Influence of the Alloy and Dynamic Loads on Demisability of Aluminum

Clean Space Industry Days, 19.10.2023

Thorn Schleutker, Ali Gülhan (DLR), Erhard Kaschnitz (ÖGI), Patrik Kärräng (HTG), Tobias Lips (HTG) and Felix Hermann (MT Aerospace)

Presenting Author: Thorn Schleutker,

Supersonic and Hypersonic Technology Department,

German Aerospace Center DLR

Contact: Thorn.Schleutker@DLR.de

DLR

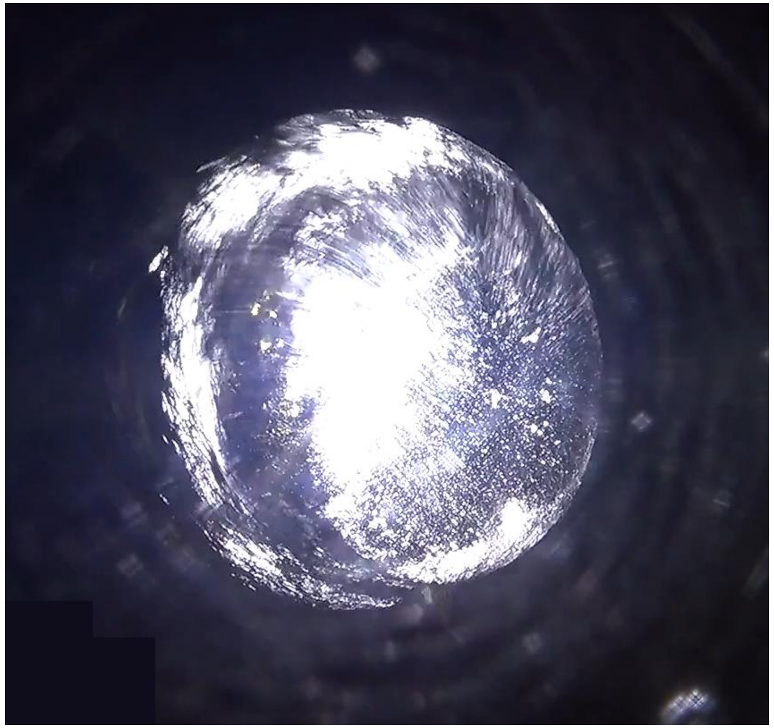
Background

Numerical demise prediction usually uses the “equivalent metal model” for simulation of the material, This means, that the material:

- Does not show any reaction other then melting
- And melts the moment the demise temperature is reached and the latent heat of demise is absorbed.

Aluminum alloys are among the materials that are closed to the ideal of a simple material that just melts when reaching its melting point.

So Aluminum is well understood and no problem. Right?



Shiny, melting aluminum at 1MW/m²

Background

Major open questions regarding aluminum are:

- Best criterion for considering the material demised.
  - -> When does aluminum demise?
  - -> At which temperature will aluminum be gone?
- Influence of the exact alloy on the behavior.
  - -> Do I have to test each aluminum alloy?
- How high is the thermal emissivity?

Same test, seconds earlier

Emissivity of aluminum

Emissivity of aluminum

Aluminum and its alloys are commonly modelled with $\varepsilon = 0.05$. But is this realistic?

Literature suggestions on thermal emissivity are often:

- A mirror finish will give emissivity of $\varepsilon = 0.05$.
- Machined surfaces are in the order of $\varepsilon = 0.2 – 0.3$.
- Rough or oxidized surfaces show $\varepsilon = 0.4 – 0.5$

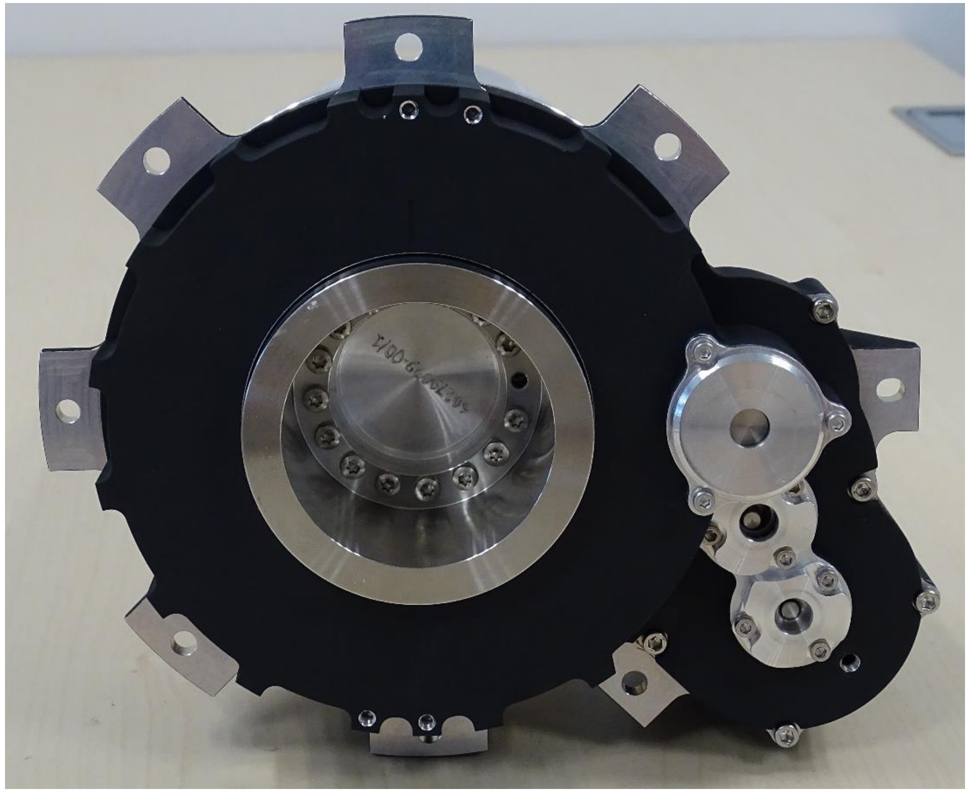
Attention! Lower values are suggested for remote temperature measurements by manufacturers of infrared sensors/cameras operating in the (near) visible range.

Thermal emissivity ≠ emissivity in the range of a sensor!

Emissivity of aluminum

And real flight hardware?

Parts made from aluminum often receive a surface coating that maximizes ($\varepsilon \approx 1$) thermal emissivity for heat management, see SADM housing on the right.



Other parts have metallic surfaces.

Do they stay shiny during the destructive entry flight?

Emissivity of aluminum

No, aluminum does not remain shiny!

AA 2050

AA 2219

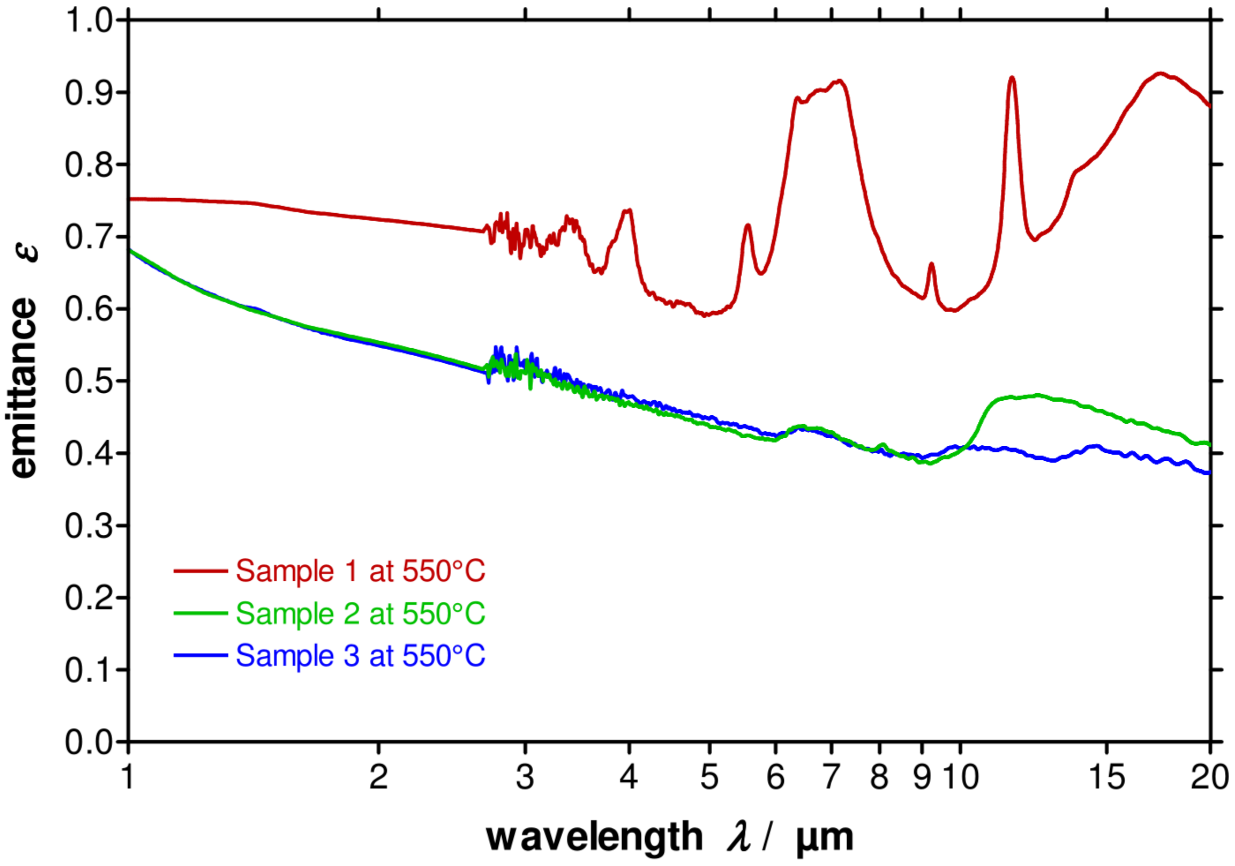
AA 6061

Emissivity of aluminum

For measuring the thermal emissivity of aluminum alloys, we exposed samples to a representative entry flight environment and measured the emissivity afterwards.

Normal $\varepsilon_{IR}(T)$ and hemispherical thermal emittance $\varepsilon_h(T)$ of the measured samples at temperature $T = 550°C$.

Sample	Temperature	normal thermal emittance $\varepsilon_{IR}(T)$	hemispherical thermal emittance $\varepsilon_h(T)$
1	**550 °C**	0.70 ± 0.02	0.68 ± 0.02
2	**550 °C**	0.46 ± 0.02	0.47 ± 0.02
3	**550 °C**	0.46 ± 0.02	0.46 ± 0.02



Demise temperature

Demise temperature

Alloys don´t have a melting point, but a melting range between solidus and liquidus temperature. The range can be quiet broad. Often, the mean of the melting range is used as demise temperature in the numerical models. Is this feasible?

The formation of strong oxide layers on the surface of aluminum alloys, which retains the liquid metal at temperatures above liquidus temperatures has been observed and shown before.

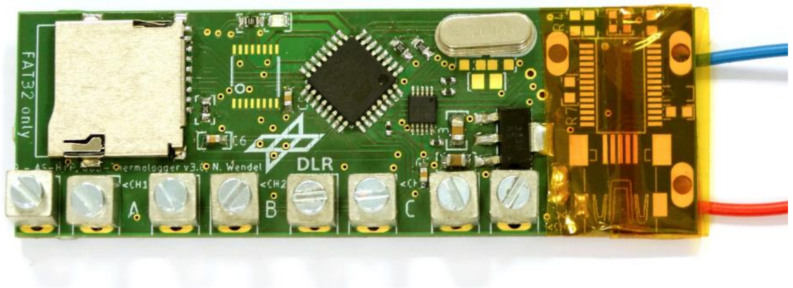
This suggests liquidus temperature + a few kelvin as reasonable threshold.


DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center
Institute of Aerodynamics
and Flow Technology
Supersonic and Hypersonic
Technologies Department

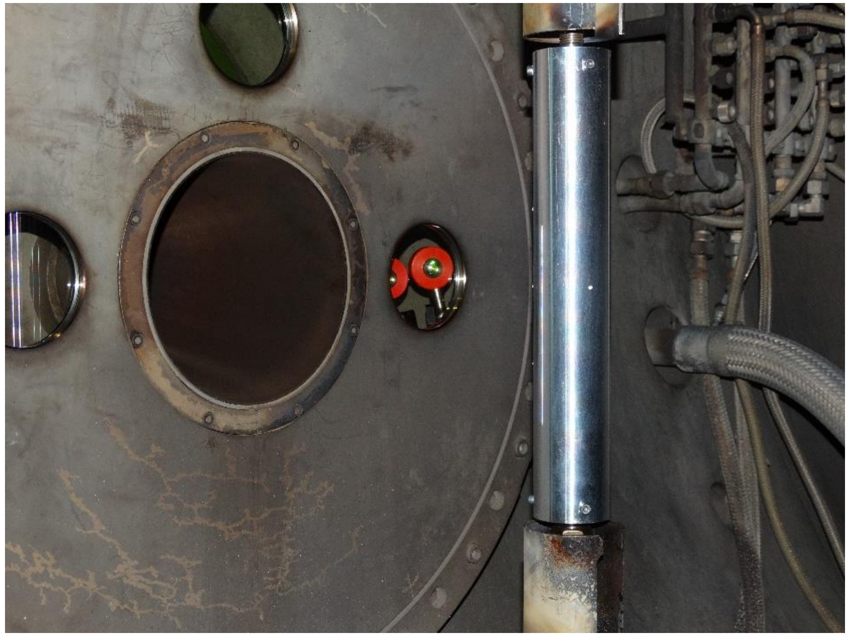
Demise temperature

What about dynamic loads? Shouldn´t they make the aluminum part fail below liquidus temperature?

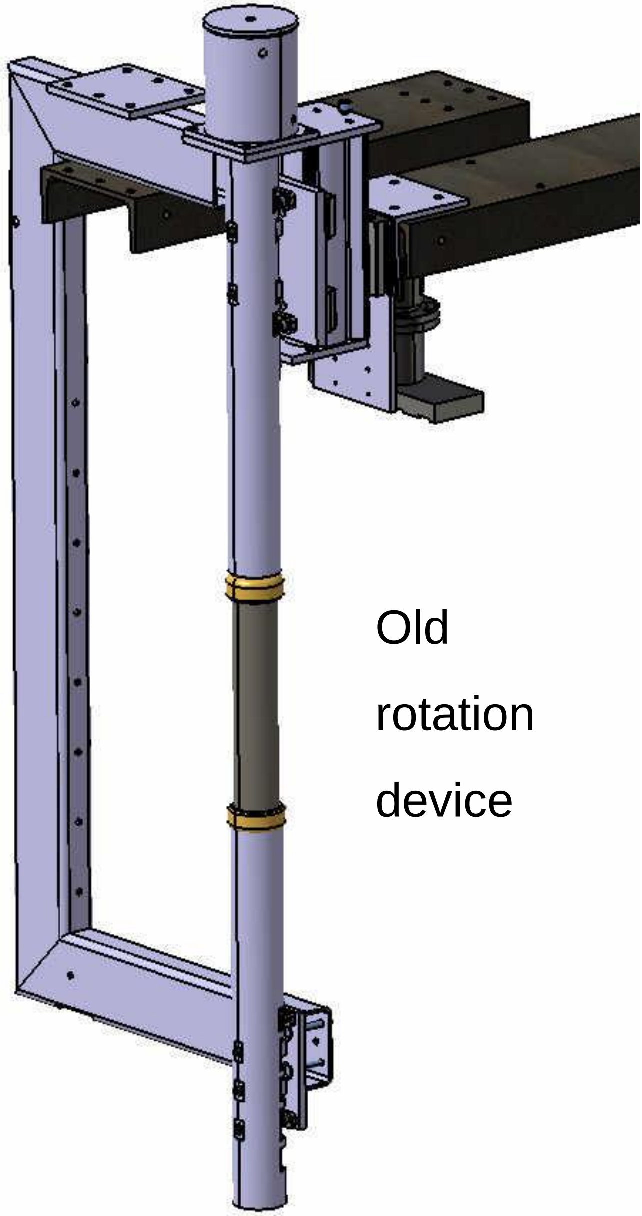
We tried that out with our rotation device.



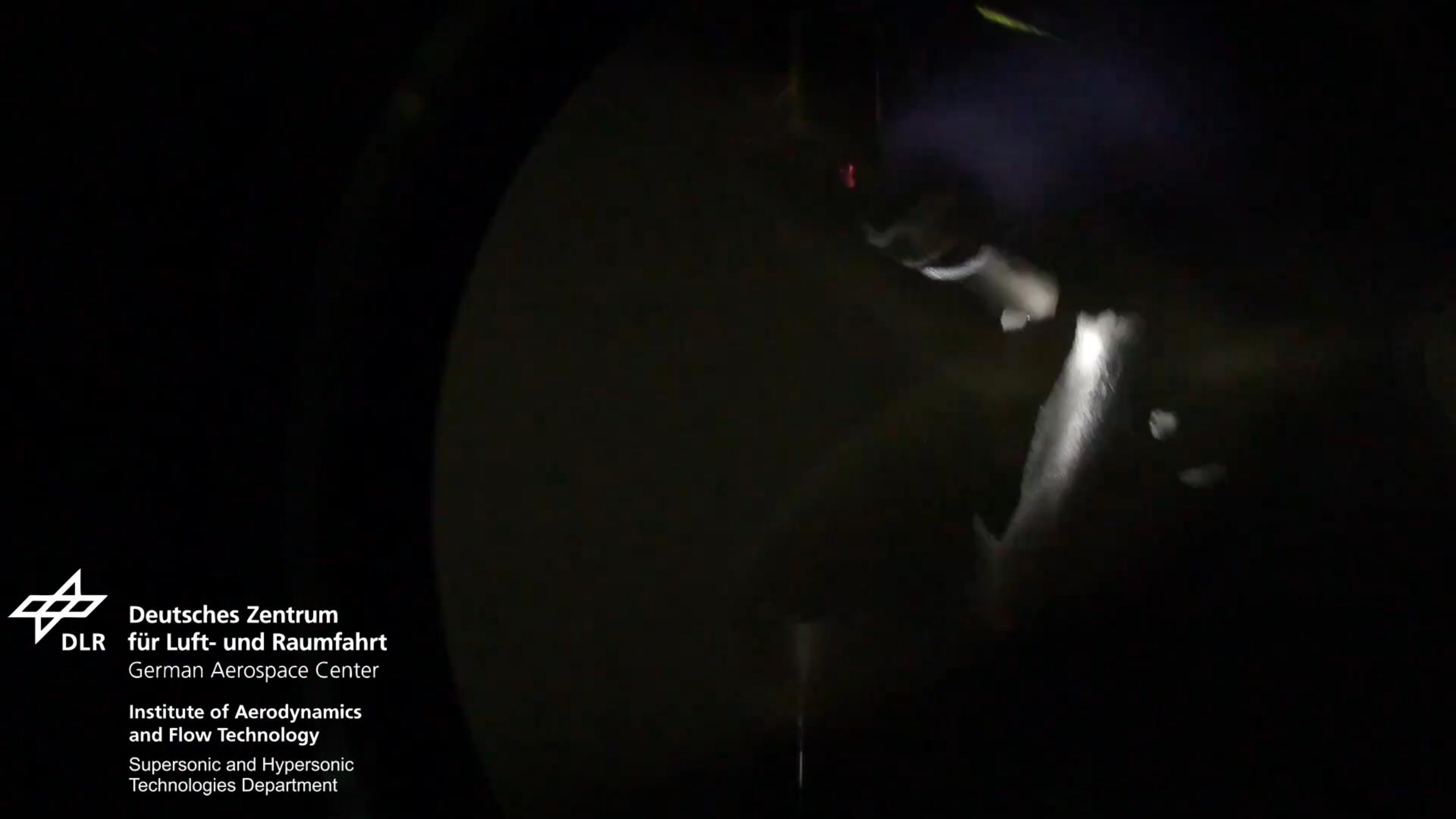
Data logger



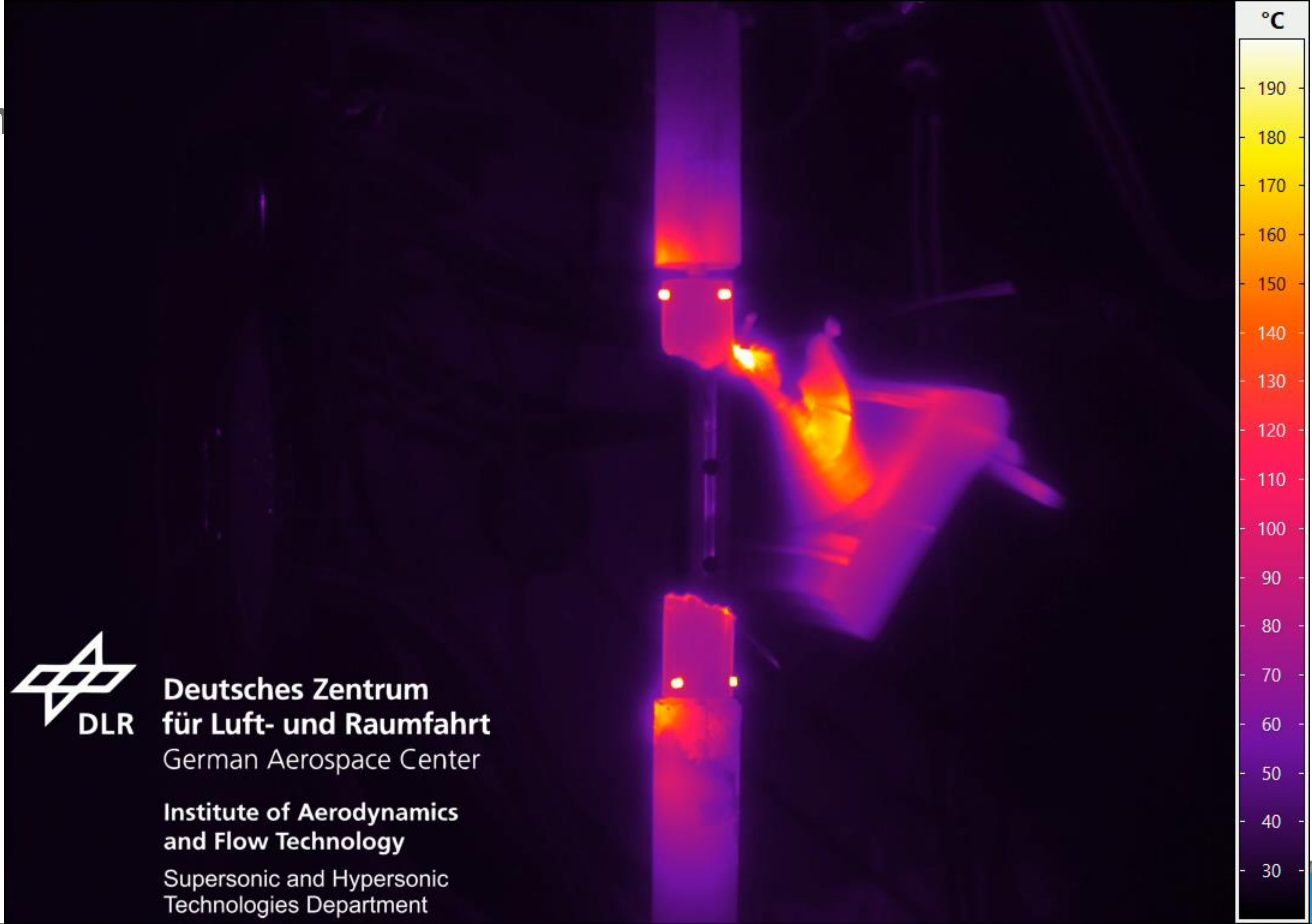
Setup



Old rotation device

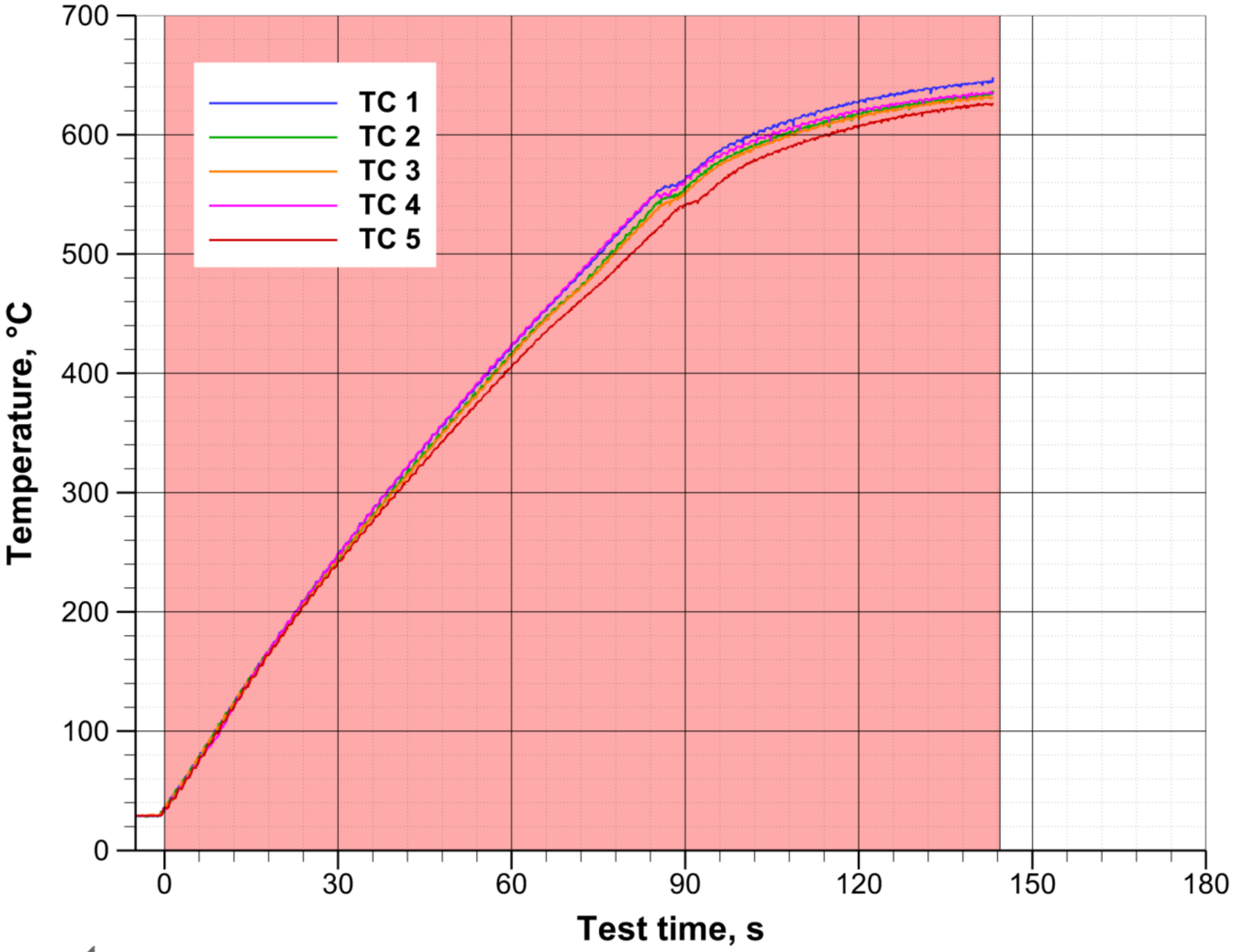

DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center
Institute of Aerodynamics
and Flow Technology
Supersonic and Hypersonic
Technologies Department

Dem


°C
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center
Institute of Aerodynamics
and Flow Technology
Supersonic and Hypersonic
Technologies Department

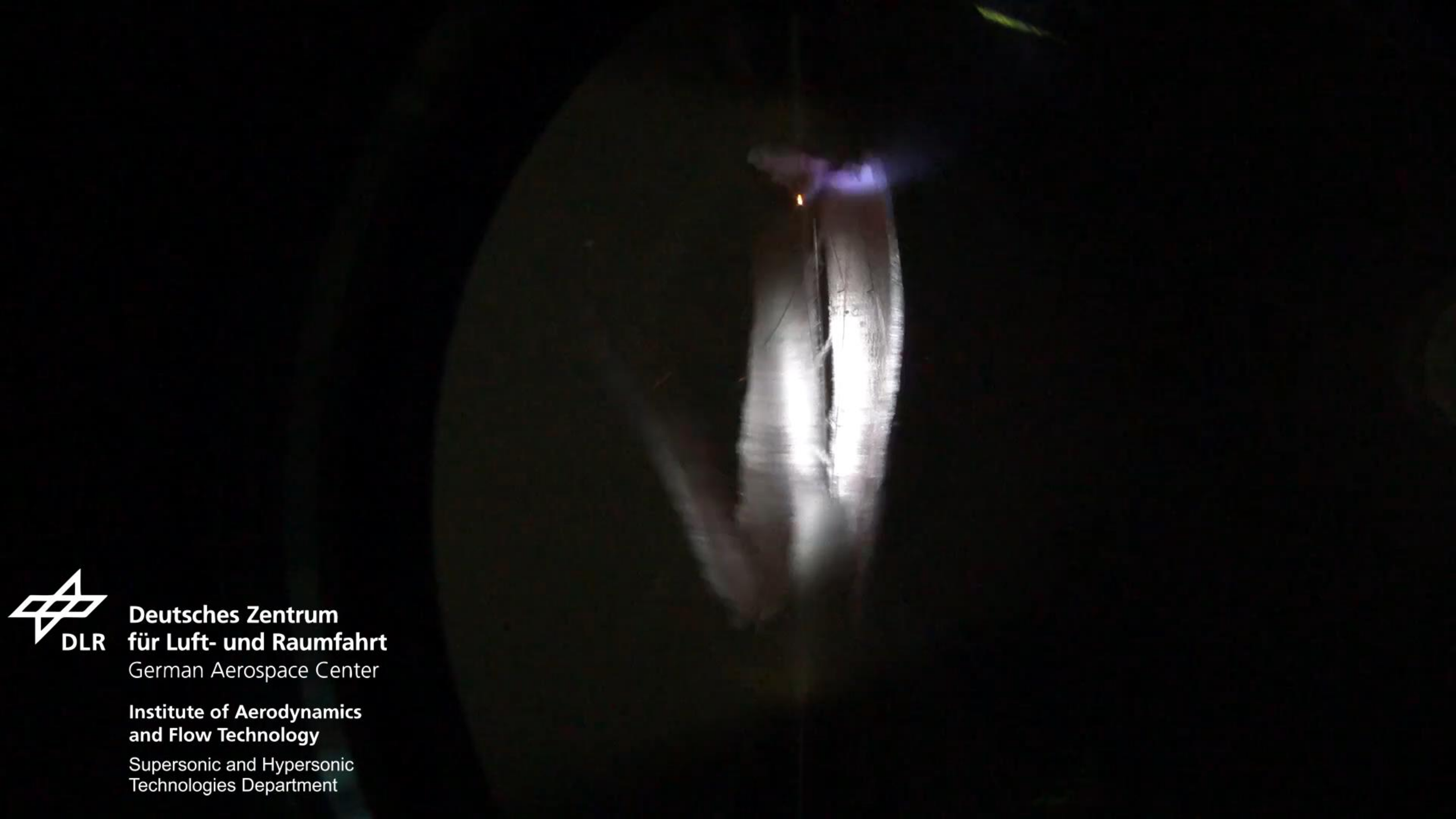
DLR

Demise temperature

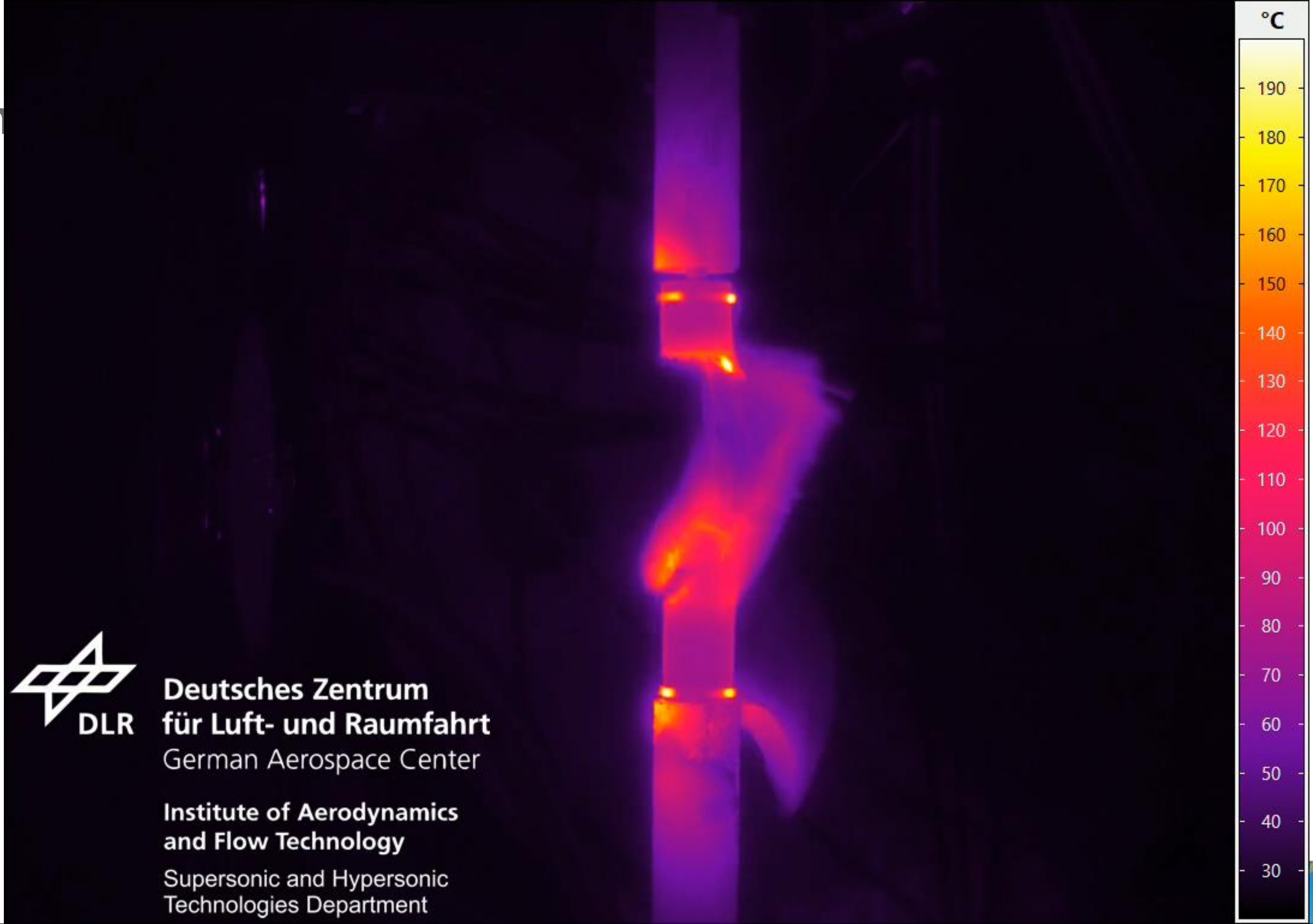


Slow rotation gives a homogeneous temperature distribution of the aluminum tube.

With the flow induced bending stress, the AA 2219 sample fails when slightly below liquidus temperature.


DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center
Institute of Aerodynamics
and Flow Technology
Supersonic and Hypersonic
Technologies Department

Dem


°C
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center
Institute of Aerodynamics
and Flow Technology
Supersonic and Hypersonic
Technologies Department

Demise temperature

Demise process at high rotation rate is very different, but the time to demise and demise temperature are only reduced by 5 seconds or 3 kelvin.

Acceleration: $a = r\,\omega^2$

Tension: $\sigma = \rho\, r^2\, \omega^2$

→ Centrifugal acceleration was high, but Tension in the metal was rather low.

→ Higher tension may by seen by larger spinning objects (e.g. tanks).

	AA 2050	AA 2219	AA 6061
Rotation rate	0.8 Hz	4 Hz	8 Hz
Centrifugal acceleration	0.6 m/s²	16 m/s²	63 m/s²
Tension	0 kPa	1 kPa	4 kPa
Time to demise	144.4 s	142.4 s	139.4 s
Demise temperature	635 °C	634 °C	632 °C

Influence on demisability

Critical heat flux

The following table shows the critical heat flux of the aluminum alloys.

$Q_{crit, old}$, uses the former assumptions

$T_{demise} = (T_{Solidus} + T_{Liquidus}) / 2$ and $\varepsilon = 0.05$.

Q_{crit} is based on the measured thermal emissivity and the liquidus temperature.

Critical fluxes are the average flux in the projected area (exposed front) in case of homogeneous temperature and radiative equilibrium for a tumbling sphere.

	AA 2050	AA 2219	AA 6061
$T_{Solidus}$, K	570	544	598
$T_{lquidus}$, K	648	646	651
Emissivity	0.68	0.47	0.46
$Q_{crit, old}$, kW/m²	6.9	6.4	7.4
Q_{crit}, kW/m²	**111**	**76.1**	**76.1**

This is high for aluminum. Can this be true? Yes! See Aluminum at 100 kW/m² in the 15 min test.

20x

DLR

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

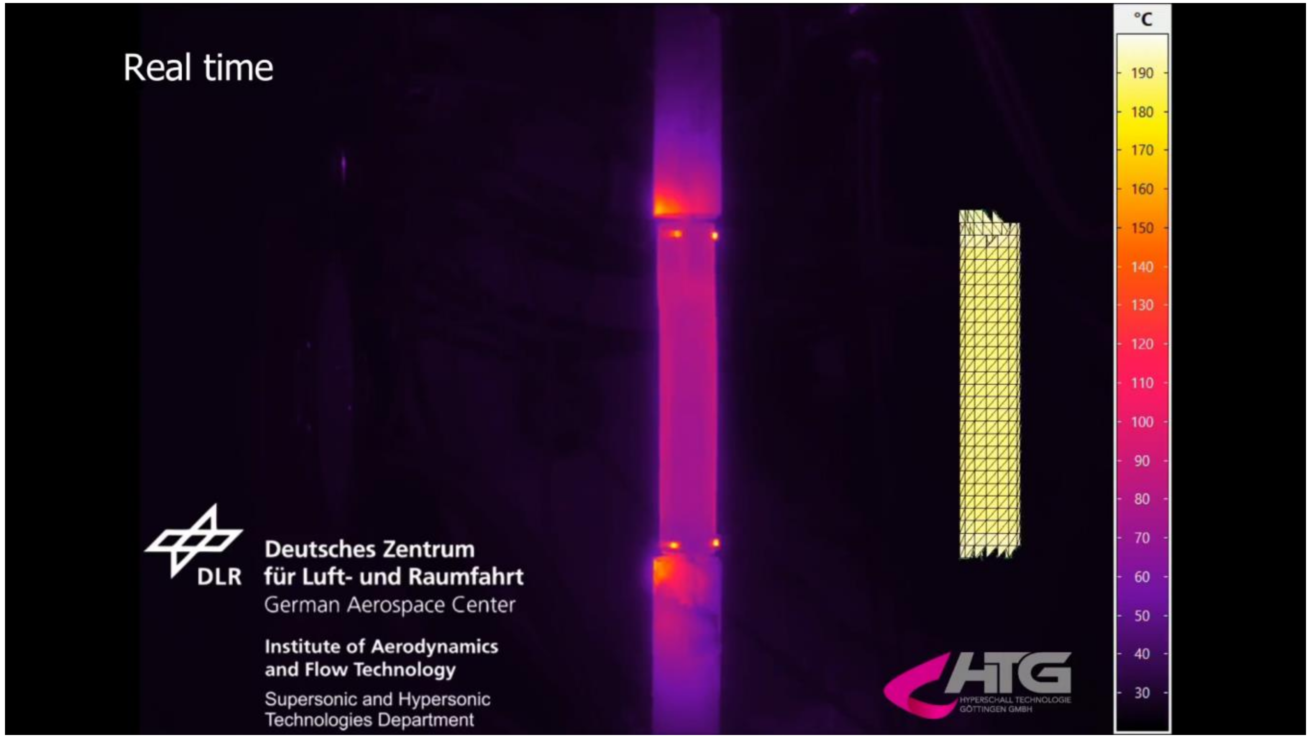
Institute of Aerodynamics and Flow Technology
Supersonic and Hypersonic Technologies Department

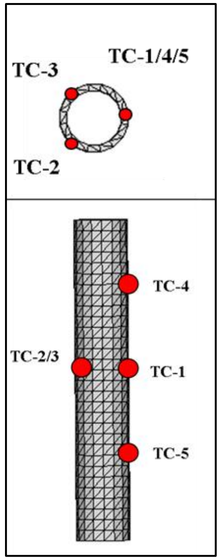
Numerical rebuilding is used to gain a deeper understanding of the demise process

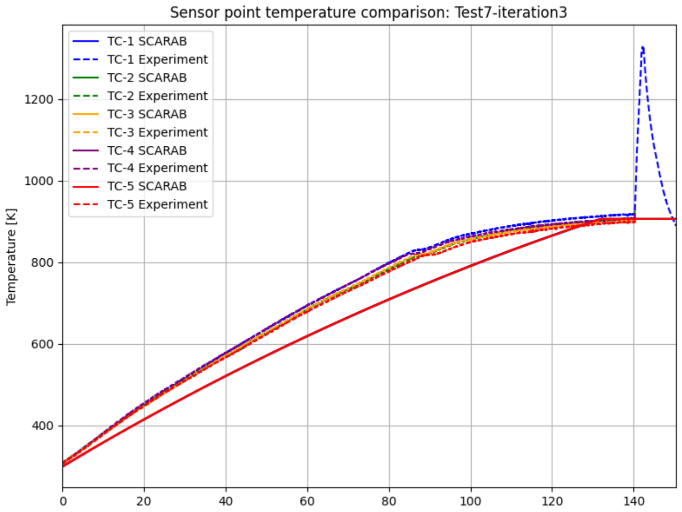
- Initial numerical predictions can be improved by rebuilding what is observed in the test.
- This can be achieved by changing material properties (e.g. emissivity, conductivity, melting temp.) or tuning the heat flux level [if justified]

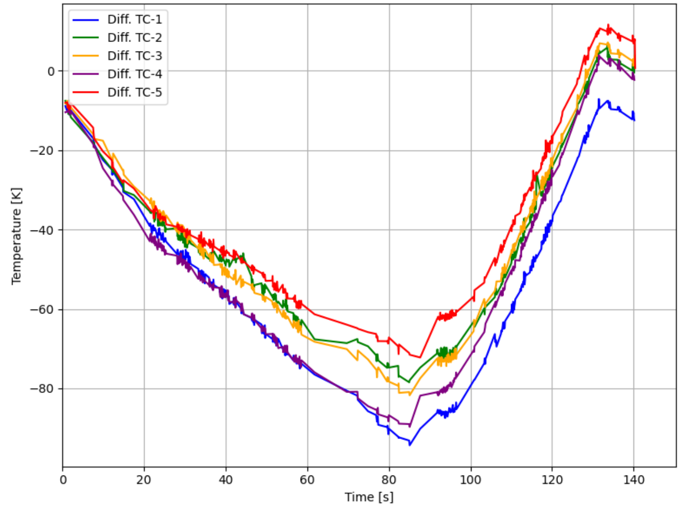
Demise time			
Predicted [Scarab4]		118.6 sec	-16.7%
Wind tunnel		142.4 sec	-
Numerical Rebuild [Scarab4]		132.6 sec	-6.9%

*Material properties of Cylinder: drama-aa2195-(al-li)





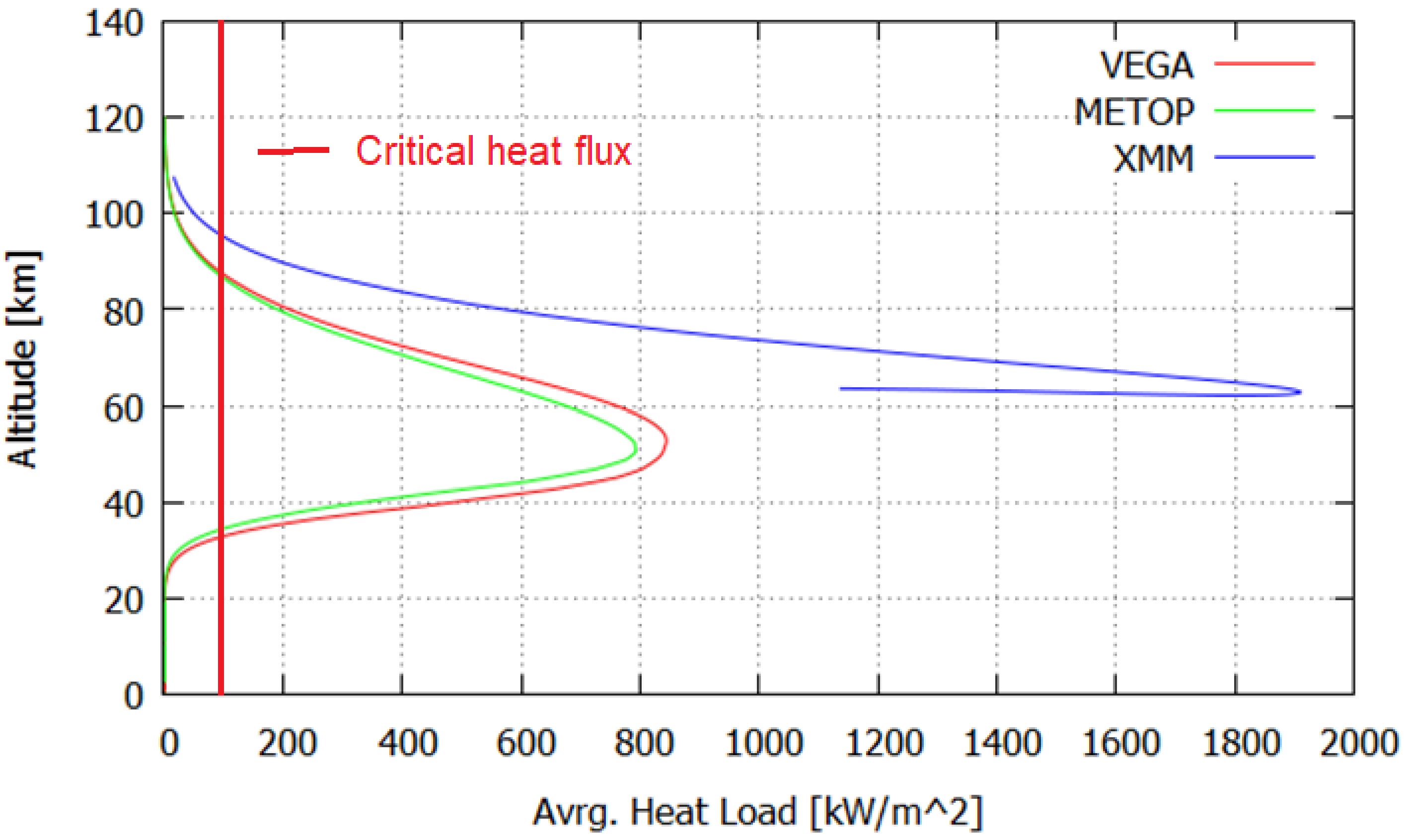




*Note: Difference = ScarabTemp - TestData

Influence on the satellite demise

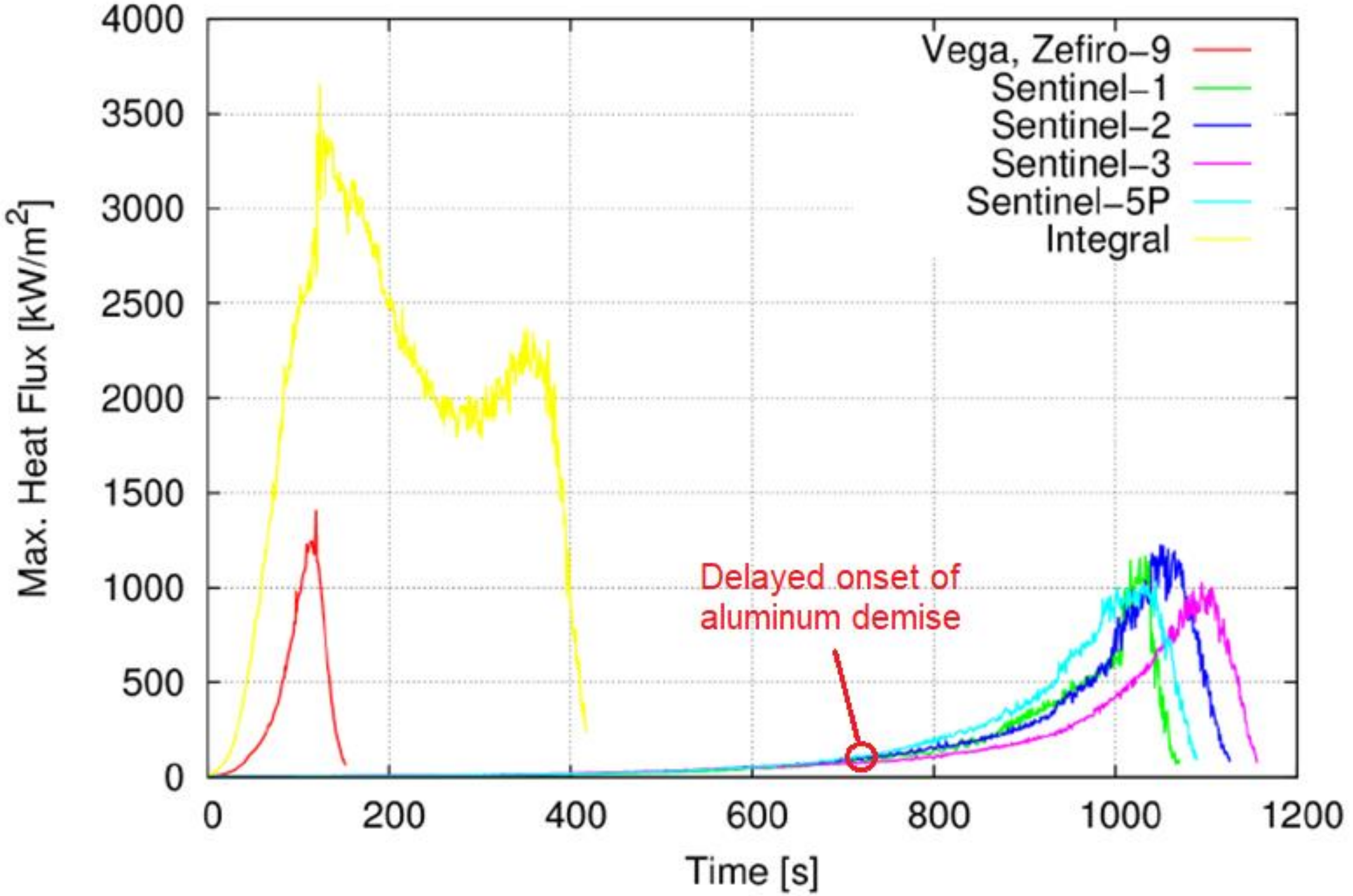
Aluminum is still a very demisable material, but the demise onset is delayed.



Influence on the satellite demise

Satellites may open up later

then previously expected!



Conclusions

Conclusions

The formerly used assumption in modelling of aluminum and its alloys were overly optimistic and cannot be used for entry flight simulations. To improve the rebuilding, we have to:

- Select a demise temperature at the liquidus temperature or higher, unless high mechanical justify a temperature a few Kelvin below that.
- Characterize the aluminum alloy that is to be used. Aluminum alloys are not the same!
- Use the correct, measured emissivity of the alloy or the surface coating.
- Investigate the influence of the oxide skin forming on aluminum parts. This may be a problem in the low force environment of the early entry flight.