strong candidates for future high temperature applications.

Ongoing and future ‘hot’ topics for collaboration:

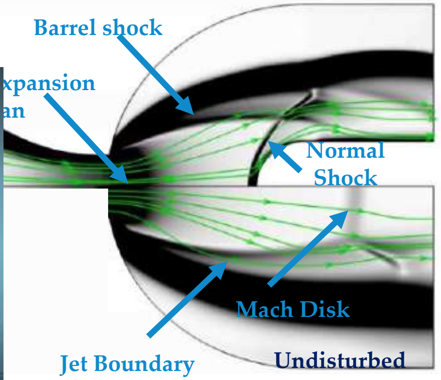
1) Hypersonic testing (M>14) in Longshot facility (Dr. G. Grossir)
   booster separation, boundary layer transition, …



2) Supersonic plasma testing & nozzles design (ARL POC: A. Ghoshal)

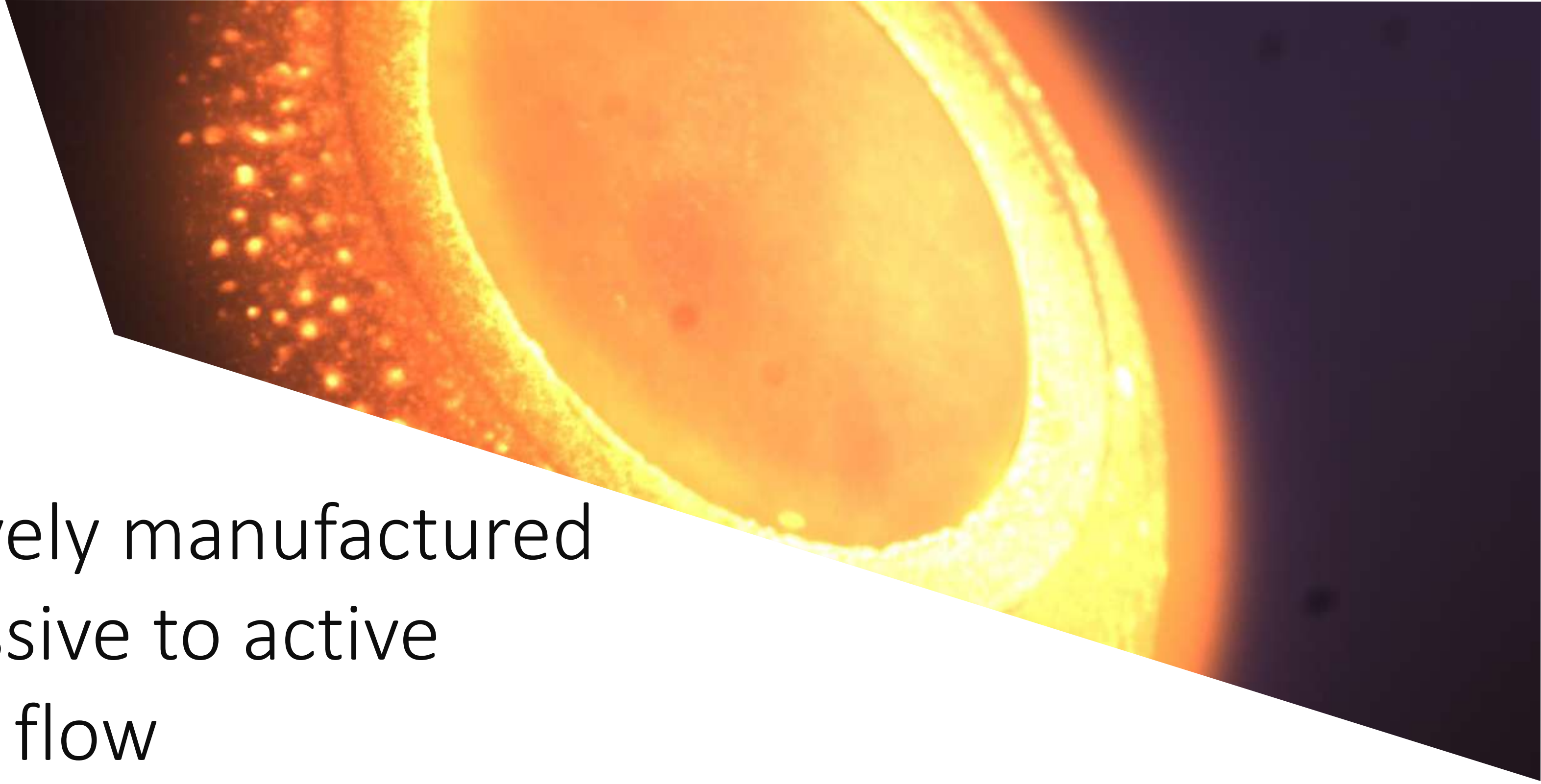
3) Hypersonic CFD using US3D: ongoing discussion with VKI specialists (T. Magin, M. Capriati)

4) Rarefied low-density facility (representative of Knudsen regime in 125



Testimony presentation

Characterization of additively manufactured ceramic composite for passive to active oxidation in high-enthalpy flow



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