Improved Understanding of Reaction Wheel Demise through Testing and Analysis

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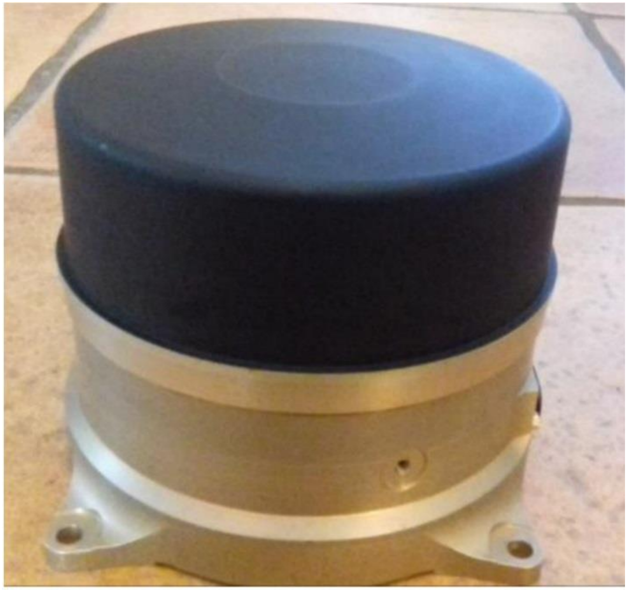
Reaction Wheels as Critical Elements

- Reaction wheels identified as critical elements
  - Many studies show the flywheels surviving
  - Multiple instances per satellite
- Testing
  - Verification of criticality in an arc-heated wind tunnel
    - Attempt to assess fragmentation of object
    - Attempt to demise the steel parts
- Modelling
  - Rebuilding of tests using the SAM tool
  - Initial assessment of demise techniques
    - What has the potential to be effective?

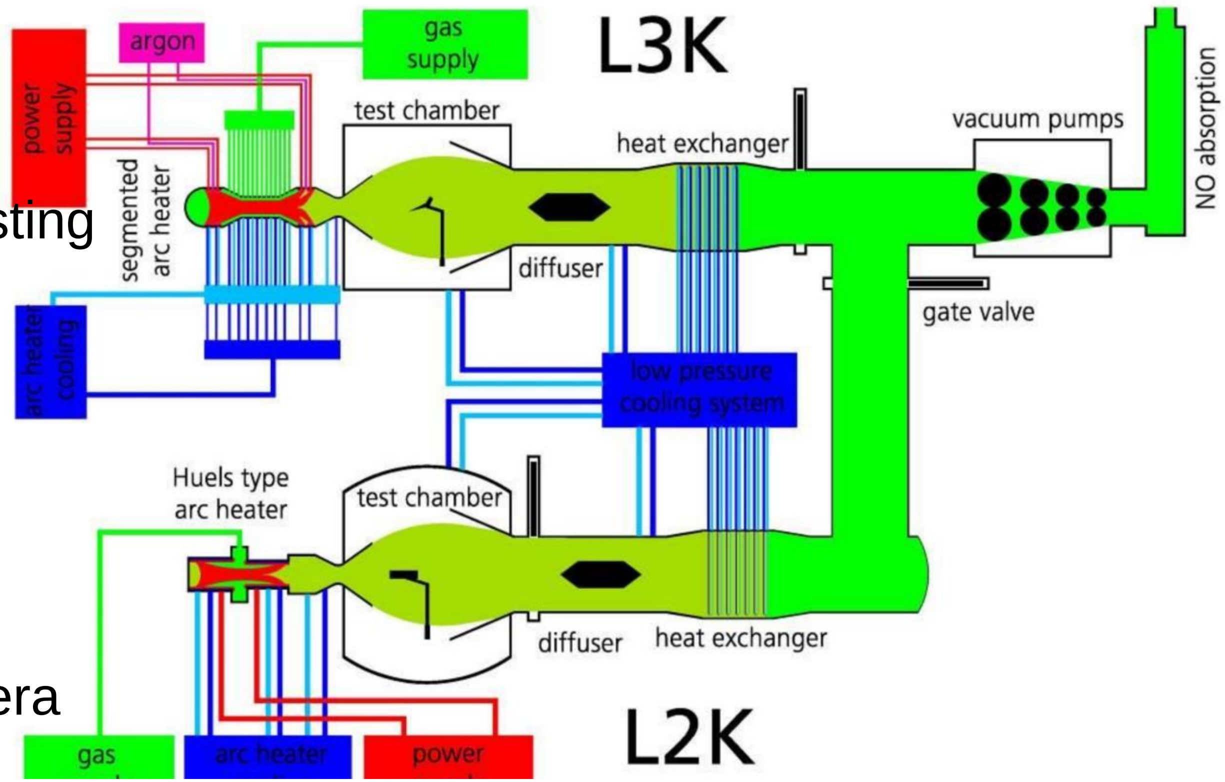
Reaction Wheel Test

- Engineering Model from Rockwell Collins
  - RSI1.6 test object selected
  - 120mm diameter will fit within core flow
    - Smaller than flight interest
    - Representative materials
  - Aluminium housing
  - Stainless steel ball-bearing unit (BBU)
  - Stainless steel flywheel



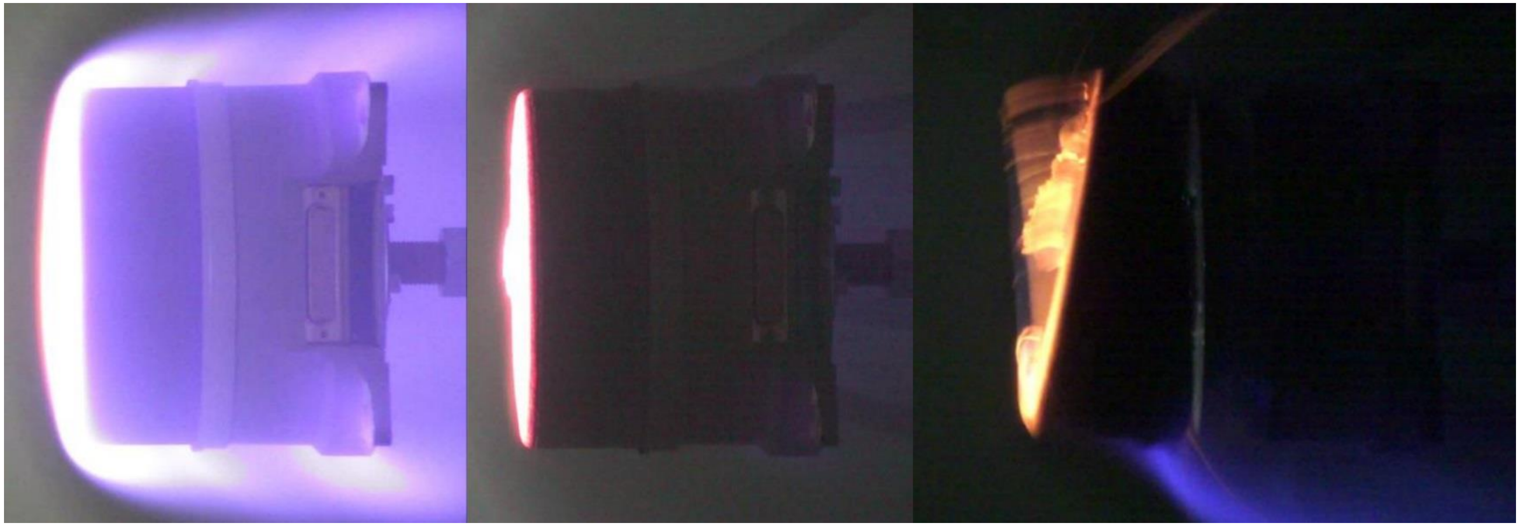
L2K Facility

- Huels type arc-heated wind tunnel
  - Hypersonic flow
  - High enthalpy
  - Dissociated gas
  - Long duration testing
- Instrumentation
  - Thermocouples
  - Pyrometers
  - HD camera
  - IR camera
  - High speed camera



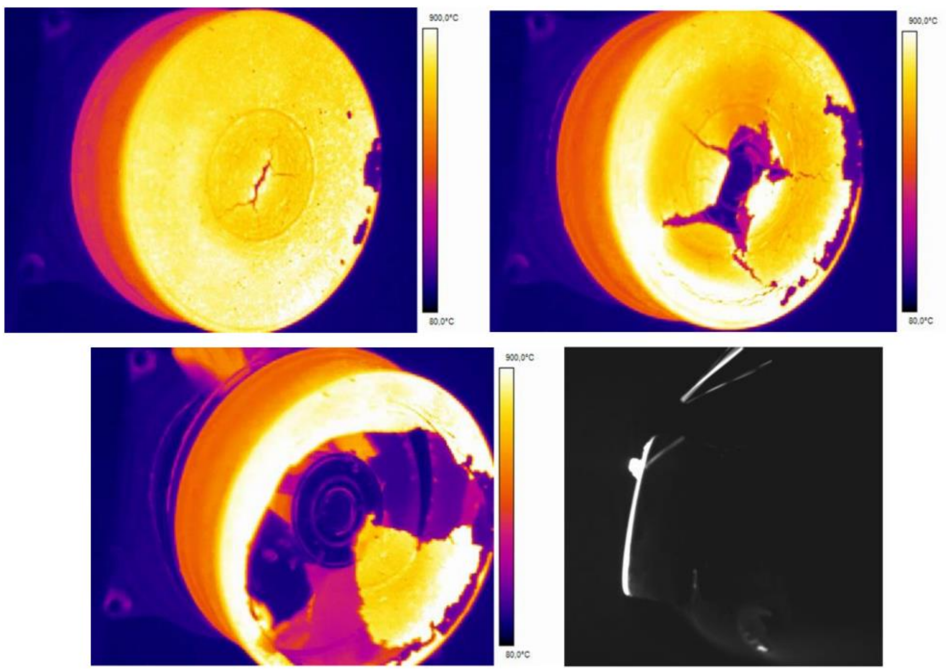
Fragmentation Test (1)

- Initial test at 100kW/m^2
  - Housing removed – front face melt and glue failure at seal
  - Rebuild suggests that front face is fully molten
  - Remaining parts survive 30 mins



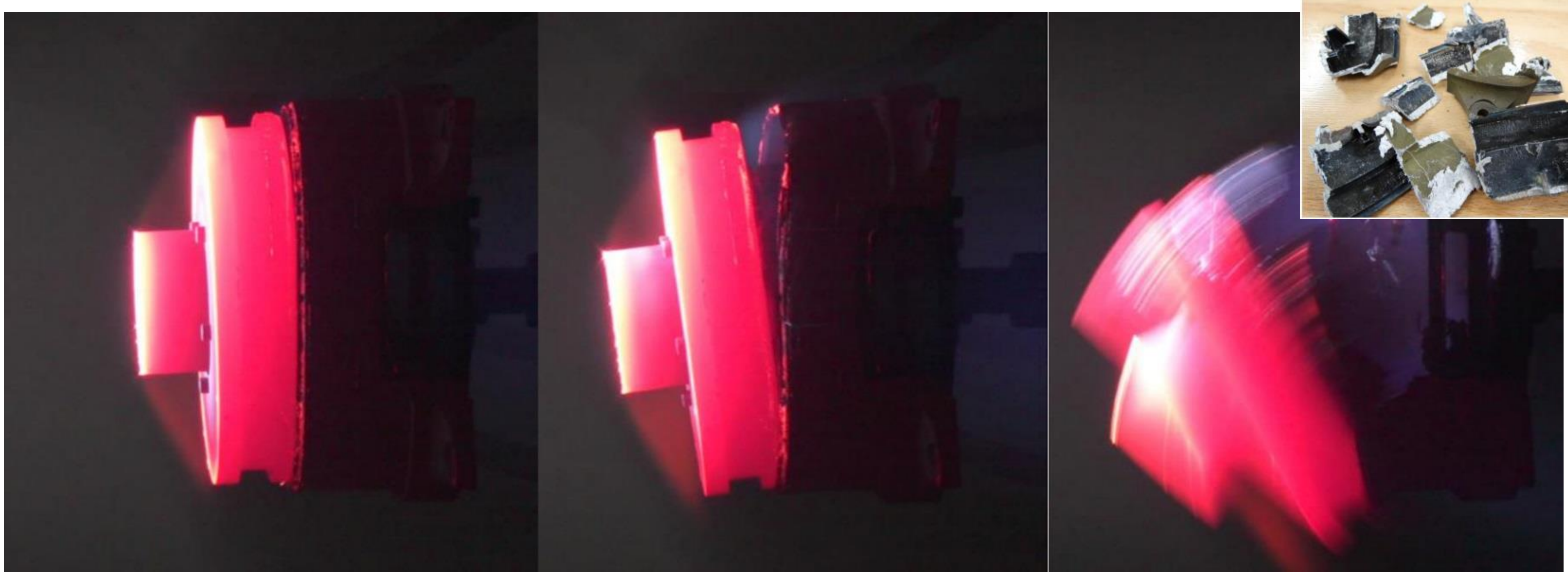
Fragmentation Test (1)

- Initial test at 100kW/m^2
  - Housing ring recovered; suggests not molten
  - Temperature increase observed (full melt?) before front face fail
  - Mechanism evident on IR camera

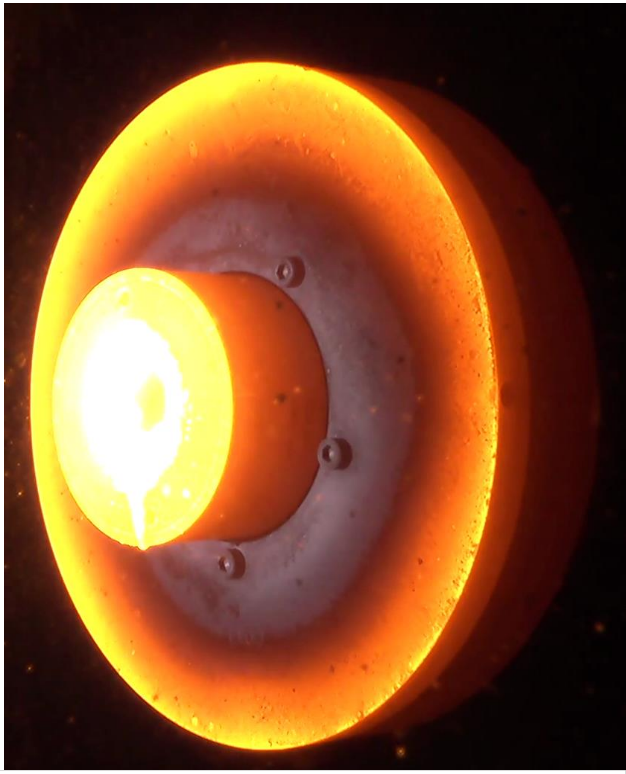


Fragmentation Test (2)

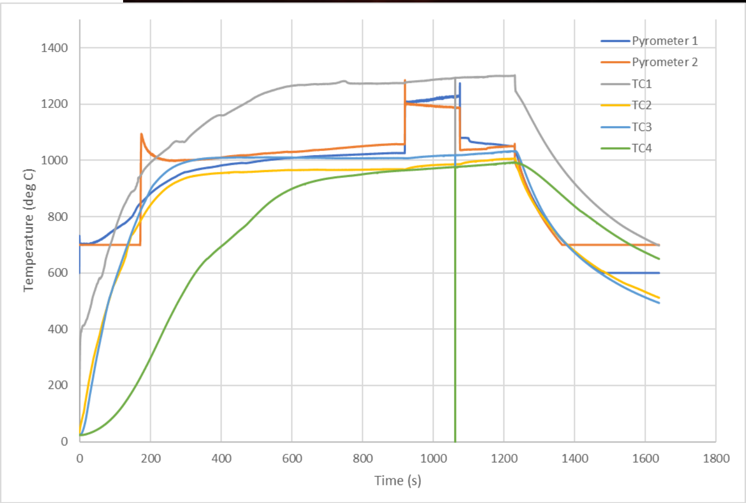
- Increase flux to 200kW/m^2
  - High temperature on steel parts
  - Poor thermal transfer
  - Failure under gravity
  - Many fragments; base shatters



Demise Test

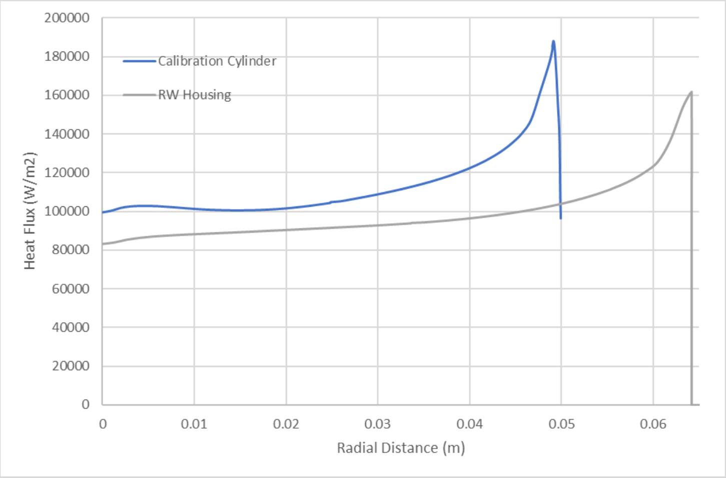


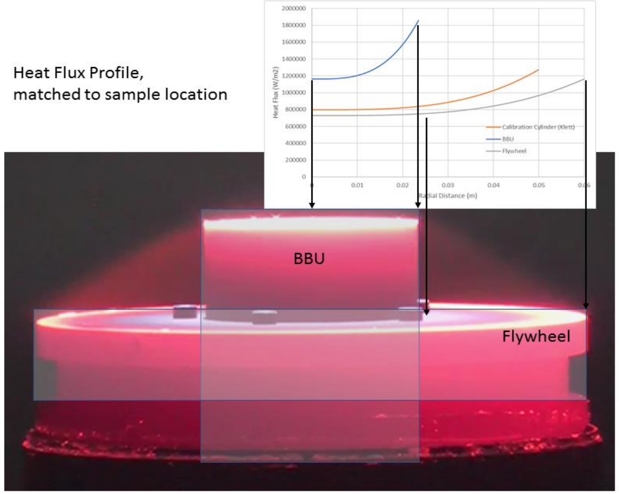
- Test of Ball Bearing Unit and Flywheel
  - Test at higher 800kW/m^2 heat flux
  - High temperatures on central part
    - Confirmation that curvature is important
    - Some damage before major heat soak
  - Radiative Equilibrium Reached
  - Temperatures of 1310^{0}C on front
    - Thermocouples in central tube (TC1)
    - Also on flywheel, flywheel rim, base
    - TC1 ~1300^{0}C, others ~1000^{0}C



Test Rebuilding

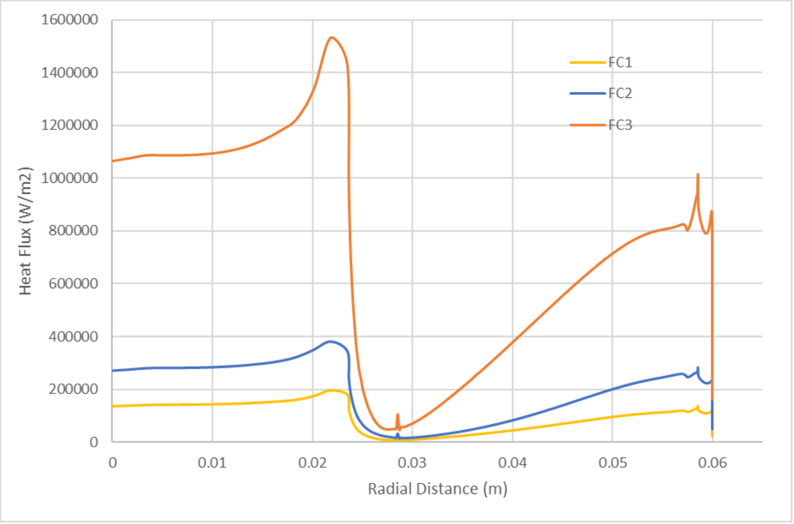
- Heat flux Profile to Surface
  - FGE CFD code TINA used
  - Original reaction wheel
    - Larger radius gives lower flux
  - BBU/flywheel
    - Note low flux in separation region





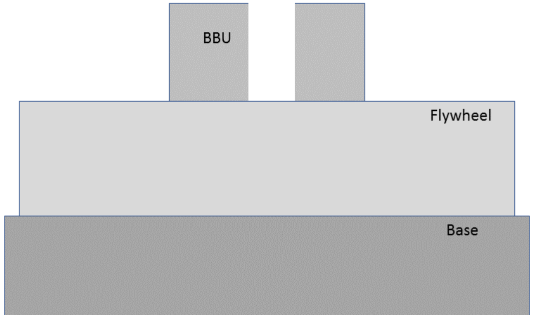
Simplified Theory

CFD



Test Rebuilding

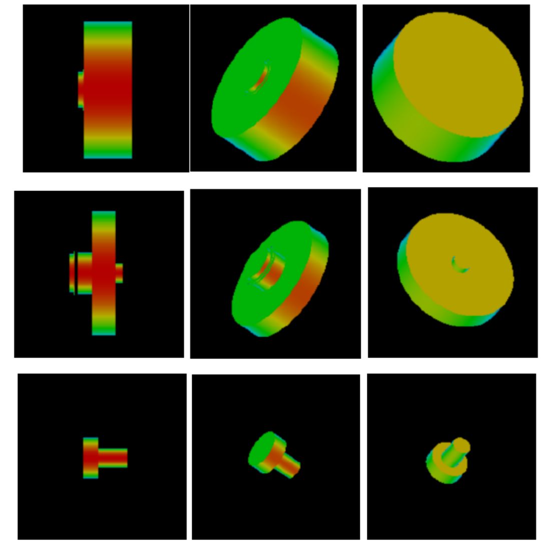
- Energy Balance Performed
  - Catalycity/emissivity from CoDM study
  - Steady state, radiative equilibrium
  - Rebuild is consistent with test results
    - Back is below aluminium melt at 100kW/m^2
    - Back is above aluminium melt at 200kW/m^2
    - Thermocouple temperatures are well matched at 800kW/m^2

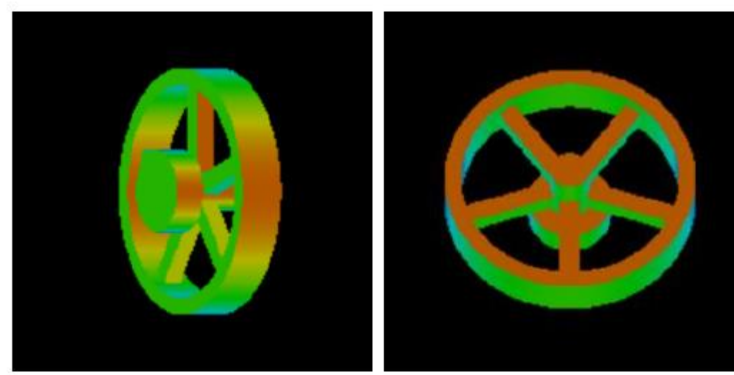


	BBU	Flywheel	BBU	Flywheel	BBU	Flywheel
Nominal Heat Flux Input (kW/m^2)	160	70	320	140	1250	520
Catalycity	0.9	0.9	0.9	0.9	0.9	0.9
Emissivity	0.87	0.87	0.87	0.87	0.87	0.87
Test Enthalpy (MJ/kg)	3.9	3.9	6.8	6.8	13.3	13.3
Air enthalpy at inferred temperature (MJ/kg)	0.63	0.52	0.86	0.74	1.46	1.12
Hot Wall Corrected heat flux (kW/m^2)	120.7	54.6	252	112	1001	429
Front diameter (m)	0.047	0.12	0.047	0.12	0.047	0.12
Front hole diameter (m)	0.014	0.047	0.014	0.047	0.014	0.047
Visible side length (m)	0.03	0.03	0.03	0.03	0.03	0.03
Radiating Area (m^2)	0.0060	0.0305	0.0060	0.0305	0.0060	0.0305
Equilibrium Temperature (^{0}C)	622	495	803	646	1247	1012

Modelling Aspects

- Multicomponent Model Used
  - BBU, flywheel, housings, motor-stator, base
  - Components connected by joints
  - Fragmentation at melt
  - Initial analysis with modified Lees model
- Probabilistic Approach
  - Uncertainties on trajectory, release, heating
- Set of Design-for-Demise Techniques
  - Adhesive Joints
  - Modular Flywheel
  - Flywheel Material
  - Spoked Flywheel Design
  - Containment





Demise Process

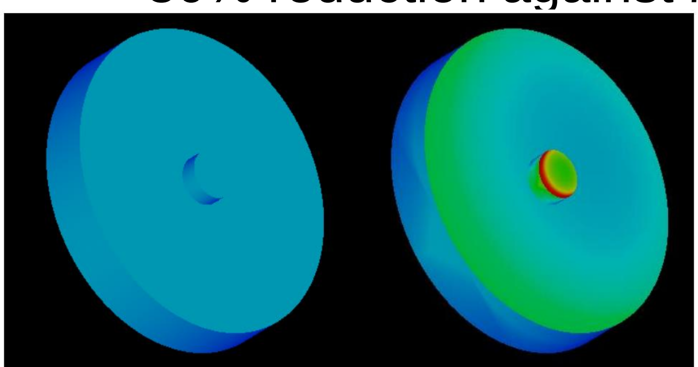
- Demise Process
  - Housings removed
  - BBU / motor-stator / flywheel can land as compound object
  - BBU / motor-stator / flywheel can land as separate objects
- Baseline Simulations
  - 23% compound objects land
  - Of separated components
    - 99% of flywheels land
    - 80% of BBU land
    - 45% of motor-stator land
  - About half the casualty risk is from the flywheel, 25% from BBU

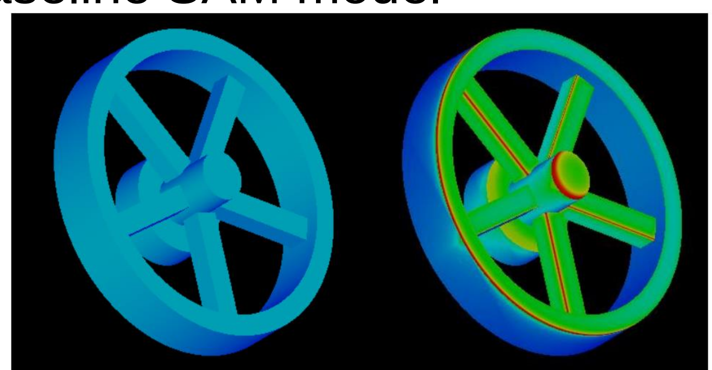
D4D Techniques

- Adhesive Joints
  - No compound objects, about 20% improvement in risk
  - Flywheel remains dominant component
- Separating / Modular Flywheel Rim
  - Ineffective, larger number of parts land
- Lower Mass / Larger Radius Flywheel Trade-off
  - Ineffective, larger landed size offsets increased demisability
- Flywheel Material Change
  - Aluminium reduces capability as low density, but 70% reduction
  - Copper, (65% reduction) Inconel (35% reduction) maintain inertia
  - Lead with casing gives 70% reduction
- Containment
  - One object of full size – about 25% risk reduction

Spoked Reaction Wheels

- Importance of Curvature Effects
  - Evident in tests
  - Lees model suggests 20% risk reduction
- Move to Improved SAM Local Heating Model
  - Captures local heating effects; heating is clearly higher
  - Baseline model has 7% risk reduction; spoked model 20%
  - Effect of spoked model substantially more evident in this case
    - >30% reduction against baseline SAM model





Conclusions

- Reaction Wheels are Highly Unlikely to Demise
  - Testing shows that housing can demise
  - Steel components unlikely to demise
  - Curvature, geometry effects on heating important
  - Rebuilds consistent with test results
- Design-For-Demise Modelling
  - Casualty risk mainly from flywheel, contribution from BBU
  - Small improvements from improved fragmentation or containment
  - Larger improvements from spoked flywheel
    - Improved local curvature model shows improved benefit
  - Material change is most effective
    - Copper flywheel maintains inertia, two-thirds risk reduction