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Developing an Experimental Procedure towards a Standardised Testing of Aerospace Material Demisability

Belstead
aerospace & advanced composites

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Clean Space Industrial Days

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Characterisation of Demisable Materials TRP

Background:

- Failure or absence of active de-orbiting systems may result in re-entry over densely populated areas.
- Impacting debris may cause harm to life and property.

Design for Demise (D4D):

- Vehicle layout encourages early breakup.
- Component survivability reduced by layout and material selection.

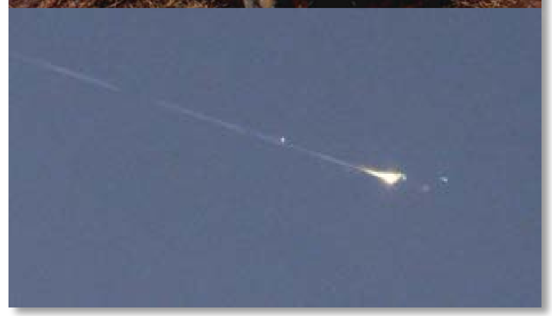
Characterisation of Demisable Materials ESA TRP *(4000109981/13/NL/CP)*:

- Focus on characterisation of materials towards understanding their behaviour in uncontrolled, destructive atmospheric Earth re-entries.
- Improvement of material (and design) choice criteria in the context of the design-for-demise philosophy.

  ➔ Reduction of on-ground casualty risk.

Credit: ESA

Credit: NASA



Credit: IAC / UAE Space Agency / NASA / ESA

The Team

European Space Agency
- Customer

Fluid Gravity Engineering Ltd.
- Prime contractor
- Definition of test objectives and matrices
- Post-test analysis support
- Database design and construction

Aerospace and Advanced Composites GmbH
- Characterisation of key material properties
- Static testing of candidate materials in re-entry chamber

Institute of Space Systems, University of Stuttgart
- Dynamic testing of candidate materials in Plasma Wind Tunnel (PWT) facilities
- Investigation of optical material properties
- Establishment of standard test procedures

Belstead Engineering Ltd.
- Identification of key parameters for demise
- Review and parametric study of re-entry trajectories and identification of test conditions
- Debris risk assessment

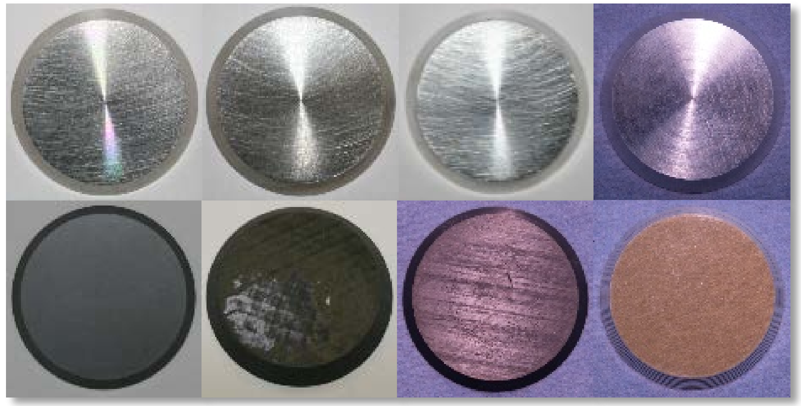
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency
- Tie-in investigation of additional high-density CFRP variant at IRS

The von Karman Institute for Fluid Dynamics
- Dynamic testing of select candidate materials in Plasmatron facility

Candidate Materials and Test Conditions

Material selection:

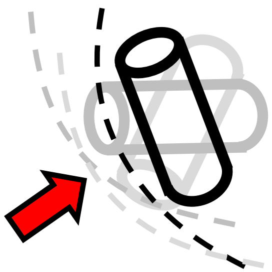
- Material selection considered representative of aerospace structures.
- 4 metal alloys, 3+1 composites, 1 ceramic, 1 heterogeneous structure.



Selection of test conditions:

- Extensive review and parametric study of re-entry trajectories by BRL.
- Further analyses and selection of test conditions by FGE.

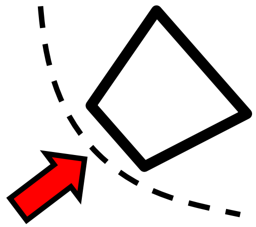
➔ Assumption of uncontrolled entry from LEO, representative peak heat fluxes for typical spacecraft components during demise:



tumble-averaged:
≈ 260 kW/m²

mid-point:
≈ 520 kW/m²

stagnation point, no tumbling:
≈ 1400 kW/m²



Credit: ESA-ESTEC

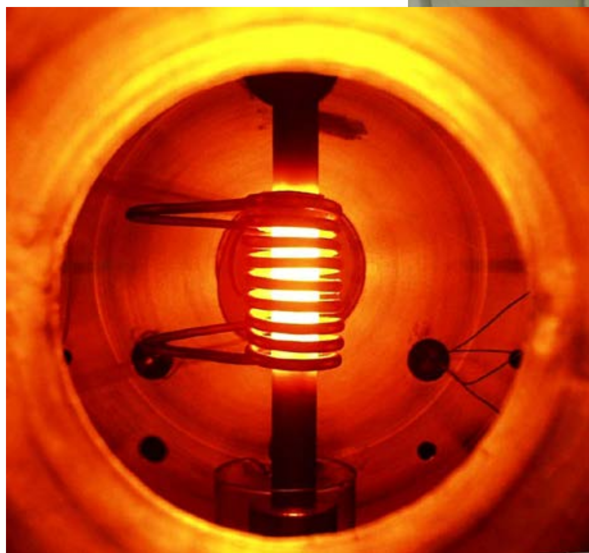
➢ Static Entry Chamber Testing at AAC

AAC Re-entry Simulation Chamber

- ➢ Heating of sample coupon via induction-powered susceptors (black body heaters), single-sided or from both sides.
- ➢ Maximum heat flux density: 3 MW/m^2
- ➢ Pressure range: 0.1 Pa to sea-level.
- ➢ Simultaneous application of static or dynamic mechanical loads up to 70 kN.
- ➢ Temperature measurements via two-colour pyrometry.

→ Investigation of thermomechanical aspects of demise and fragmentation

- ➢ Reproduction of flight-representative temperatures by radiative heating.
  → Extensive parametric sensitivity analyses possible due to comparatively (dynamic facilities) reduced costs.
- ➢ Exploration of mechanical strength at these elevated temperatures.
  → Augmentation of destructive re-entry models.



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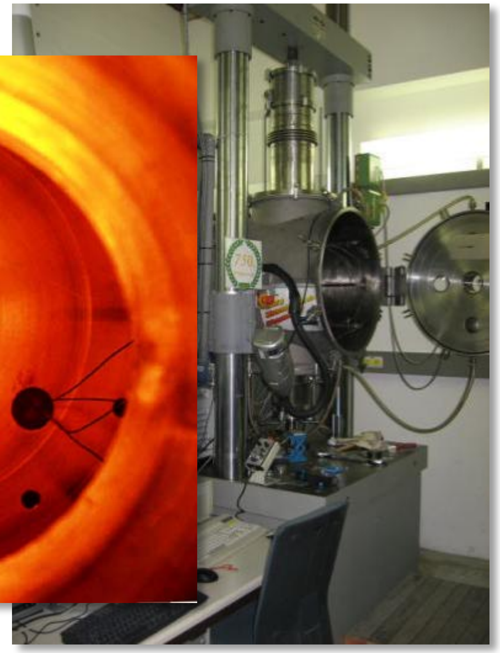
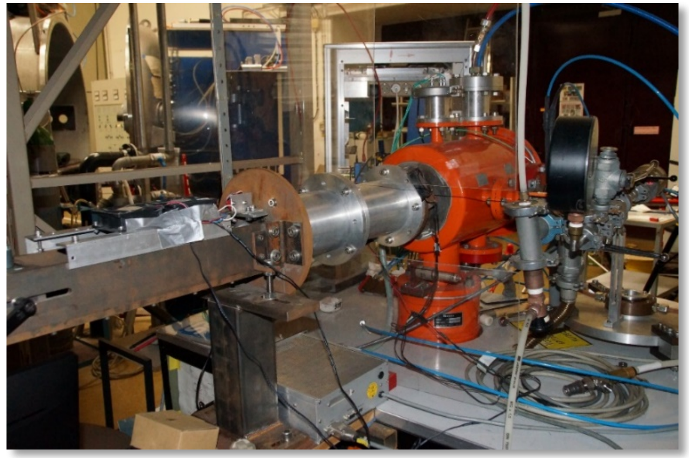


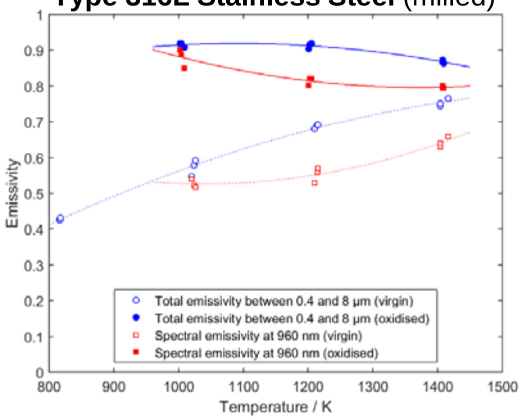
Credit: AAC

Emissivity Measurement Facility (EMF) at IRS

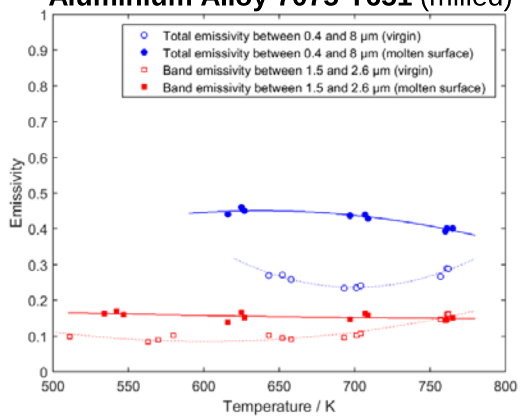
- Spectral and narrowband pyrometers used for PWT investigations at IRS
- Temperature-dependent emissivities determined using the Emissivity Measurement Facility (EMF)
- Pyrometer-specific spectral emissivities for iterative temperature correction of data measured during PWT testing.
- Total emissivity for modelling.
- PWT-compatible sample geometry: Test of both virgin and post-test material specimens.



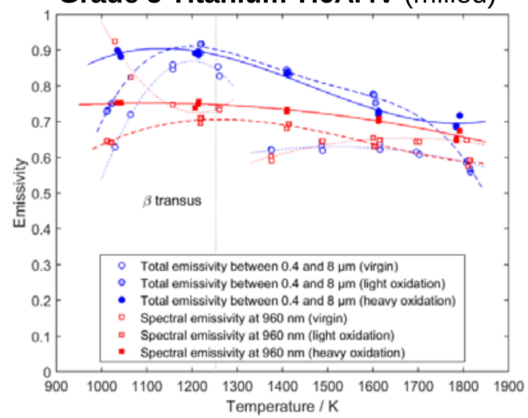
Type 316L Stainless Steel (milled)



Aluminium Alloy 7075-T651 (milled)



Grade 5 Titanium Ti6Al4V (milled)



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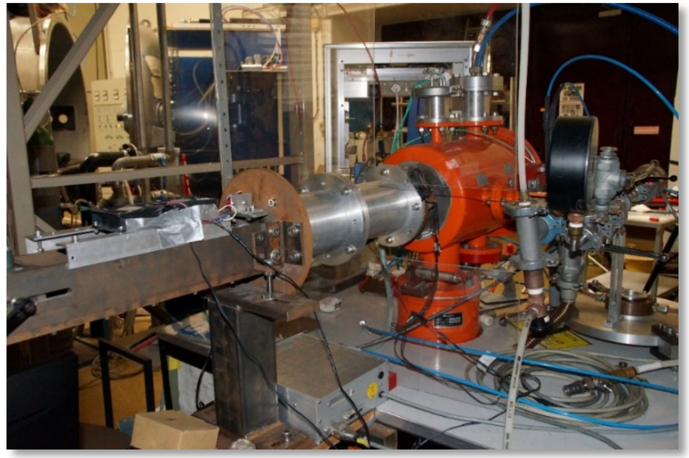

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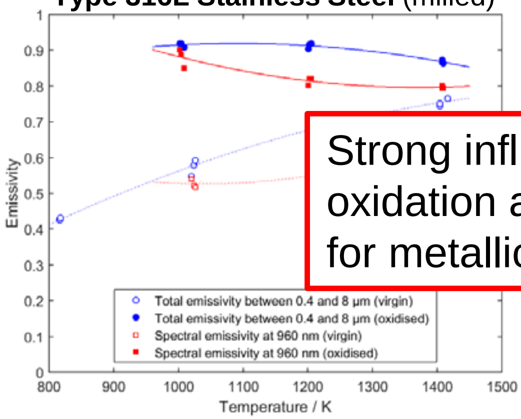

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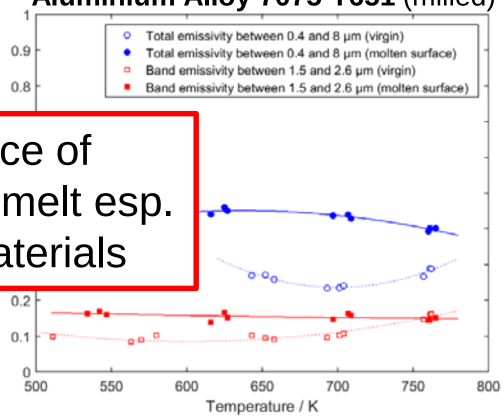
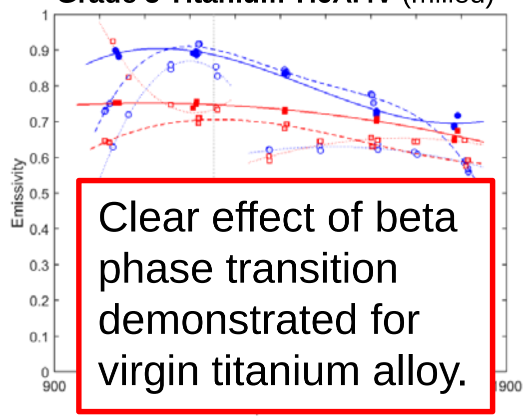


Strong influence of oxidation and melt esp. for metallic materials

Grade 5 Titanium Ti6Al4V (milled)

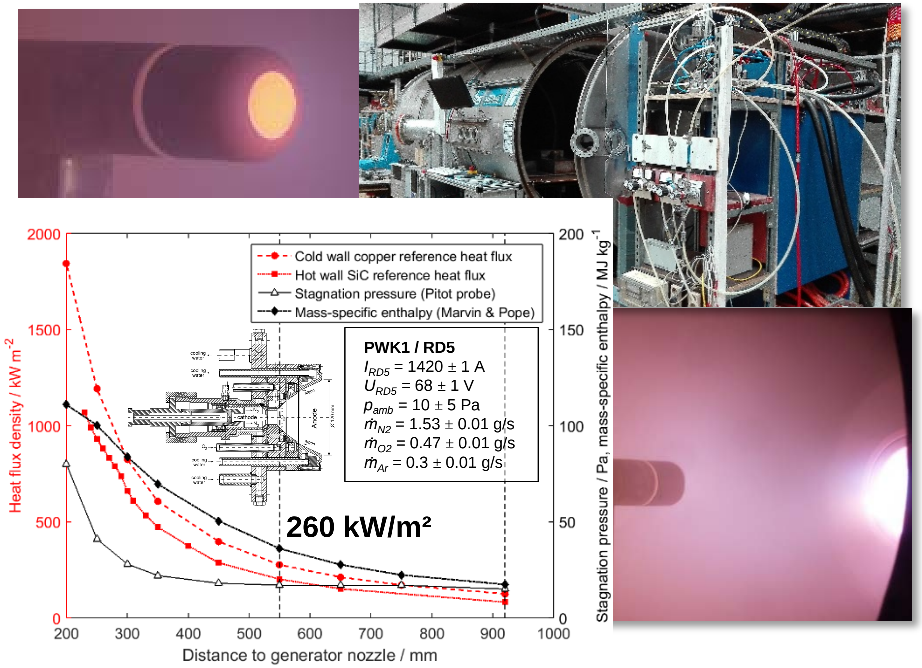


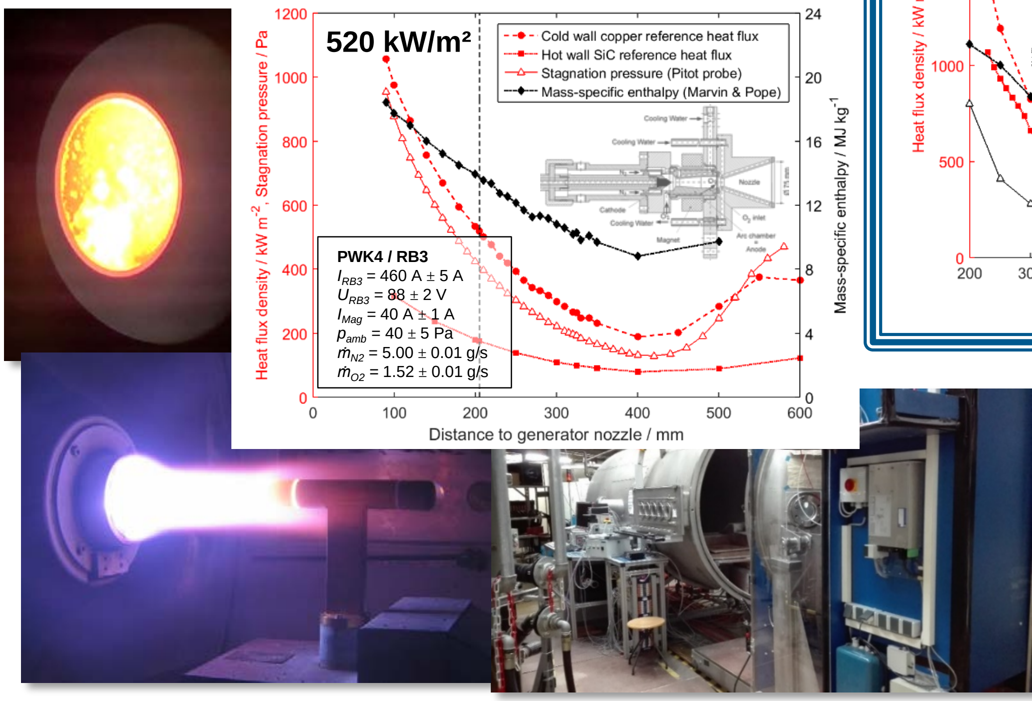
Clear effect of beta phase transition demonstrated for virgin titanium alloy.

PWT Test Facilities and Conditions at IRS (Selection)

PWK1

- Magnetoplasmadynamic (MPD) generator RD5
- Mass-specific enthalpy: 2 to 150 MJ/kg
- Maximum heat flux density: >15 MW/m²
- Stagnation pressures: 0.1 to 50 hPa





PWK4

- Thermal plasma generator RB3
- Mass-specific enthalpy: up to 20 MJ/kg
- Maximum heat flux density: >3 MW/m²
- Stagnation pressures: up to 200 hPa

PWT Testing Methodology

Steady state testing

- Suitable for materials which do not pyrolyse (or are already fully charred), e.g. high-temperature ceramics and metal alloys.
- Provides access to surface energy balance.
  - Catalytic efficiency
  - Emissivity
- Direct measurement of emissivity at various oxidation states is very valuable when interpreting test results.

Transient testing

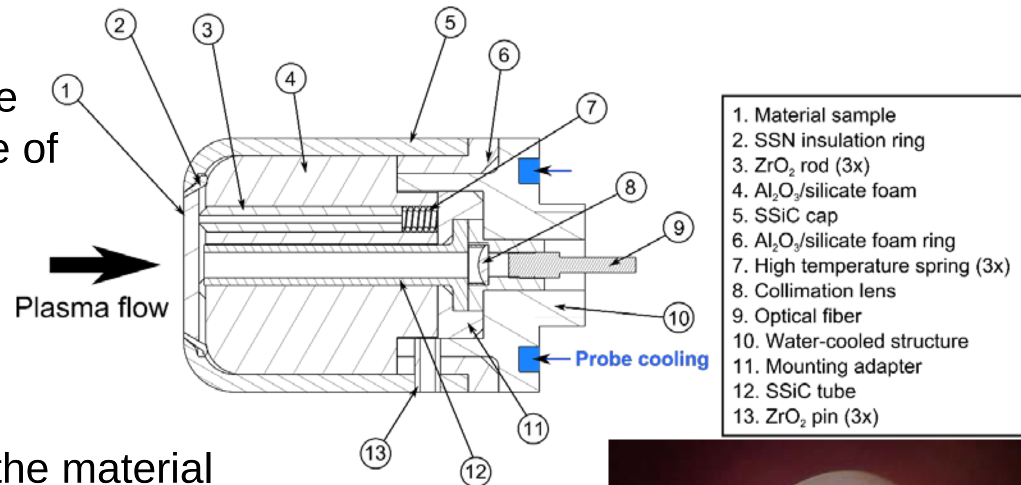
- Test modelling consistency with representative heat load.
- Test modelling consistency up to thermal demise (possibly to destruction).
- More suitable for pyrolysing materials (e.g. CFRP).
- Important for highly demisable materials (e.g. aluminium).
- Harder to access the energy balance without steady state surface temperatures.

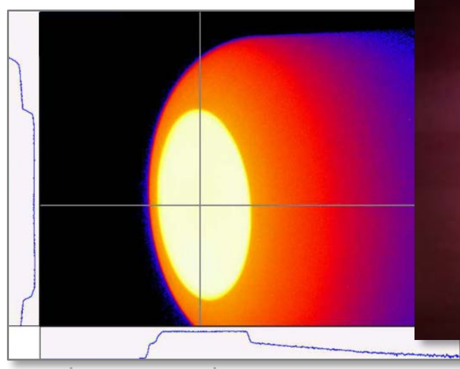
Material Probe for PWT (IRS)

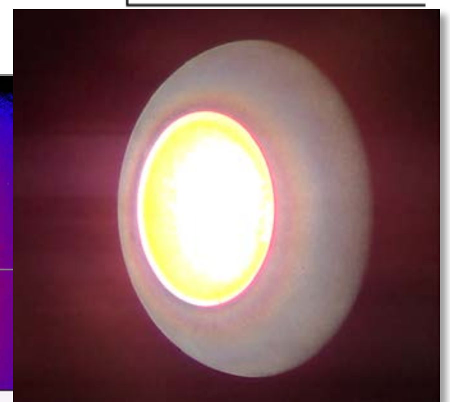
- Radiation-cooled 50mm material probe with SiC cap, structure is water-cooled. Temperature limit: >2200°C or until active oxidation of SiC cap.
- Optical instrumentation can be implemented for contactless measurement of rear surface temperature of sample.
- Compatible with flat conical sample geometry, thickness representative of aerospace structures (2 to 4 mm).
- Heat flux and stagnation pressure probes available in analog sizes and geometries.
- Good lateral thermal insulation of the material sample through addition of insulation ring (considerably reduces contact surface area to radiation-cooled SiC cap).

➔ **Essentially 1D heat transfer scenario**

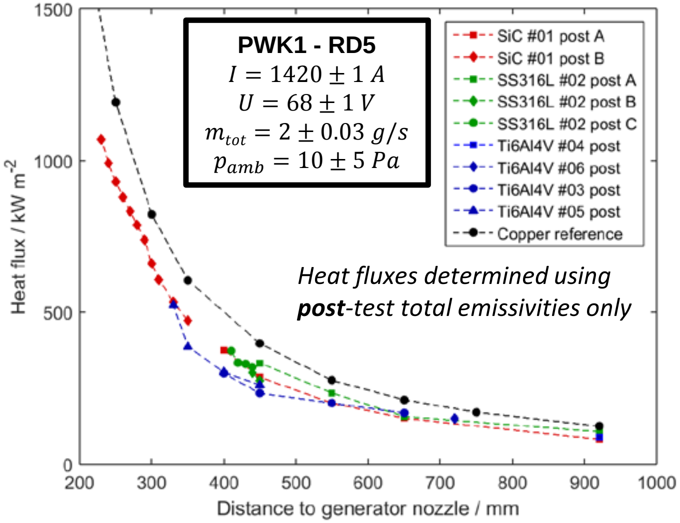
➔ **Suppression of shear forces**

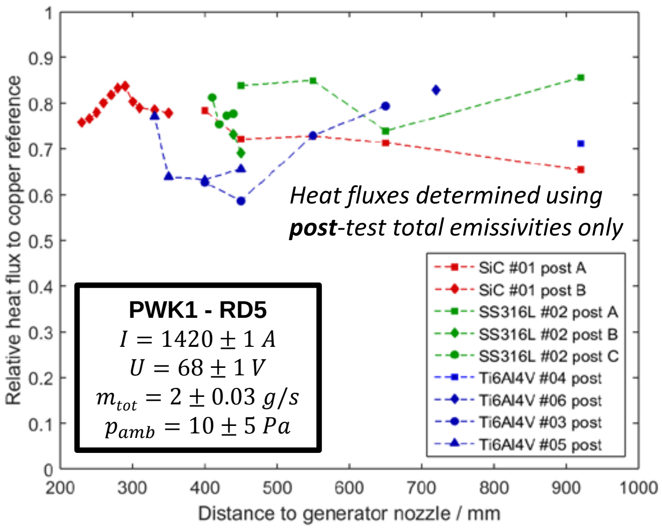






Steady State Response Investigation

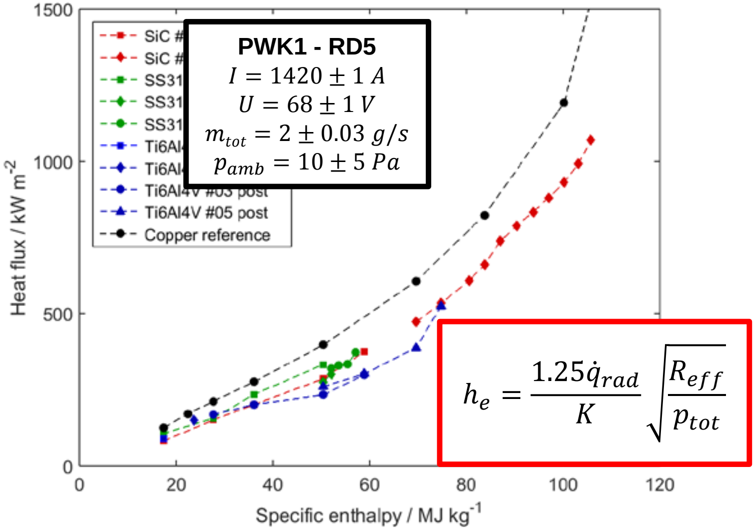


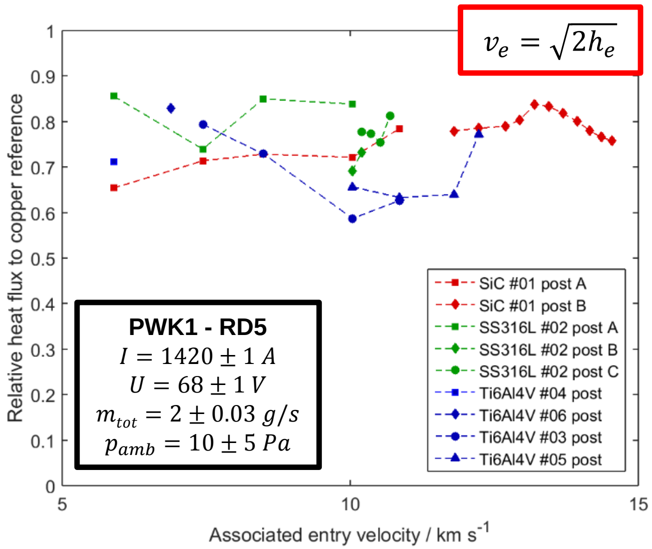


- Investigation of thermal steady state responses for three candidate materials (SSiC, Steel 316L, Ti6Al4V) under varying conditions.
- Resulting temperature profiles were corrected using emissivities obtained from EMF
- Heat fluxes approximated via Stefan-Boltzmann and measured emissivities.
- Very diverse range of surface morphologies resulted for Ti6Al4V alloy in particular:

Generator conditions	Unit	$x_{mean} \pm s$
Current	[A]	1420 ± 1
Voltage	[V]	68 ± 1
Electric power	[kW]	96.6 ± 5
Nitrogen mass flow	[g/s]	1.53 ± 0.01
Oxygen mass flow	[g/s]	0.47 ± 0.01
Argon mass flow rate	[g/s]	0.3 ± 0.01
Total mass flow	[g/s]	2.3 ± 0.03
Ambient pressure	[hPa]	0.1 ± 0.05
Specific enthalpy - nozzle outlet (effective)	[MJ/kg]	31.5 ± 0.1 (from analysis)

Steady State Response Investigation





Results:

- Strong dependence of material response on heating history, though re-entry relevant heating histories are generally short.
- Indication of relative material-specific catalycities.

➔ **Surface catalycity is a crucial factor for material demise!**

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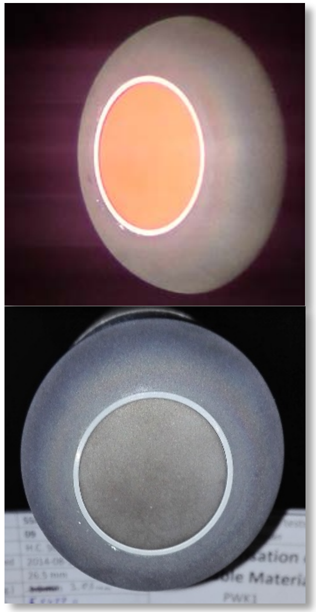
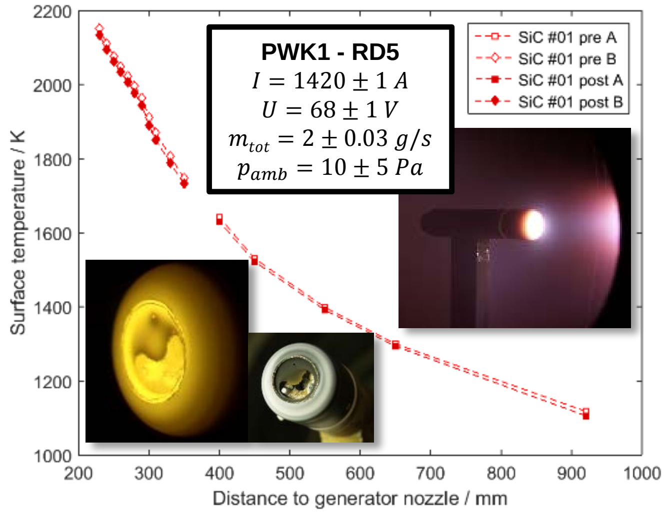
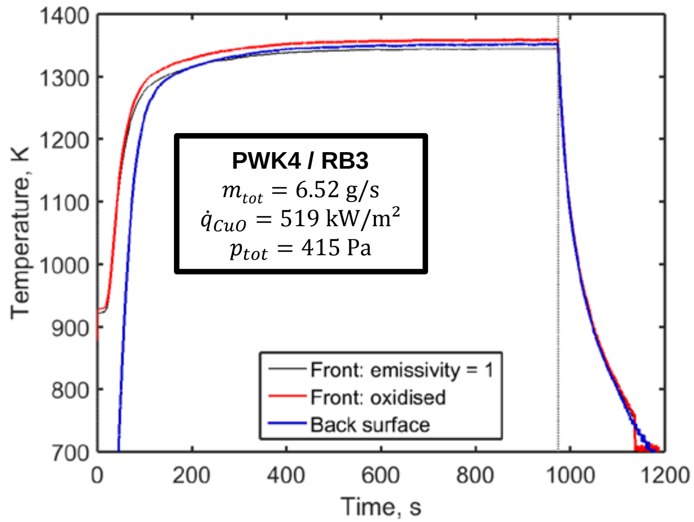
High-Temperature Ceramics: SSiC

- Very “well-behaved”, i.e. reproducible response behaviour
  - → Generally low effective heat fluxes due to low surface catalycity
  - → Steady state investigation provides additional low-catalytic heat flux reference
- Onset of active oxidation at very low pressure (10 Pa) observed above 1500 kW/m²
- **Projection:**
  Unlikely to demise even at “full” 1400 kW/m² reference heat flux

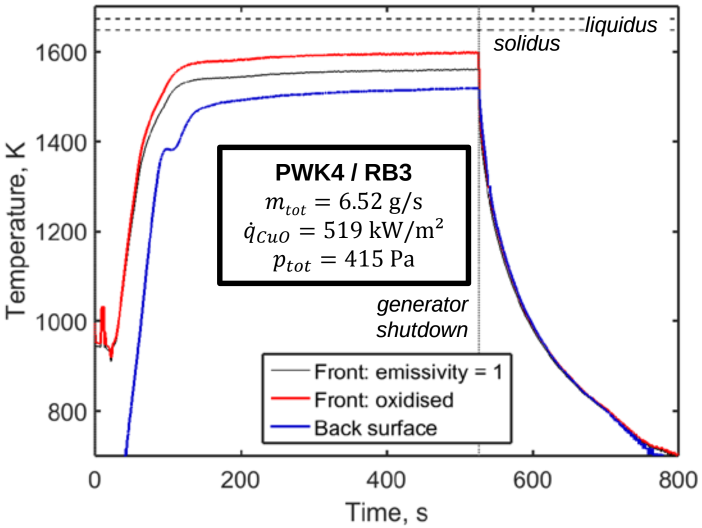


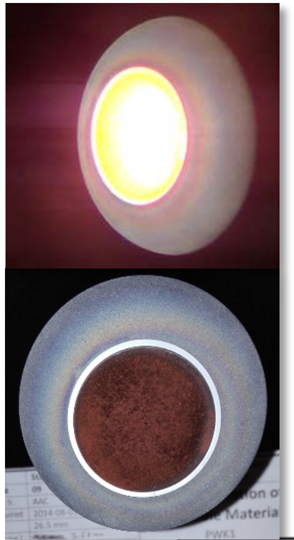




Metals: Type 316L Stainless Steel & Grade 5 Titanium

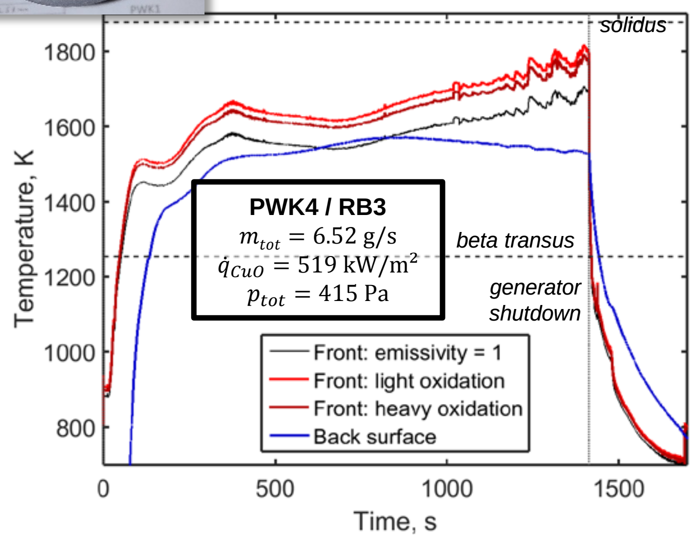
Type 316L Stainless Steel

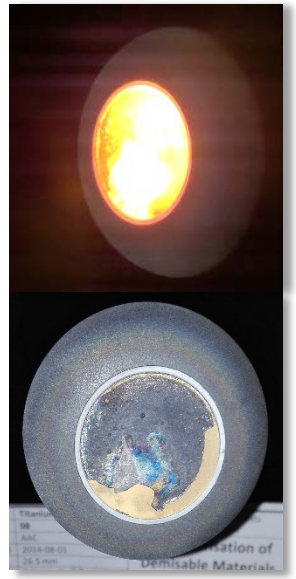




- No demise of either alloy at low and moderate heat flux condition (260 kW/m² and 520 kW/m²).
- Interesting features found in temperature histories of front and back faces, esp. at low heat flux.
- Erratic behaviour of Ti6Al4V (mod. HF), perhaps due to phase changes?

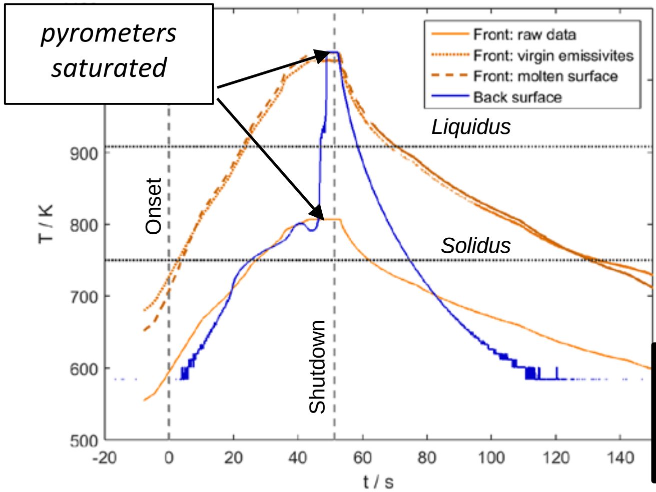
Grade 5 Titanium Ti6Al4V

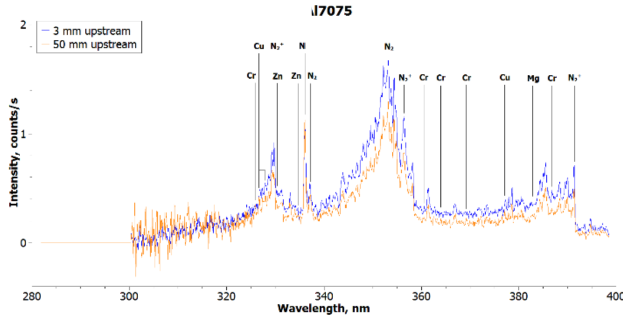




- Stainless steel is “well-behaved”.
- Significant influence of emissivity corrections at different surface states (virgin, oxidised, different stages of oxidation, etc.).
- Strong environmental influences on thermal response (catalycity) observed.

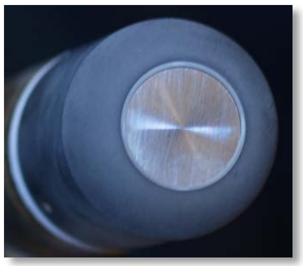
Metals: Aluminium Alloy Al7075-T651





PWK1 / RD5
$m_{tot} = 2$ g/s
$\dot{q}_{CuO} = 263$ kW/m^2
$p_{tot} = 10$ Pa

- Very rapid demise → additional low heat flux condition (125 kW/m²).
- Direct comparison of heating curve and video indicates direct link between onset of melt and "dent" in temperature history.



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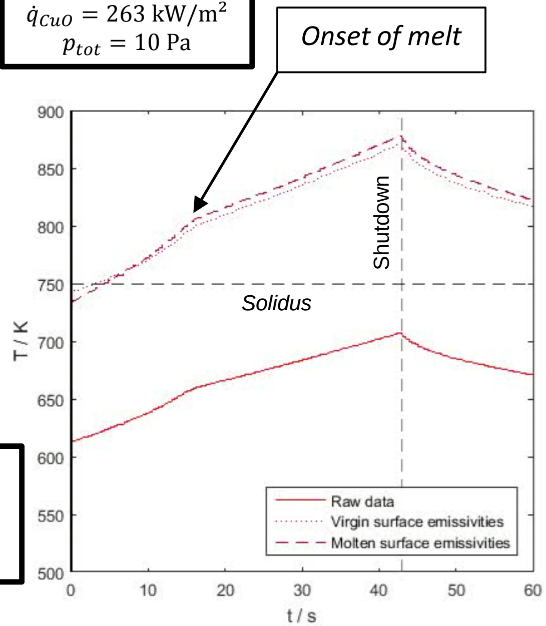
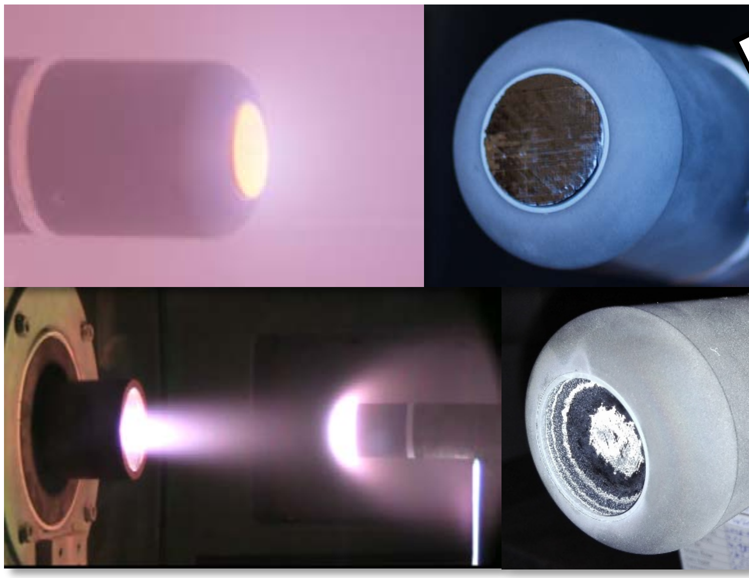
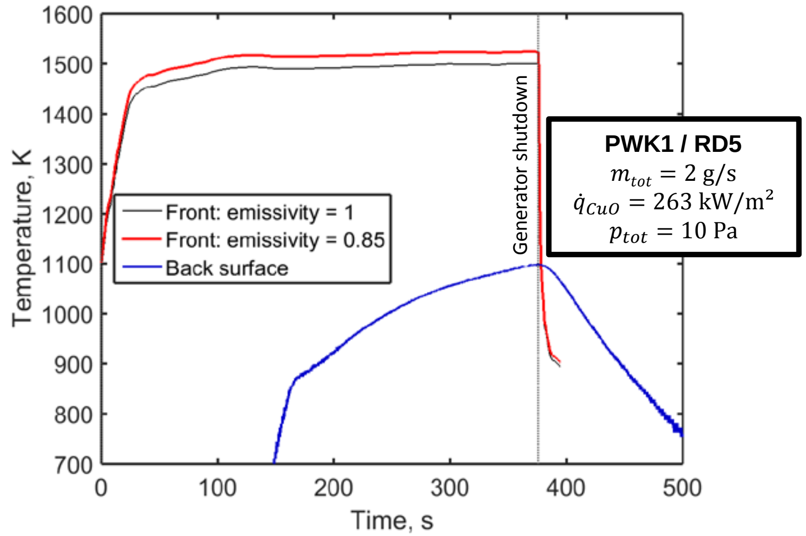
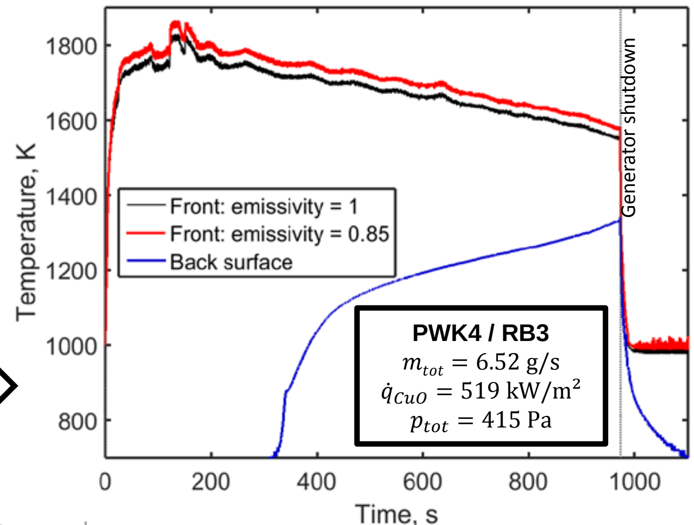


Organic Composites: CFRP EX1515/M55J

- Real-time surface recession tracking using laser-based measurement system (mod. HF only).
- Behaviour corresponds to that of a typical ablator. Initial bloating from outgassing.
- Remarkable thermal insulation properties and resilience observed over extended test durations (up to 16 minutes at 520 kW/m² at >80% loss in both mass and thickness).
- Delamination is largely avoided (no exposed edges).







Some Observations

- **On ceramics:**
  - High-temperature ceramics such as SSiC remain a tough nut to crack.
  - Essentially radiative TPS candidates (high thermal resistance, high emissivity).
- **On metals:**
  - Aside of the thermophysical properties, differences in catalycity and surface emissivity are particularly relevant for metals, surface emissivity is often under-predicted in models.
  - Emissivity and catalycity highly dependent on surface state, environment-dependent catalycity of metals is complex and highly relevant influence, merits additional investigations.
  - Heating histories may significantly affect demise-relevant material properties, however the investigated timescales often exceed those of typical entry manoeuvres.
  - Aluminium demises fast, however rate of demise is over-predicted in current models.
- **On CFRP (organic laminate composite materials) demisability in particular:**
  - Essentially behave like ablators (pyrolysis, outgassing → convective blockage).
  - High apparent survivability if shear forces/delamination are/is suppressed at least.
  - Relevant aerospace components such as tanks are often “wrapped” in laminate composites:

    → Closed structure may provide an inherent protection against delamination.

    → Could a deliberate cutting / tearing / exposure of edges spark a reliable demise?

Conclusions

- Evidence suggest that material models need improvement in destructive entry codes.
  - Such an improvement could make a big difference to our view of casualty risk.
  - Maybe more so than prospective improvement to heating and aerodynamics.
- Surface chemistry and evolution of emissivity with oxidation level and temperature must be treated with more realism.
  - Requires analysis beyond “burn to learn”.
  - Surface chemistry particularly dependent on (partial) pressures and enthalpy.
  - Testing in multiple plasma facilities at diverse conditions is proving very valuable for distinguishing these effects.
- Thermo-mechanical processes clearly play some role in the fragmentation and demise of components.
  - This also requires characterisation (e.g. the re-entry chamber).

Ongoing and Future Activities

- Conclusion of static facility (AAC), plasma wind tunnel and emissivity investigations (IRS).
- Remaining tests to be conducted at higher pressure regimes
  → More accurate representation of aeromechanical effects.
- Further post-test analyses, computational rebuild of test cases (BRL, FGE).
- Investigation of heterogeneous structures, e.g. tank wall segments (IRS).
- Formulation of standardised demisability test procedure (IRS).
- Debris risk assessment (BRL).
- Construction of material demisability database (FGE).