Theoretical and Experimental Progress in the understanding of destructive re-entry

JAMES BECK, IAN HOLBOUGH - BELSTEAD RESEARCH LTD
THORN SCHLEUTKER, ALI GÜLHAN – DLR

4TH INTERNATIONAL WORSHOP PN SPACE DEBRIS RE-ENTRY, DARMSTADT, 28 FEB – 1 MARCH 2018
PR00011 / D22

Campaign Objectives

Provide basic phenomenological data on the demise of particular spacecraft materials and structures:

- aluminium,
- CFRP and sandwich materials and
- representative spacecraft components.

Tests designed to extend work in a number of recent projects (ESA, UKSA)

- Complementary to ESA D4DBB project
- Identification of key gaps in knowledge
- Shear testing of aluminium
- What happens to facesheets when removed?
- Complete complex structures; Reaction Wheel and CubeSat

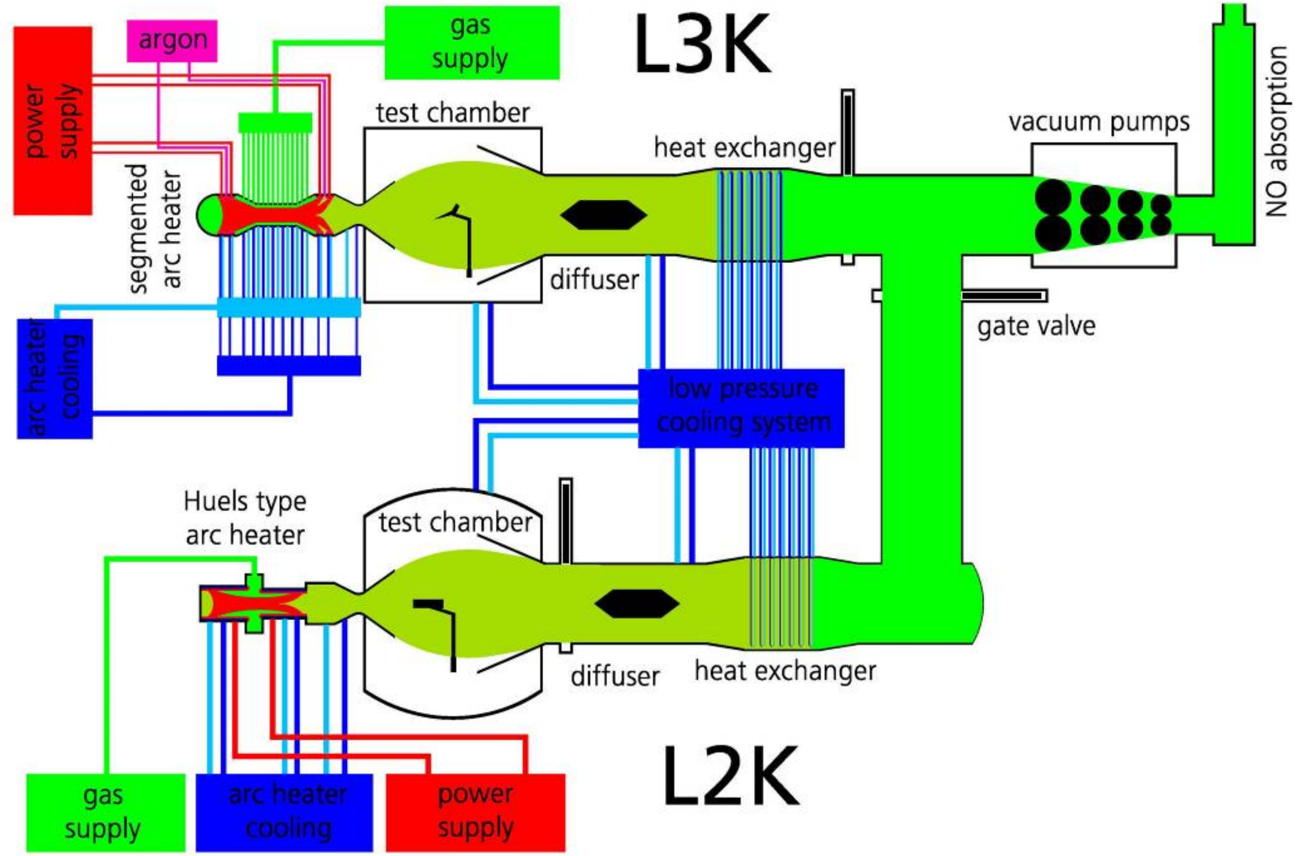
Significant number of innovative tests performed, in total 22 samples and 24 tests.

Test Facility

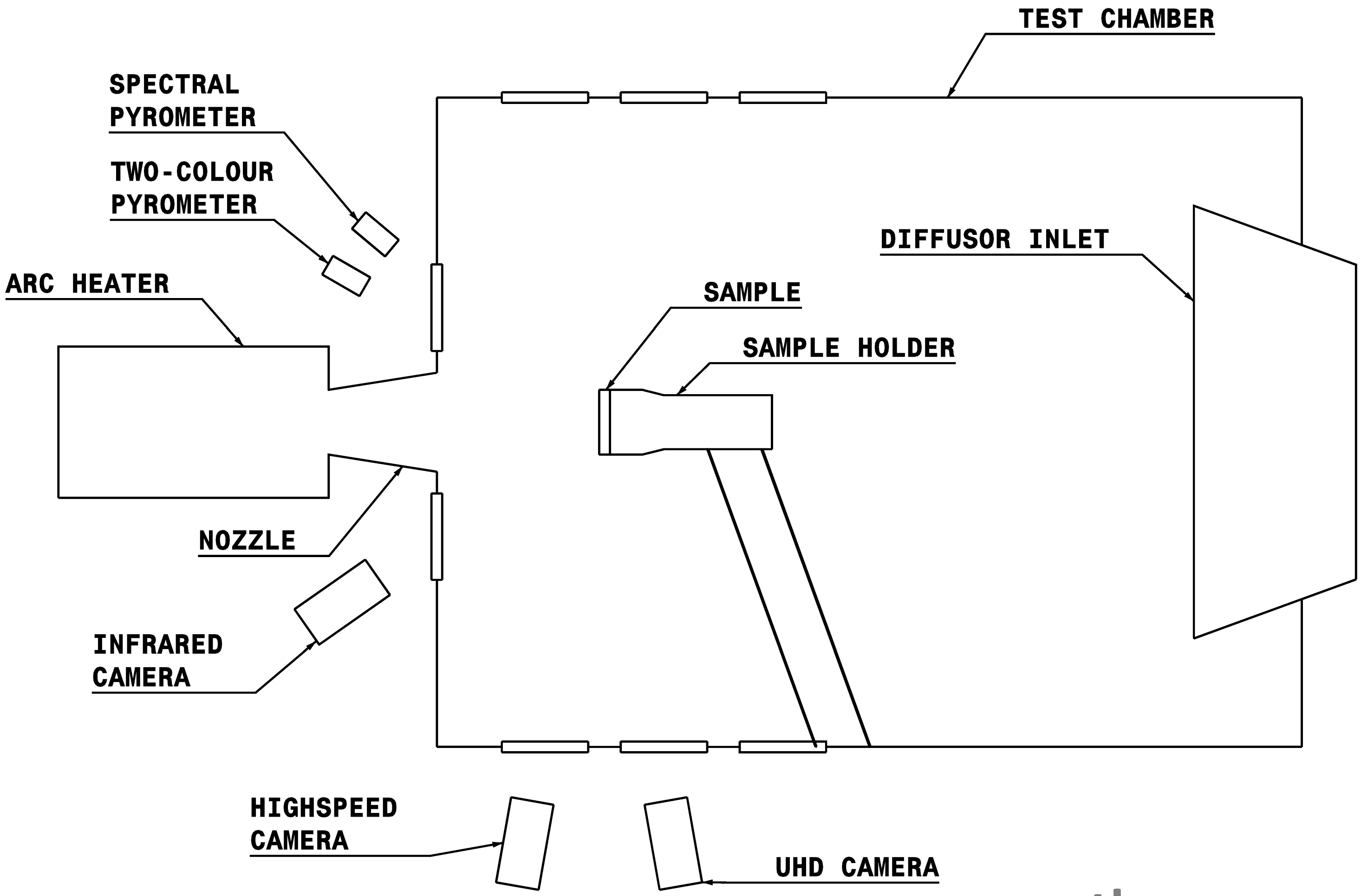
General test conditions

- Hypersonic flow
- High enthalpy
- Dissociated gas
- Long duration testing
- Working gases:

  Air, $CO_{2,}$ CH4 etc.



Test Instrumentation

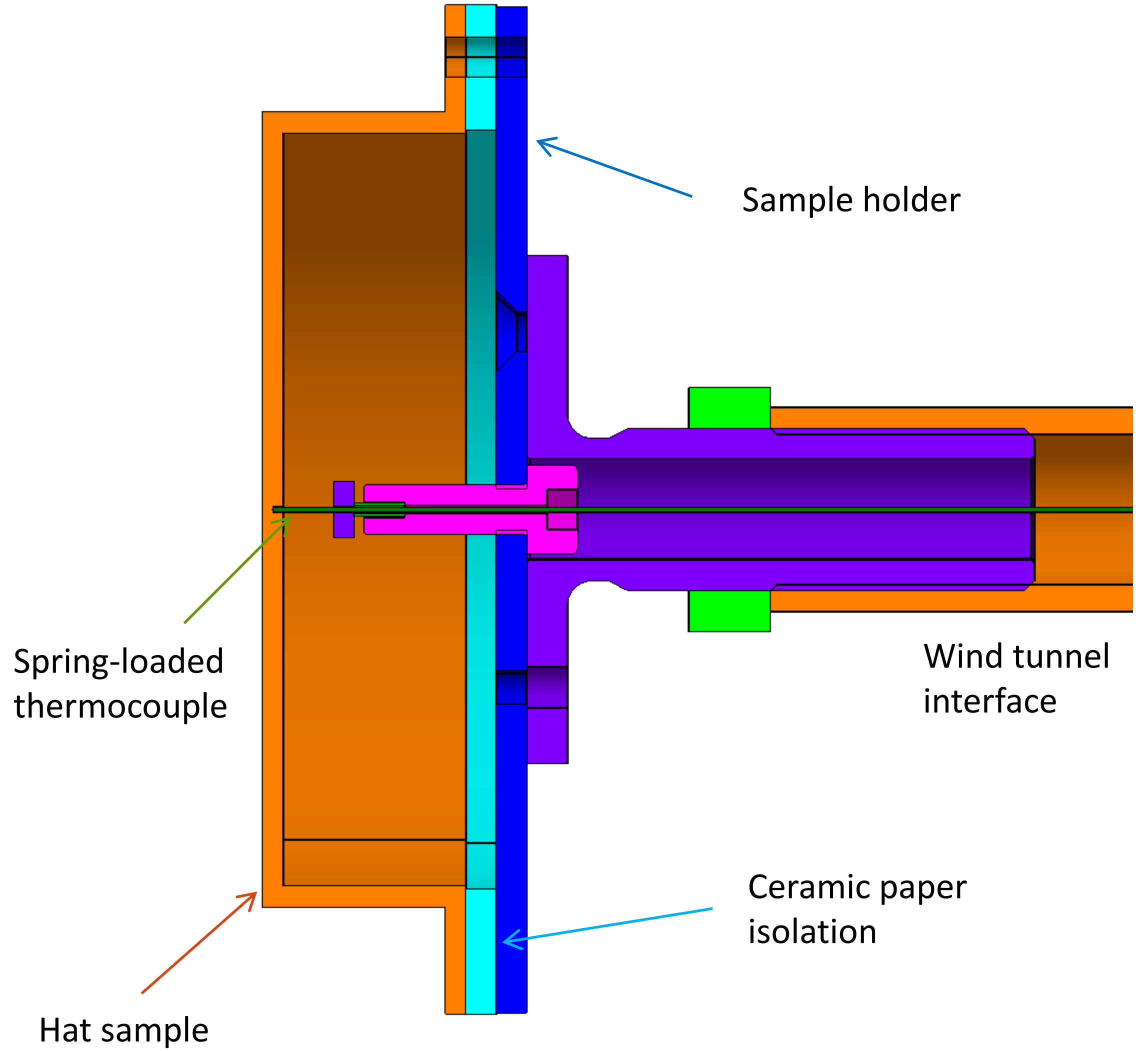


+ thermocouples

Sample Holder

Sample holder…

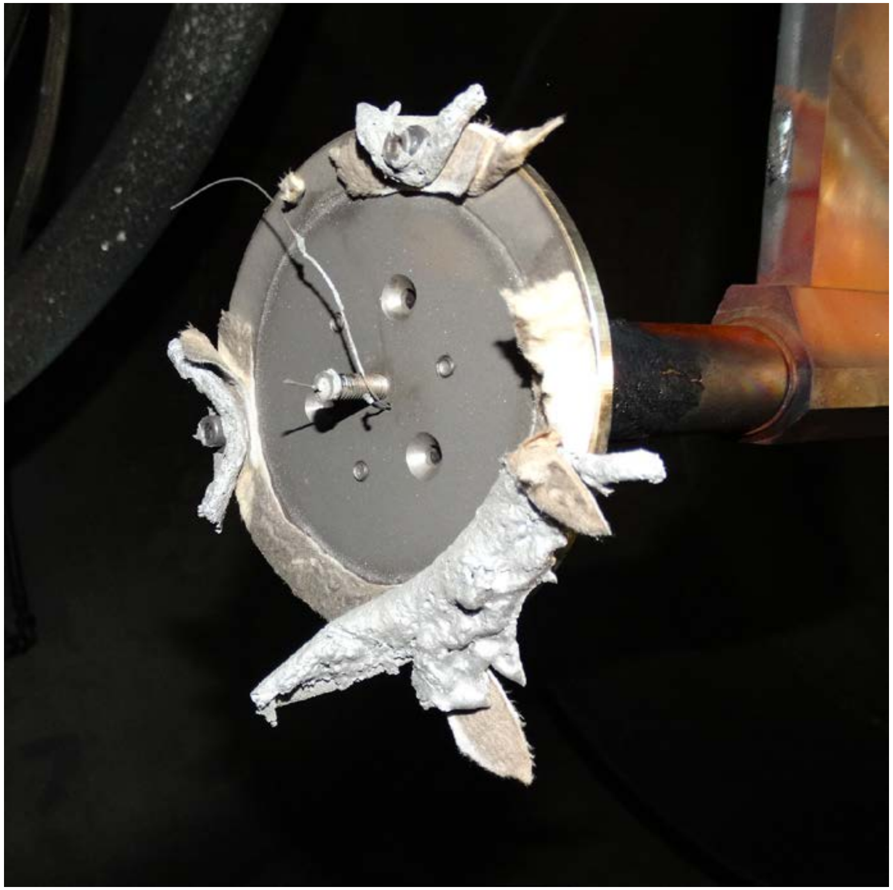
- parts generally made from stainless steel.
- thermally isolated from sample.
- holds thermocouples in its nominal position mechanically.



Aluminum Hat

Sample set up in the wind tunnel

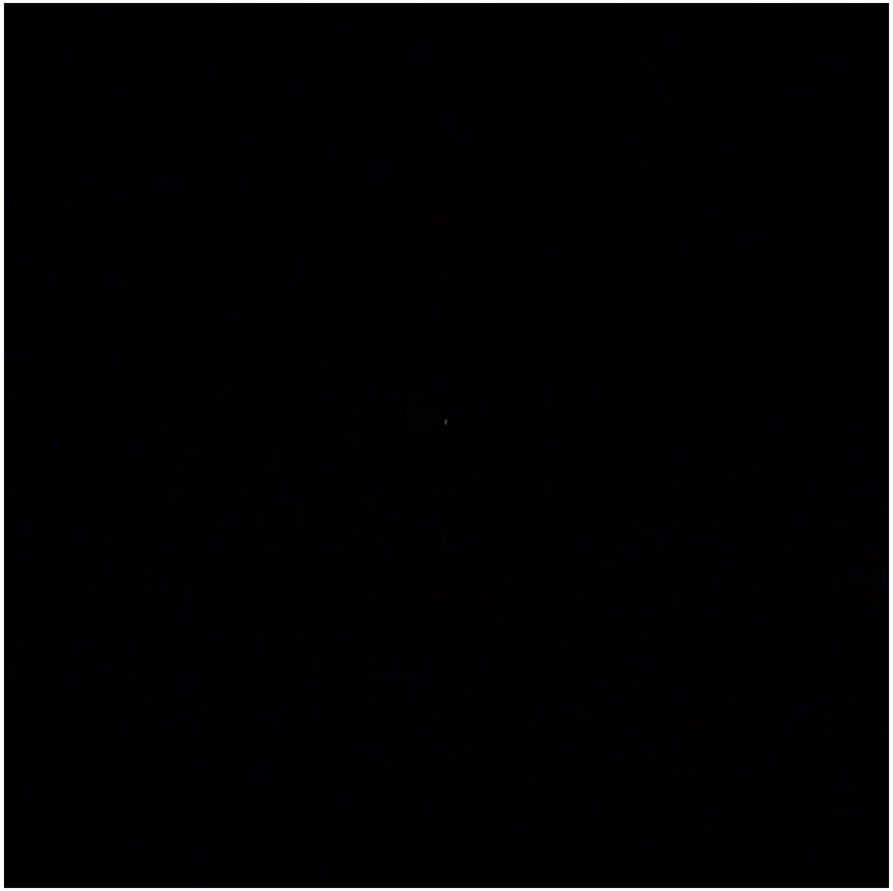
before testing



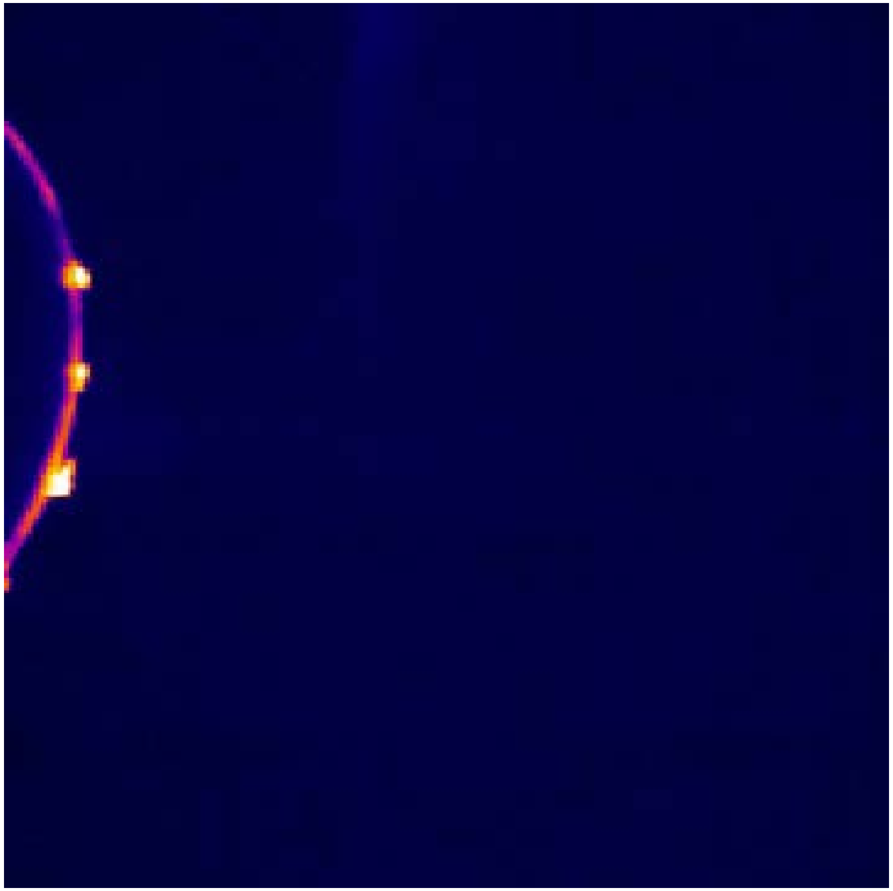
After testing

Aluminum Hat

Test videos



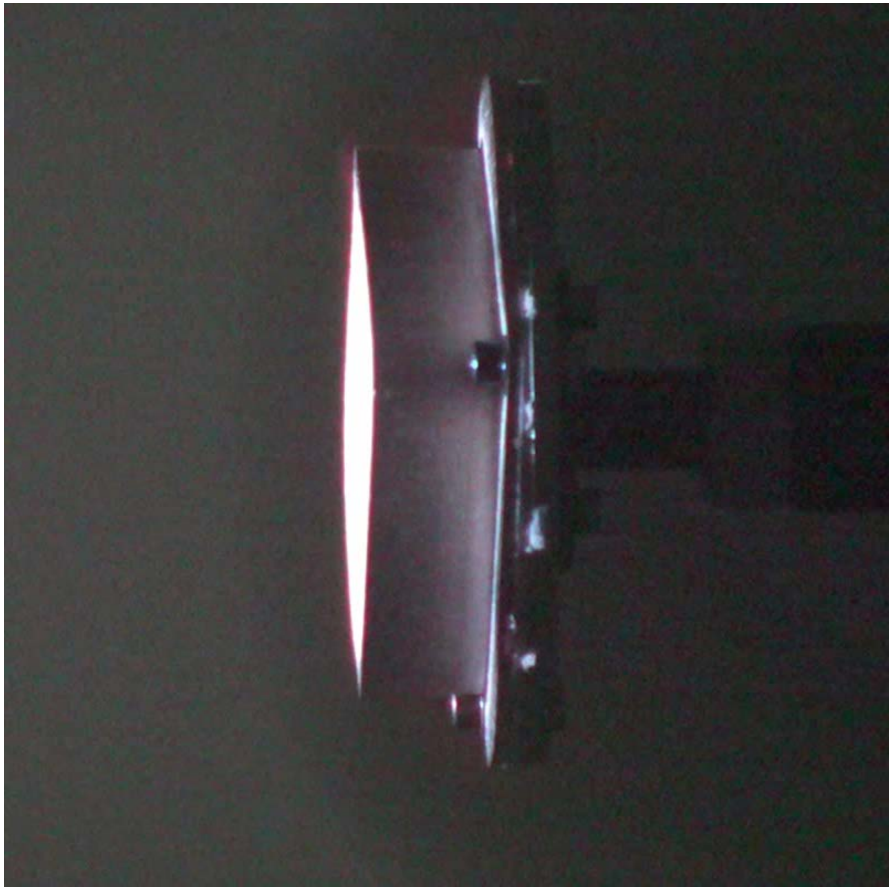
Visual camera



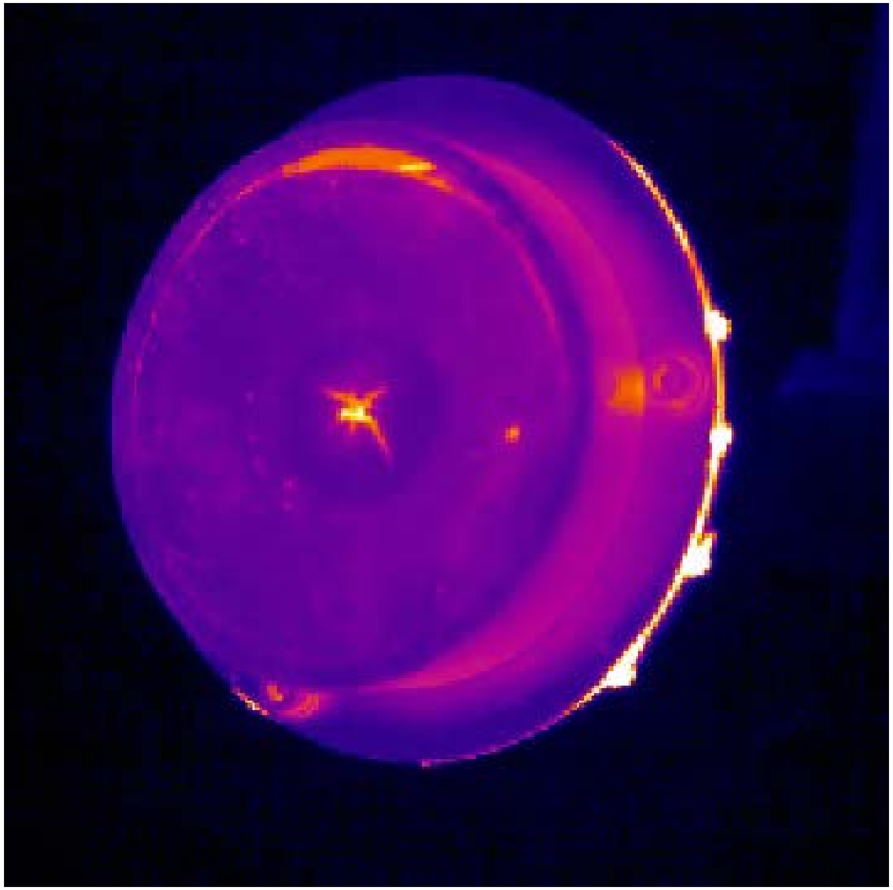
Infrared camera

Aluminum Hat

Test videos – slow motion



Visual camera



Infrared camera

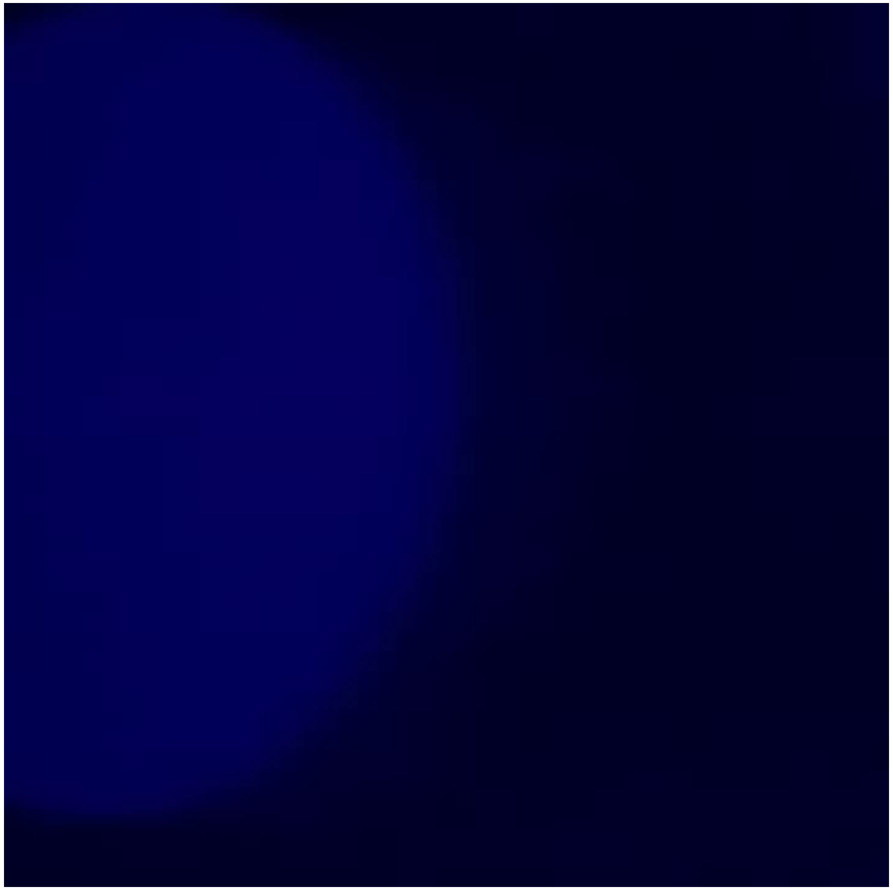
Aluminum cover of Reaction Wheel

Reaction wheel cover…

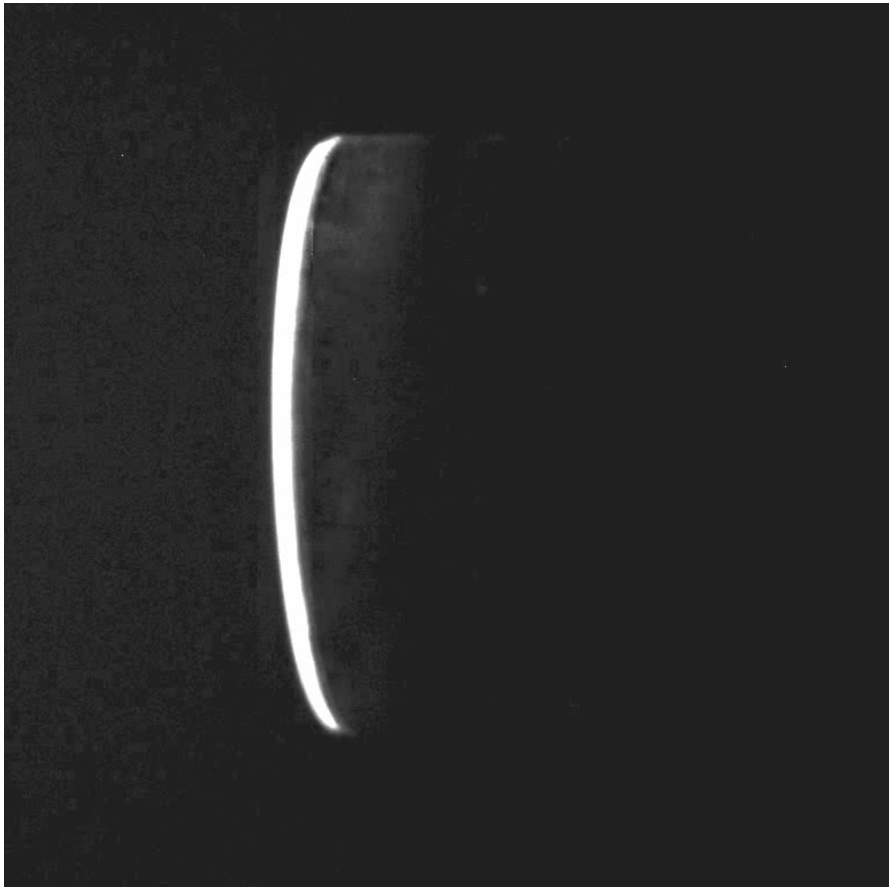
- is similar to hat samples (aluminum, thin).
- glued in place.
- painted black for good (infrared) radiation of heat.

Aluminum cover of Reaction Wheel

Test videos



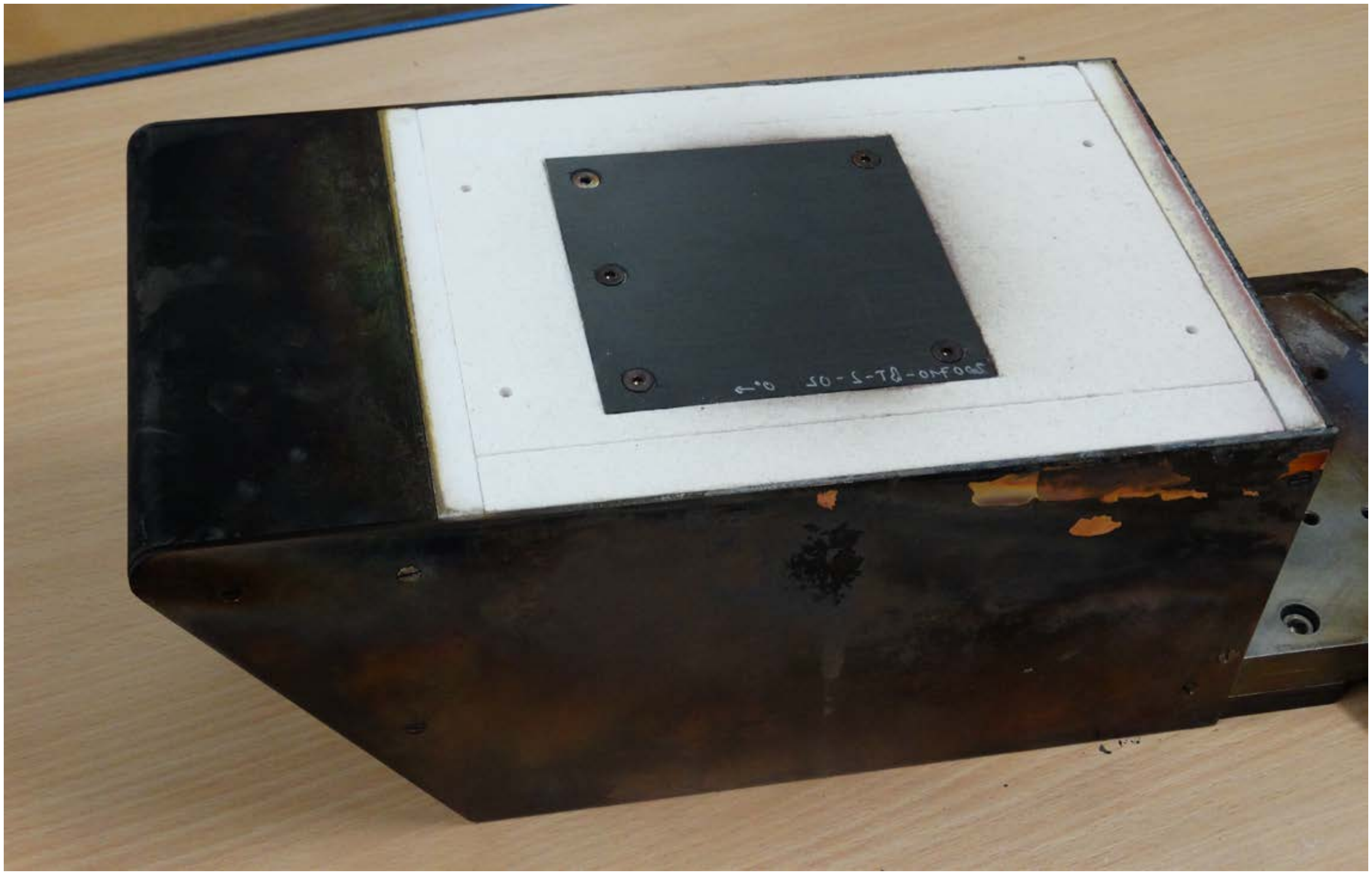
Infrared camera



Highspeed camera

Aluminum Shear Tests

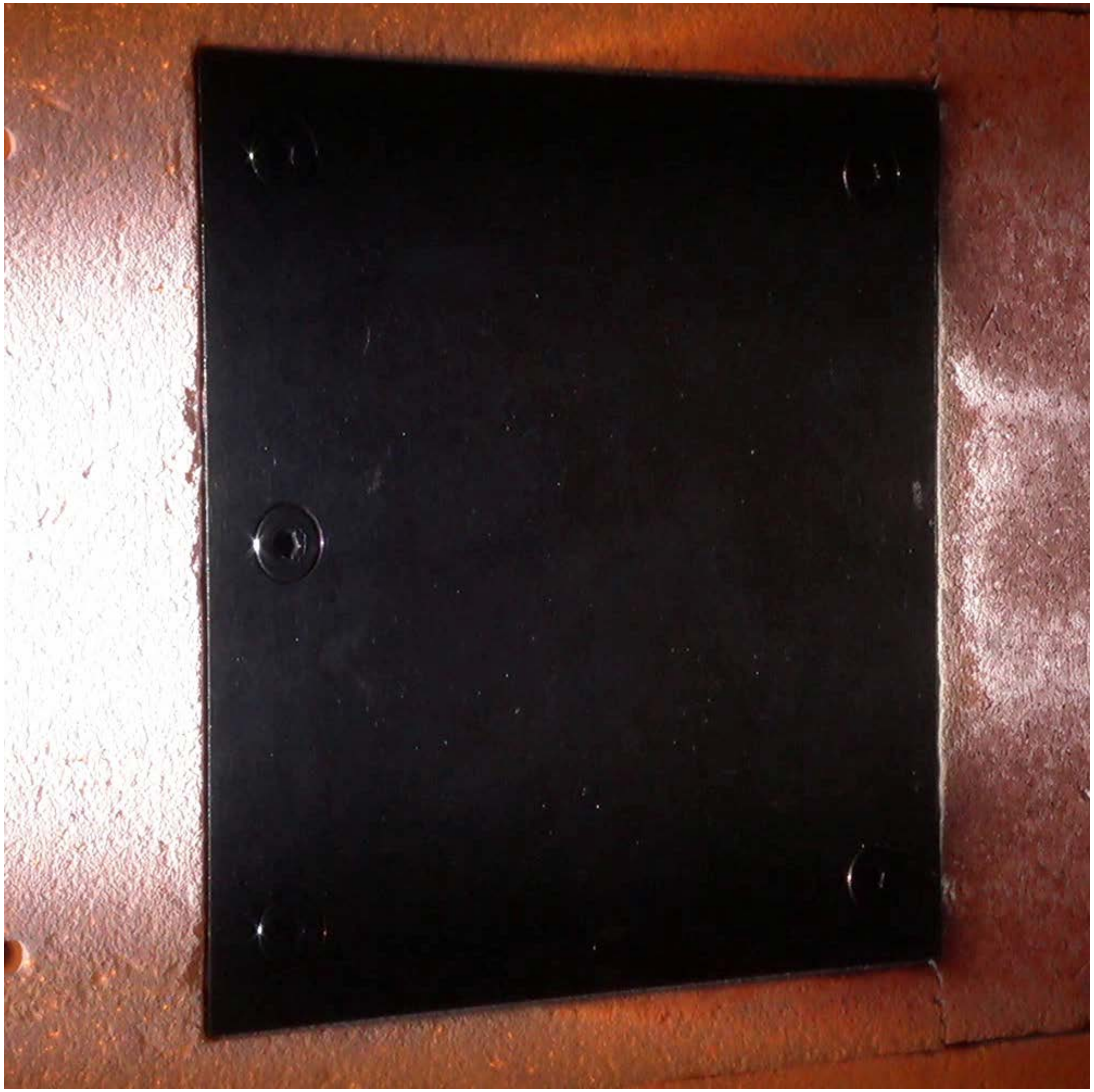
Shear test sample holder



Aluminum Shear Tests

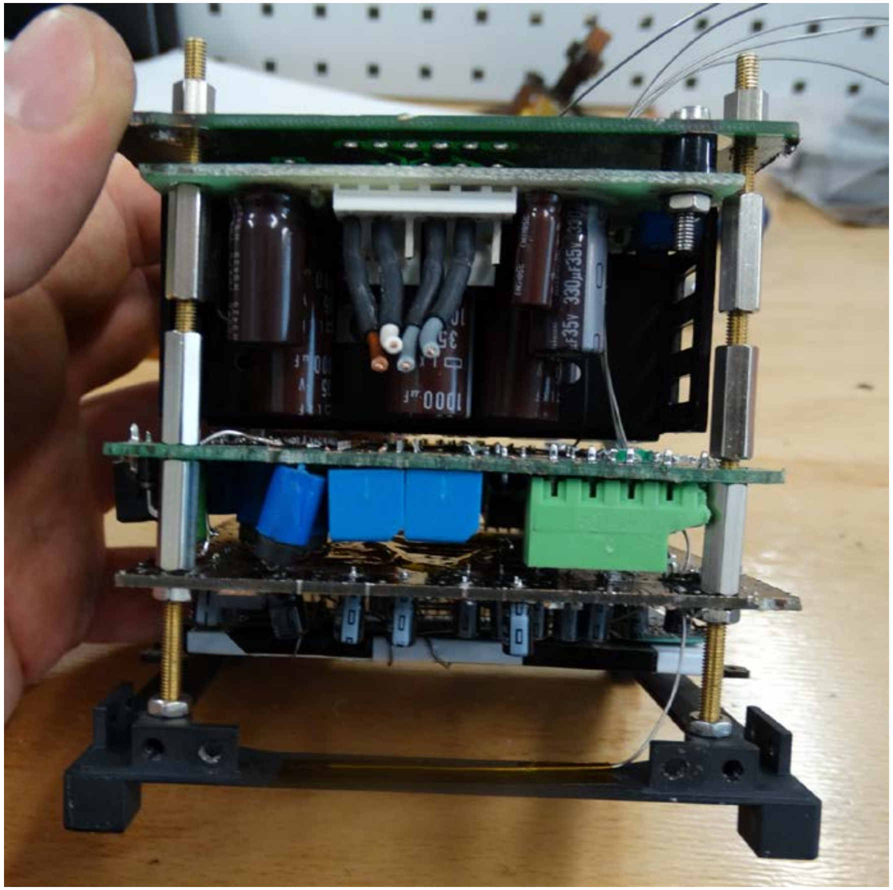
Shear tests show…

- bubble formation on surface when alloy components start vaporizing and
- aggregation of molten aluminum below oxide skin.
- spilling of melt when oxide bag breaks.



CubeSat

CubeSat before testing

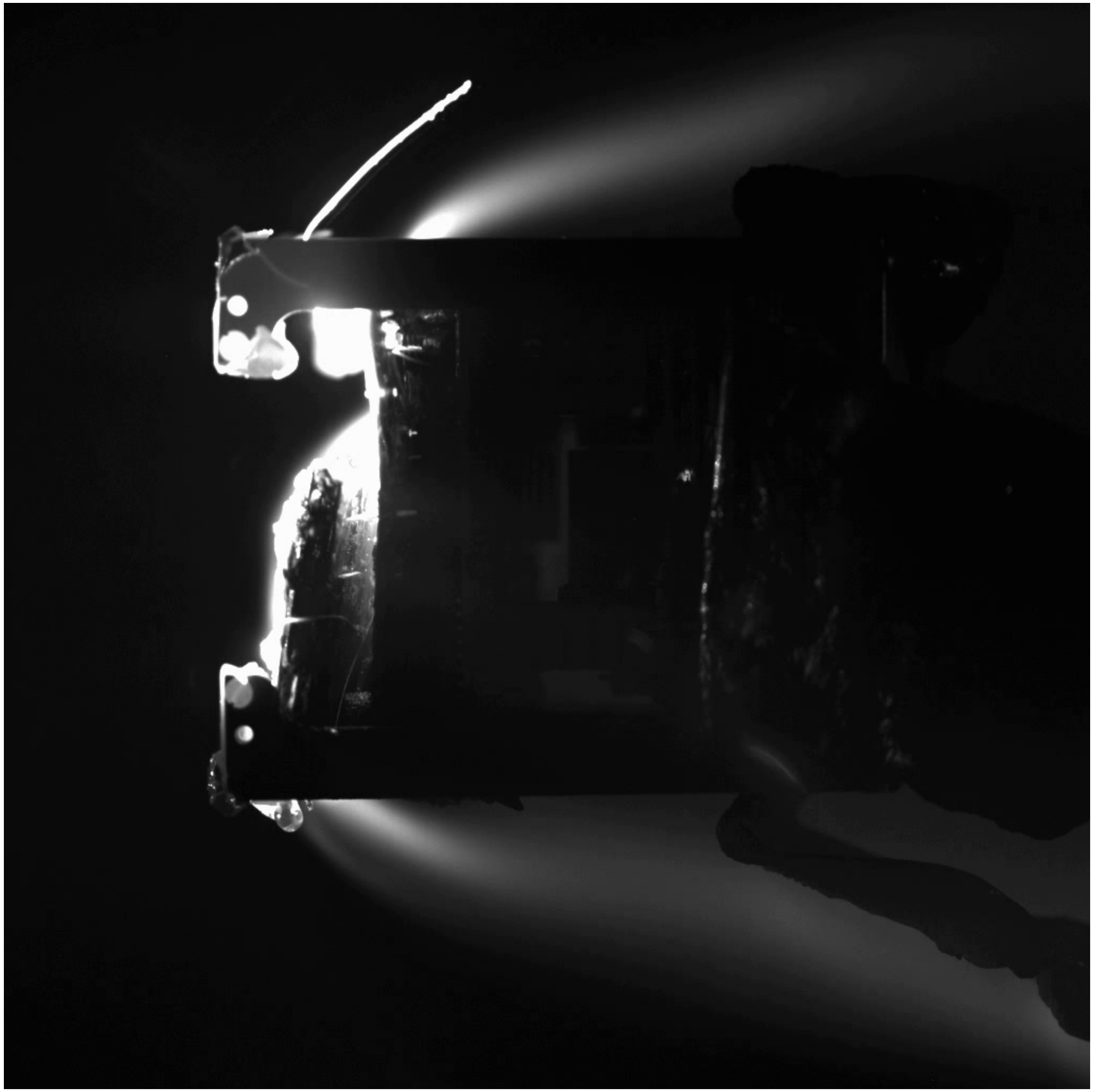


during integration, PCBs exposed

sample set up in the wind tunnel

CubeSat

CubeSat

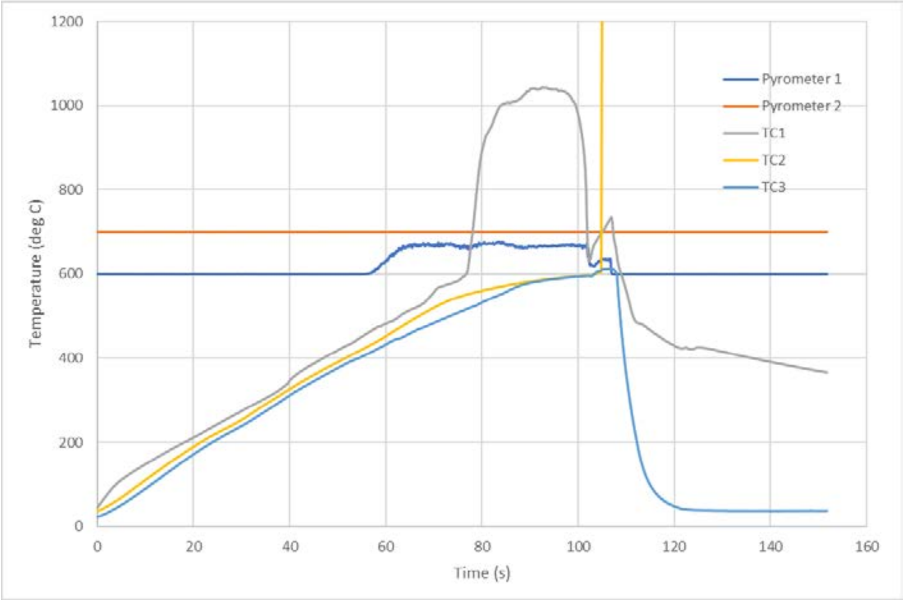


Aluminum

Important structural material

- Oxide layer is very important
- Sudden catastrophic failure (<1s)
- Internal pressure driven – blows out
- Front face to melt ~ 70s
- Front face overheat / TC @ 77s
- Failure @ 104s
- Expected time for latent heat ~45s

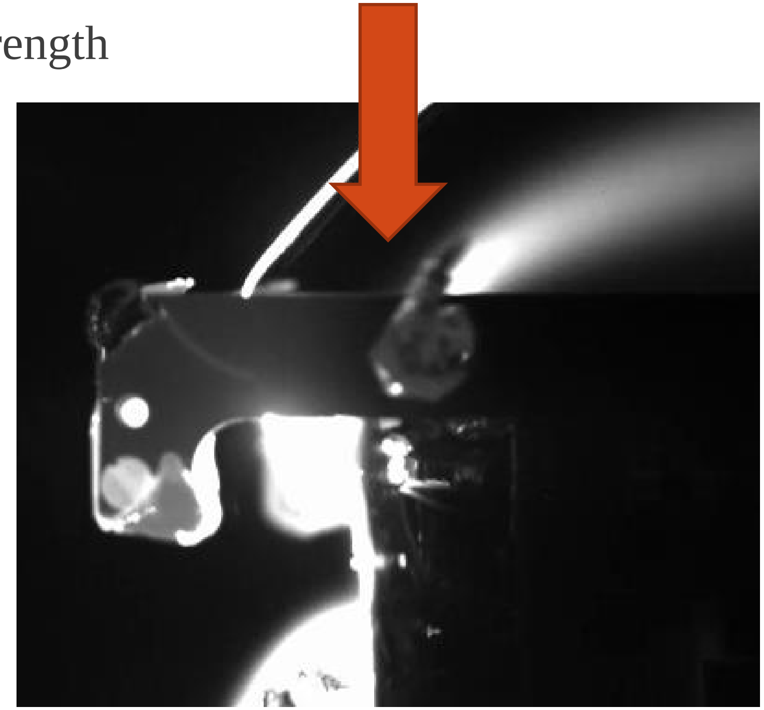
- Failure is after melt start…
- …but before full melt
- Catastrophic in nature
- Similar to reaction wheel housing failure



Aluminum

Shear of Aluminum

- 4mm plate – zinc outgassing, melt inside bag, no shear
- Failure of oxide bag under gravity – loss of molten aluminum
- High mass of oxide remains; could be an issue for larger aluminum structures
- Achieved aluminum droplet production from thinner CubeSat structure
    - Large droplets observed, driven by oxide strength



CubeSat

First Complete Satellite Demise Test

- Aluminium structure melts/shears
- Structure supported by threaded steel spacers
- GFRP electronics cards charred, but not molten

Double Heat Flux

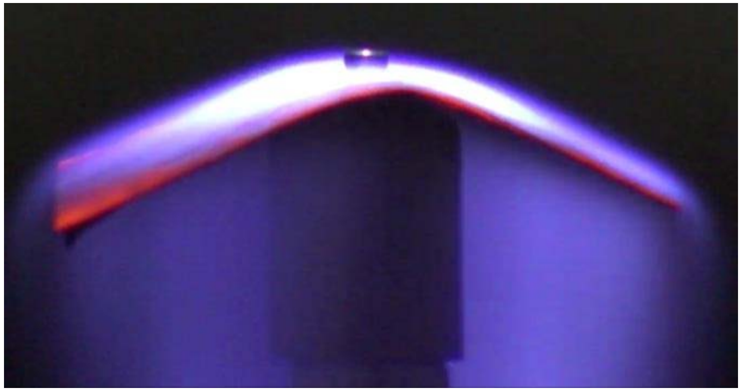
- GFRP cards have melt run-off, but are essentially intact
- Structure is weak, can be expected to break-up
- Some care is needed with electronics cards
  - Much mass is lost; outgassing from electronics
- Heat transfer through CubeSat is slow

Demise expected, but maybe not as easily as previously thought

CFRP

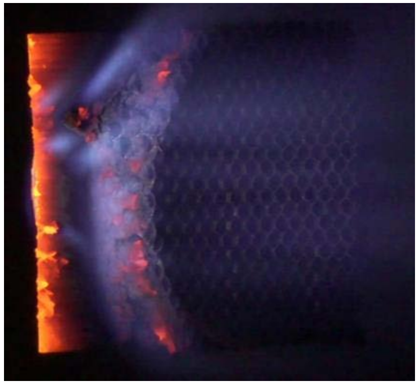
What happens to facesheets?

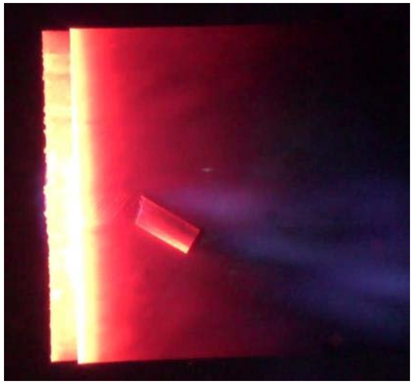
- Bend, but very resistant to breakage
- Facesheets will survive, perhaps in parts
- Will be very light; no risk expected



Sandwich Panels

- Facesheet thickness has an impact
- Thicker facesheets harder to remove
- Test with Kapton tape – removed by shear
  - Adhesive Space Grade?
- Removal of facesheets on tunnel shutdown
  - Small disturbance to remove
- Panels should not be expected to remain intact

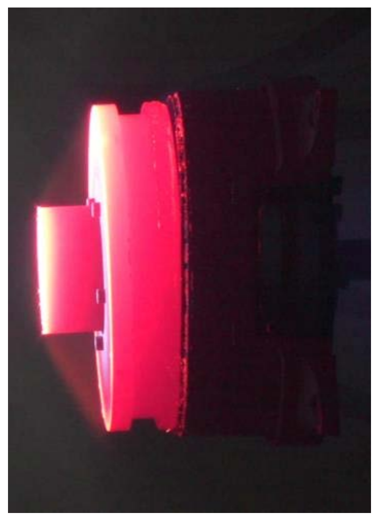




Reaction Wheel

Learn something of demise process

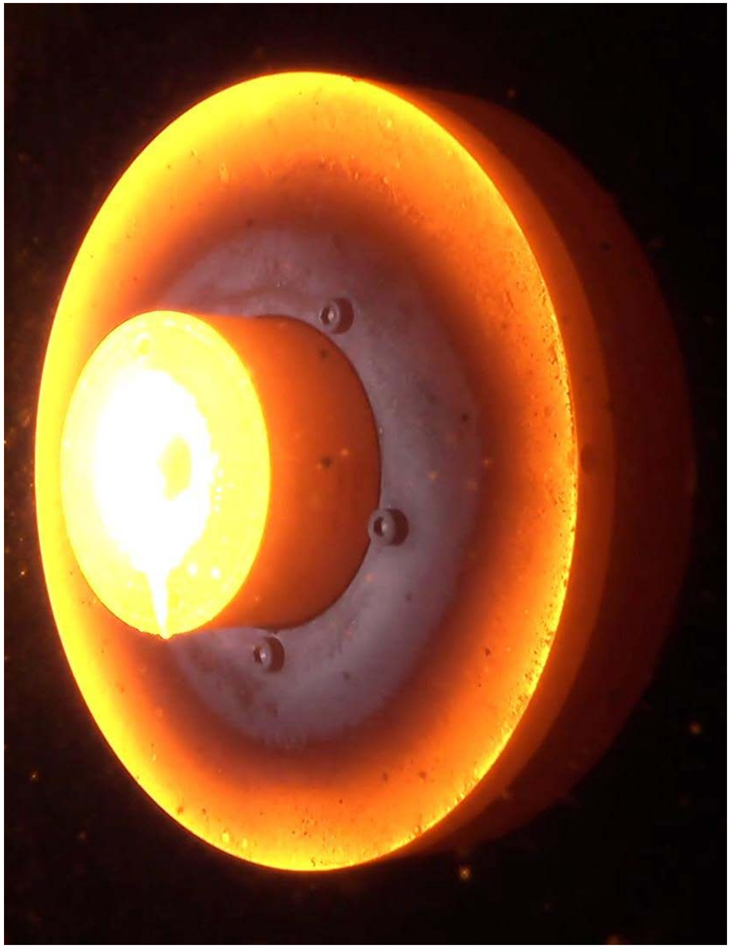
- Housing failure similar to aluminium failure in blow off; but glue failure at connection
- Higher temperatures on BBU and at edges; high radiative emission
- High level of thermal isolation of aluminium base; tumbling motion important
- Large collection of fragments – lots of small electronics parts



Reaction Wheel

Test of Ball Bearing Unit and Flywheel

- High temperatures on smaller radius central part
  - Confirmation that curvature is important
  - Some damage before major heat soak
- Radiative Equilibrium Reached (~800kW/m 2)
  - Temperatures of 1310 0 C on front surface
  - Lower temperatures ~1000 0 C on flywheel
- Energy Balance Performed
  - Equilibrium heat transfer
  - Suggests ~10% catalycity; 0.9 emissivity
  - Consistent with ESA Materials Characterisation
- Not quite as bad for demise as it looks…
  - Large radiating area; No tumble
  - More work to be done on implications for demise
  - But massive steel objects are clearly an issue



Conclusions

Many “Firsts” in Demise Test Campaign

First tests of aluminium thin structures

- Top hat, Plate, CubeSat Structure, Reaction Wheel Housing
- Strength of oxide observed; some force is required for removal; oxide cracks
- There is some delay in separation/fragmentation after melt point is reached

First tests of complete satellite

- Structure melts; steel rods for mounting can support structure
- GFRP electronics cards more robust than expected

First tests of real spacecraft equipment

- Reaction wheel demise process very different from models
- Many small parts produced
- Heating distribution evident; curvature is clearly important