PRODUCERS: Spectrographic Response of Break-up Fragments to the Re-entry Environment – Final Presentation

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Agenda

1. Introduction
2. Plasma Wind Tunnel Experimental Findings
3. Overview of PRODUCERS modelling software
4. Coffee / Tea
5. Software Verification
6. Cluster Model
7. Future Work – Observations / Experiments
8. Future Work – Modelling
9. Conclusion

Introduction

Consortium

- **Fluid Gravity Engineering** – Project lead and aerothermal modelling
  - Jim Merrifield, David Evans, Holly Whitehouse, Nathan Donaldson
- **Institut für Raumfahrtsysteme** – Wind tunnel experiments and observations
  - Adam Pagan, Johannes Oswald, Michael Winter, Georg Herdrich
- **Belstead Research Limited** – Re-entry demise and PRODUCERS software
  - James Beck, Ian Holbrough
- **Instituto de Plasmas e Fusão Nuclear** – Spectroscopic database
  - Mario Lino da Silva

Objectives

Can we use spectroscopic data to unambiguously identify what is happening during re-entry demise?

1. **Review** spectroscopic observations, ground tests and modelling applied to understanding demise processes.

2. **Ground tests** shall be executed to establish verification data for numerical radiation prediction models, based on materials expected to be involved in destructive re-entries.

3. A **software package** shall be developed to predict spectroscopic emissions from re-entry trajectory and expected demise events (melting, breaking off etc.).

4. An application case shall be derived from the upcoming re-entries of four ESA **Cluster-II** spacecraft between 2024 and 2026, including a roadmap development of an observation campaign, and sensor and processing.

Development of the predictive software has not been done before, as far as we know, and is a challenging task.

Outcomes of Review

- Observations
  - Not always obvious which lines will be seen based on the materials present
  - Need to better understand the mechanisms of emission
    - For example, when Aluminium demises, we seem AlO but rarely Al but Al emissions are seen from certain alloys where other materials dominate
- Experiments
  - Experiments have a big role to play in addressing the questions about emission mechanisms
  - The details of the flow-field are important but the precise conditions of re-entry are difficult to recreate
- Modelling
  - As indicated, the details of the flow-field are important but it is difficult to model these in way that is compatible with the current, simple dynamics of re-entry demise models.
  - Ideally, we want 3D, chemically reacting flow simulations but what we have are collections of point particles programmed to break up under certain conditions.
  - This is not a criticism of DRAMA and other similar codes, rather the fact that DRAMA and PRODUCERS have significantly different requirements.
- Spectroscopic Database
  - This was expanded using data from other sources (e.g. NIST, SPARK) to include all the species of interest

Plasma Wind Tunnel Experimental Findings

PRODUCERS: Summary of Experimental Findings

Motivation

Motivation

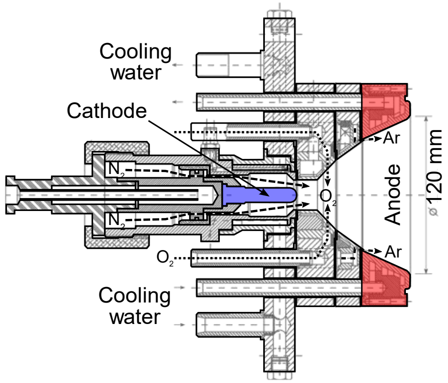
- **Objectives:**
  - Generation of experimental reference datasets for relevant S/C materials and typical components
  - Identification and characterization of spectrographic phenomena associated with destructive processes and events

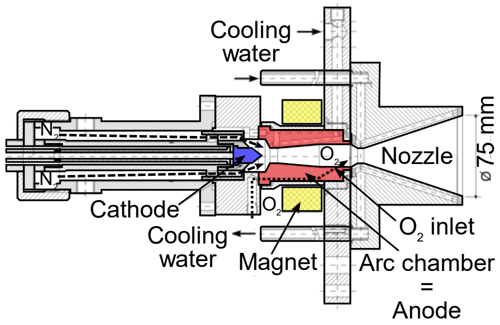
  ➔ Calibration database for computational models
- **Three Phases of Testing:**
  - **Phase A – Materials:** Determination of material-specific emission signatures under flight-relevant test conditions
  - **Phase B – Components & Structures:** Assessment of emissions of heterogeneous components and structures relevant to Cluster II re-entry using original Cluster hardware items
  - **Phase C – Splitter Probe Tests:** Investigation of whether and how a physical separation of objects under hypersonic destructive re-entry conditions manifests itself in its radiation signature

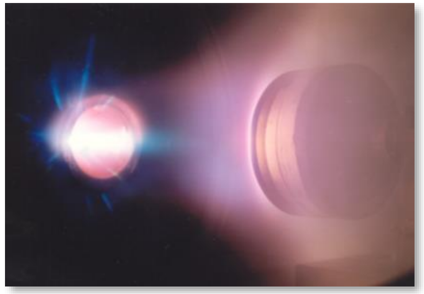
Experimental Methodology

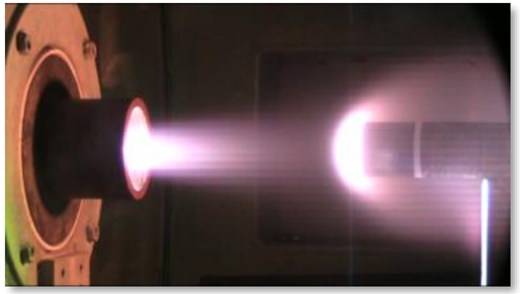
Experimental Method

Test Facilities

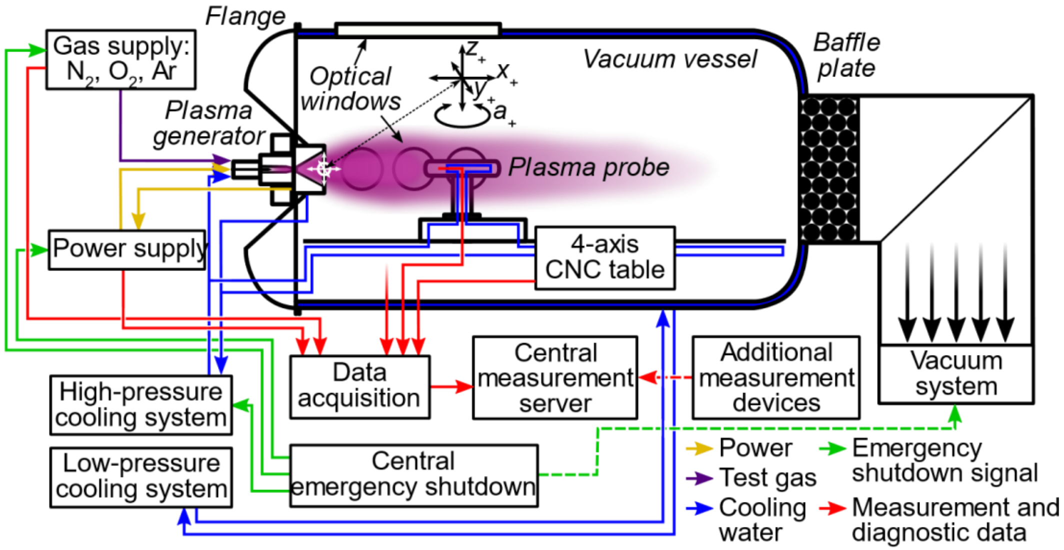








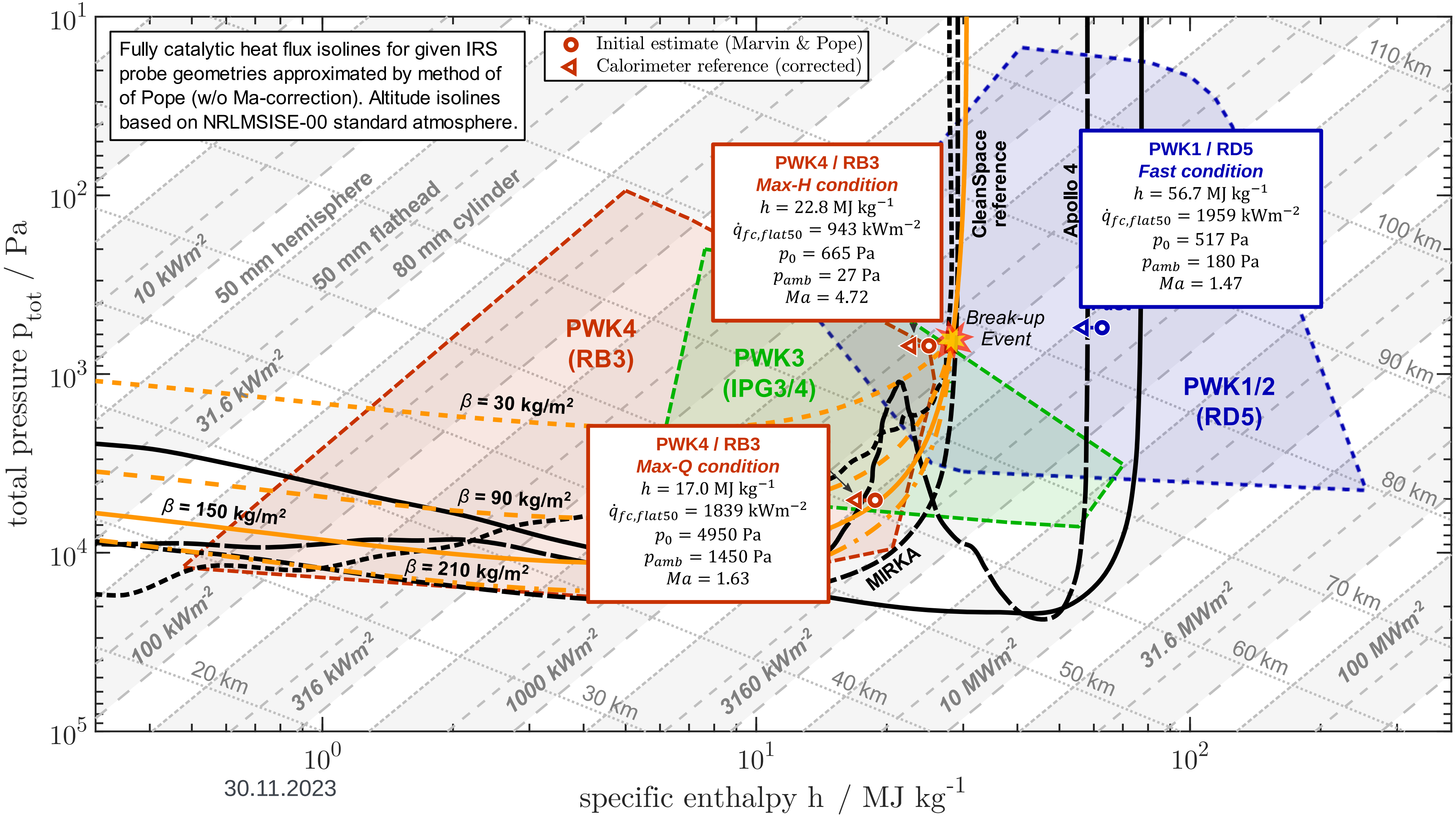
- PWK1 with RD5 Self-Field MPD Generator:
  - Low pressure, high enthalpy, high purity → Ideal for early and high-velocity entries
- PWK4 with RB3 Thermal Arcjet Generator:
  - High pressure, moderate enthalpy, high purity, high Ma → Closest similarity to typical break-up (LEO) and burn-up / post-break-up conditions



Dynamic facilities	PWK1	PWK4
Plasma Source	Magnetoplasma-dynamic (MPD) generators RD5 (and RD7)	Thermal Plasma Generator (TPG) RB3
Mass-specific enthalpy	10 to 220 MJ/kg	0.5 to 30 MJ/kg
Total pressure range	0.1 to 50 hPa	1 to 200+ hPa
Max. heat flux (50 mm flat head geometry)	125 to 18 000 kW/m²	250 to 5000 kW/m²
Mach number	0.5 to 2	< 5

Experimental Method

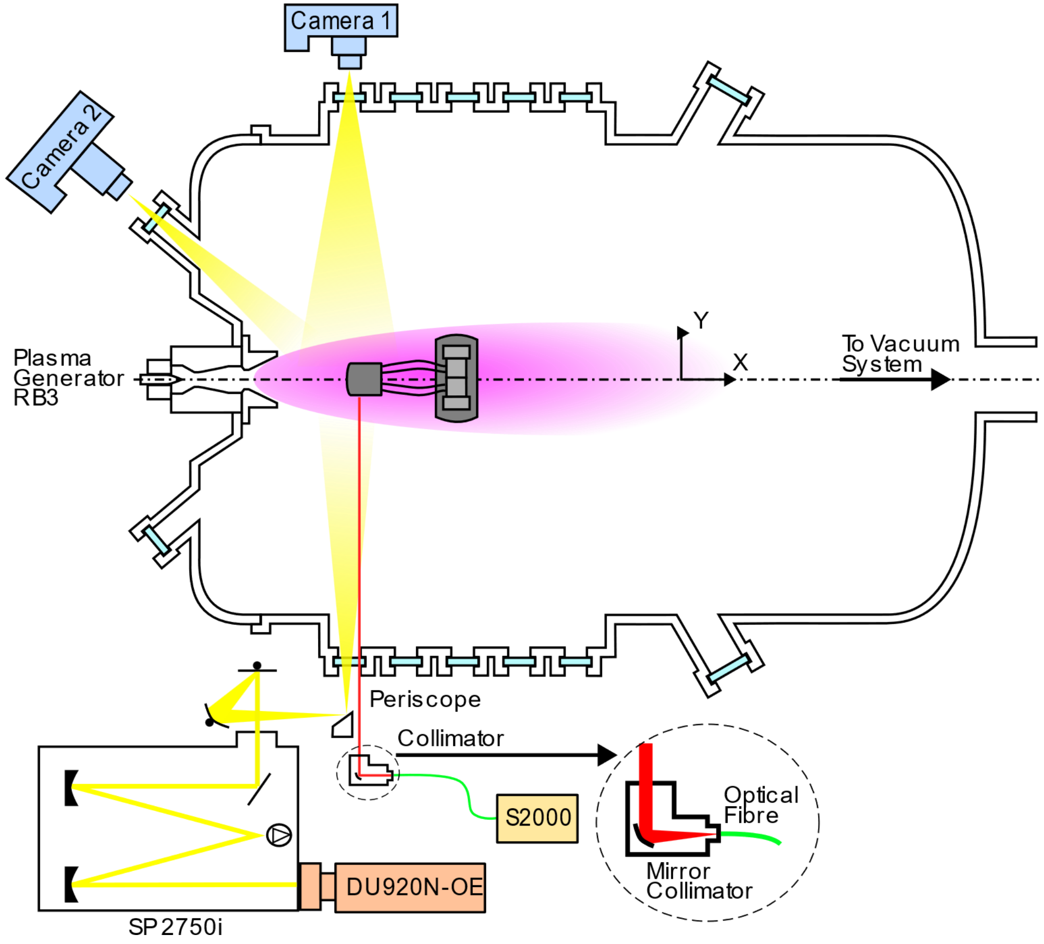
Test Conditions



Experimental Method

Test Setup and Diagnostics

- **Sample Holder Hardware:**
  - **Phase A:** Standard 50 mm IRS material sample holder (for 3 mm thick frustrum “coin” with 26.5 mm front diameter) for insulated 1D heat conduction environment
  - **Phase B:** Flexible mount (as used for AVUM Rebuild tests) with stainless steel mounting bracket for C-II electronics hardware
  - **Phase C:** Dedicated splitter probe design (more later)
- **Measurements:**
  - UHD (4K) video (Sony Alpha 6400)
  - Infrared thermography (LumaSense MCS640)
  - OES: Ocean Optics S2000 mini-spectrometer (lo-res, 300 nm to 880 nm)
  - OES: Andor SpectraPro SP 2750i with DU920N-OE CCD camera (high-res, variable waveband, optional periscope setup for 1D spatial resolution)
  - Thermocouples for selected component/structure tests

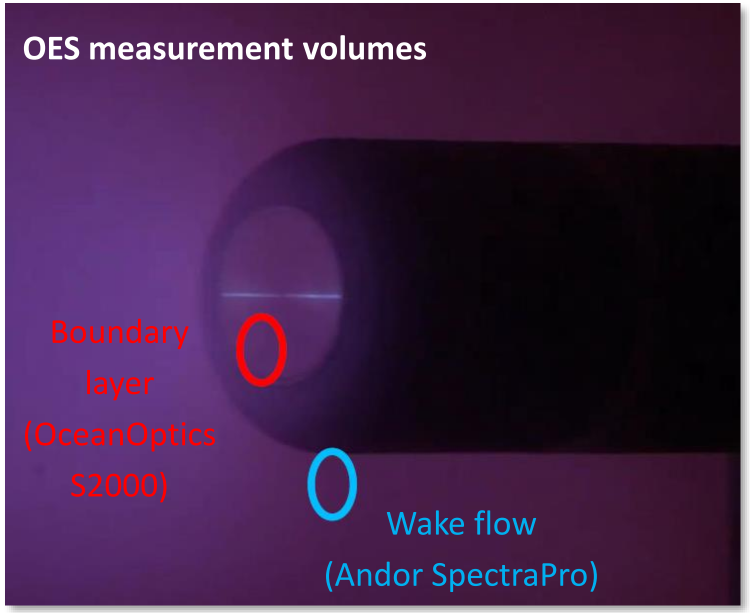


Results and Discussion

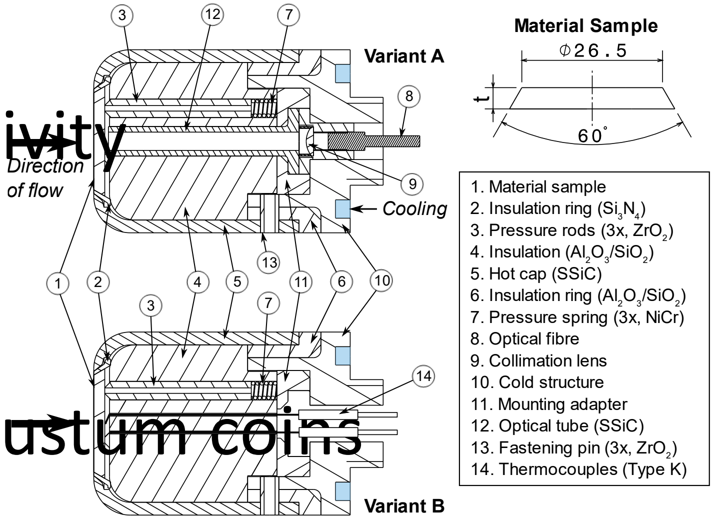
Phase A: Materials

Phase A: Material Tests

Overview



- Materials tested (14 samples total):
  - Type 316L stainless steel (w/ and w/o Aeroglaze Z306 coating)
  - Aluminium alloy 7075 (w/ and w/o Aeroglaze Z306 coating)
  - Aluminium-Lithium alloy 2099
  - Grade 5 Titanium Ti6Al4V
  - CFRP EX-1515/M55J
- Material selection mostly mirrors past CoDM activity
- Attempted capture of boundary layer and wake flow emissions
- IRS 50 mm sample holder with 26.5 mm diam. frustum coins
  - Highly effective lateral insulation → essentially 1D heat conduction



Phase A: Material Tests

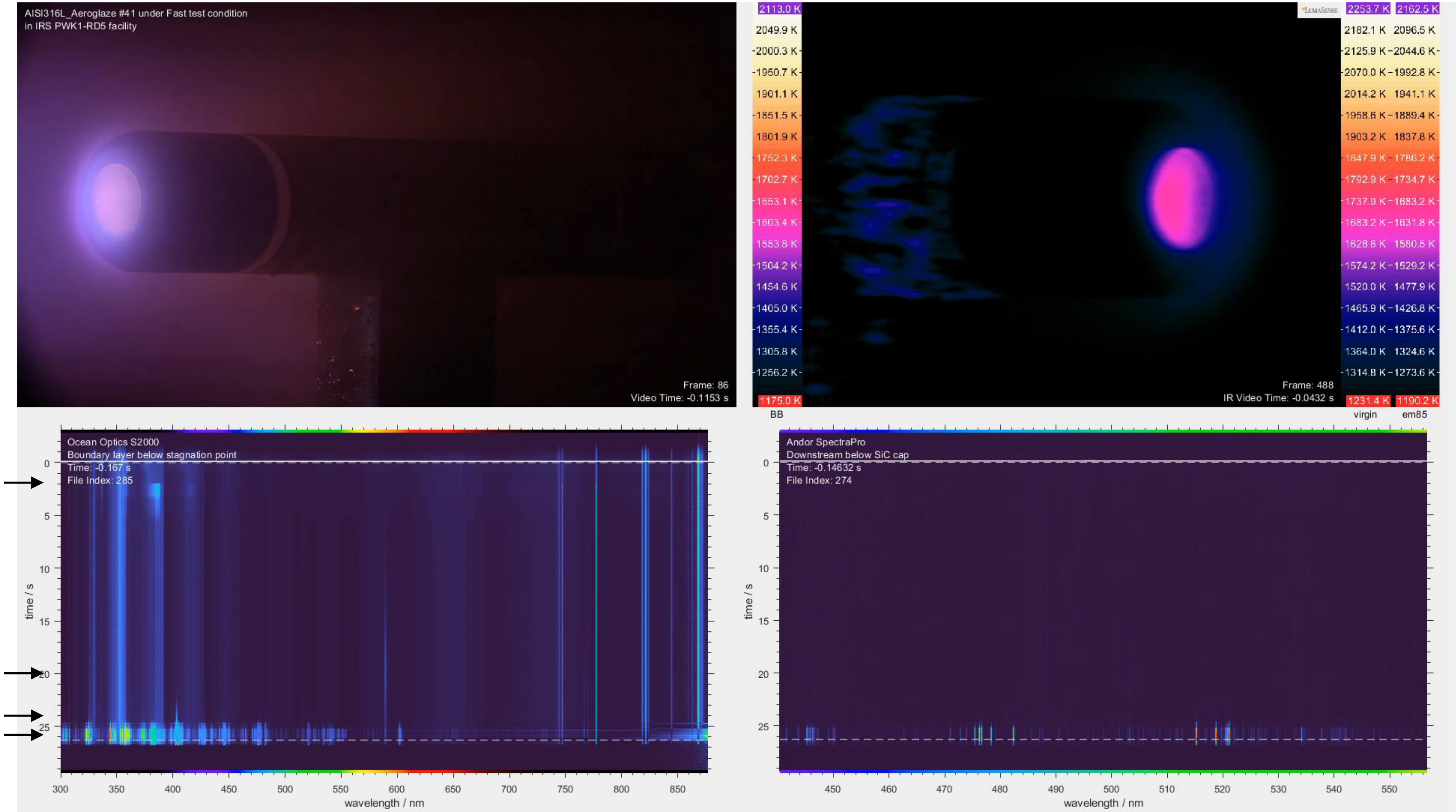
AISI316L w/ Aeroglaze coating #41 (Fast)

Purple haze

Dark orange haze

Oxide layer breaks

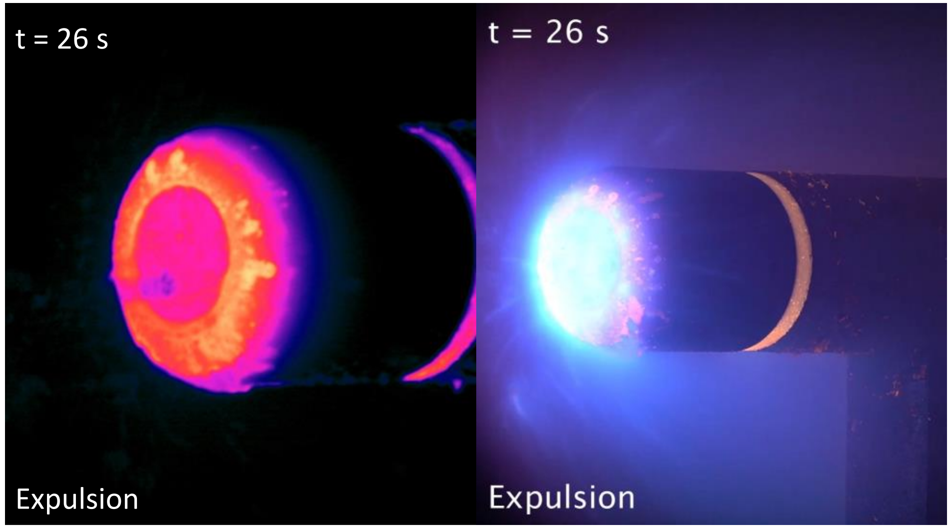
Expulsion

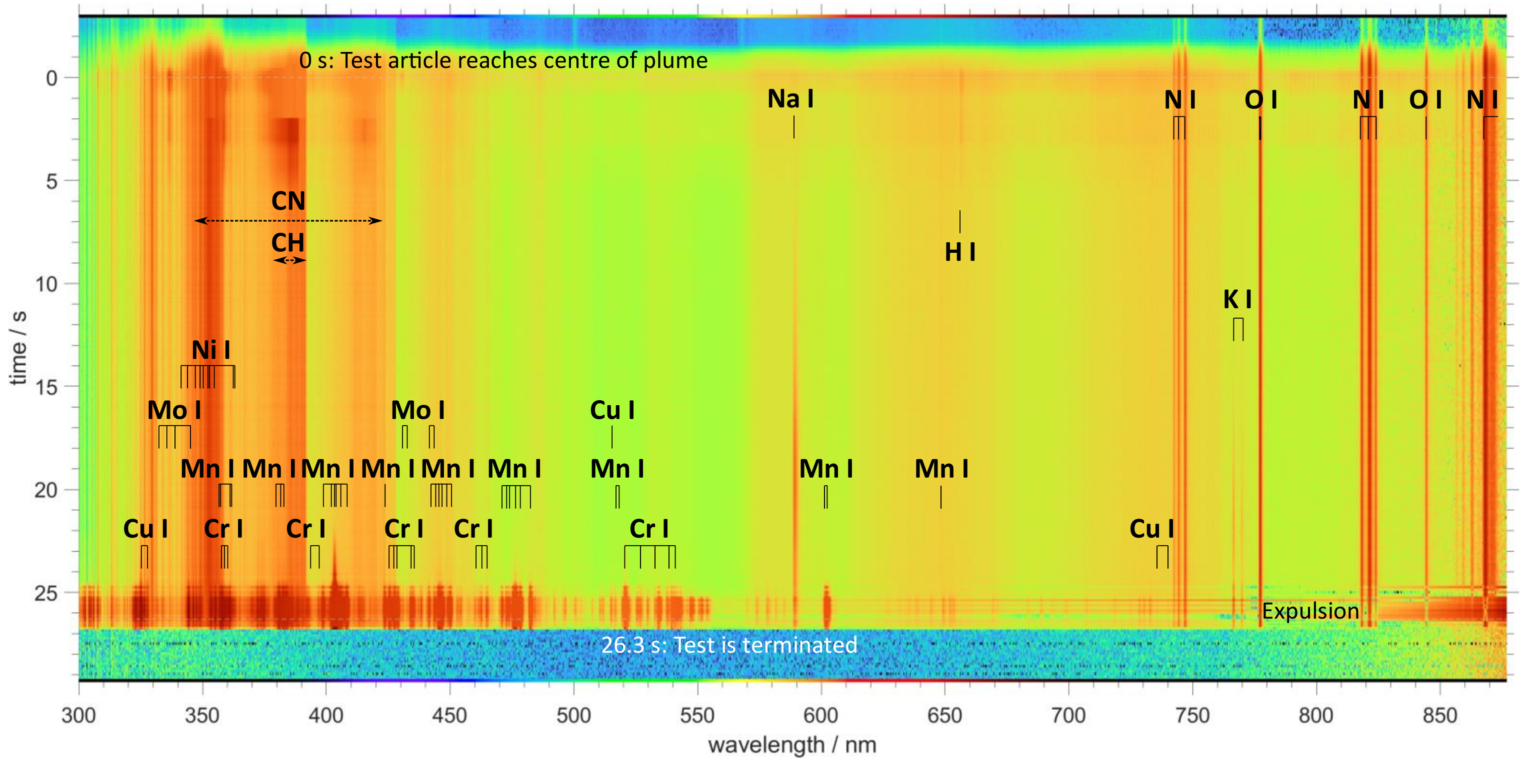


Phase A: Material Tests

AISI316L w/ Aeroglaze coating #41 (Fast)

- Aeroglaze coatings (primarily carbon) appear to extend survivability of metallic samples by 10%-20%.
- Dark orange haze with organic compounds (e.g. CFRP): **CH, CN, H I, C I**
- followed by braking of oxide layer and massive expulsion event
- Super-heated droplets betray type / composition of alloy (here: **Mg I, Cr I, Cu I**)

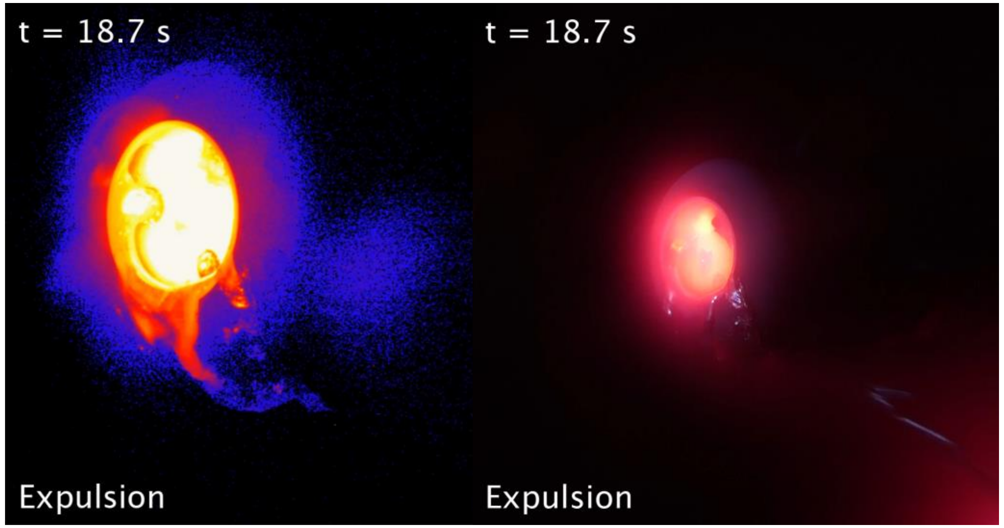


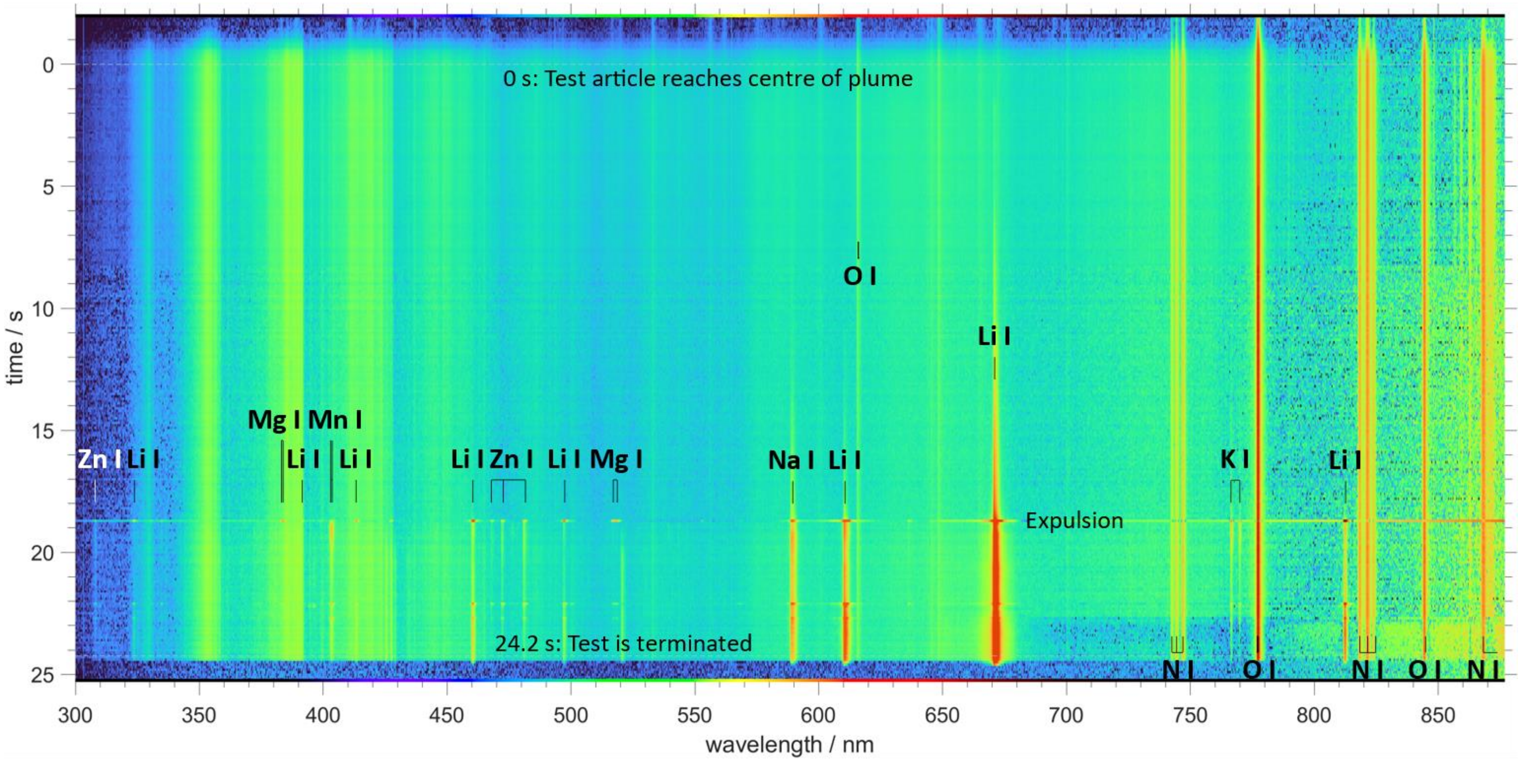


Phase A: Material Tests

AA2099 #42 (Max-H)

- Comparison with earlier tests (e.g. from CoDM) and literature indicate need of extreme heating rates for emissive droplets / expulsions to form from aluminium alloys
- Appearance of primary alloy elements (**Mg I, Zn I, Mn I, Li I**) mainly in super-heated, excited droplets!
- **Li I** emissions are dominant prior to expulsion event in NIR

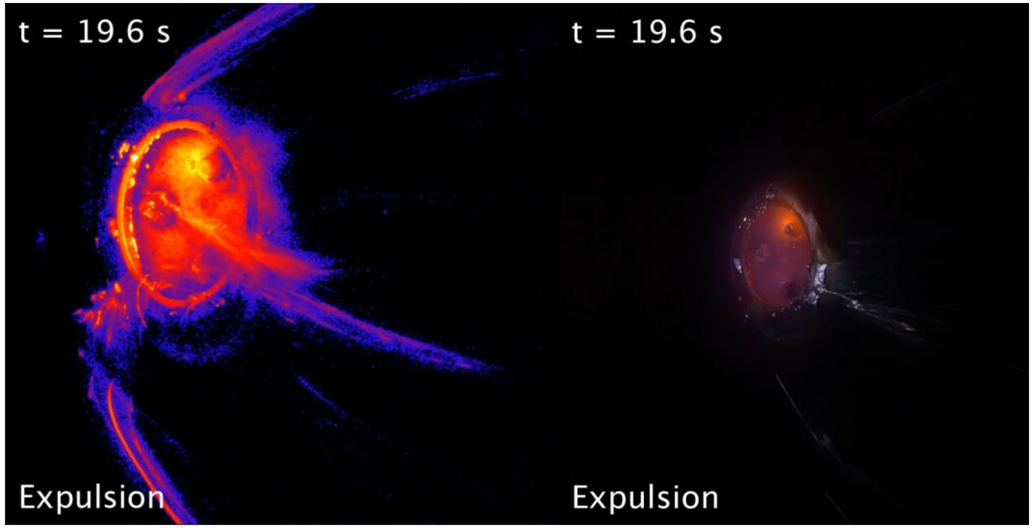


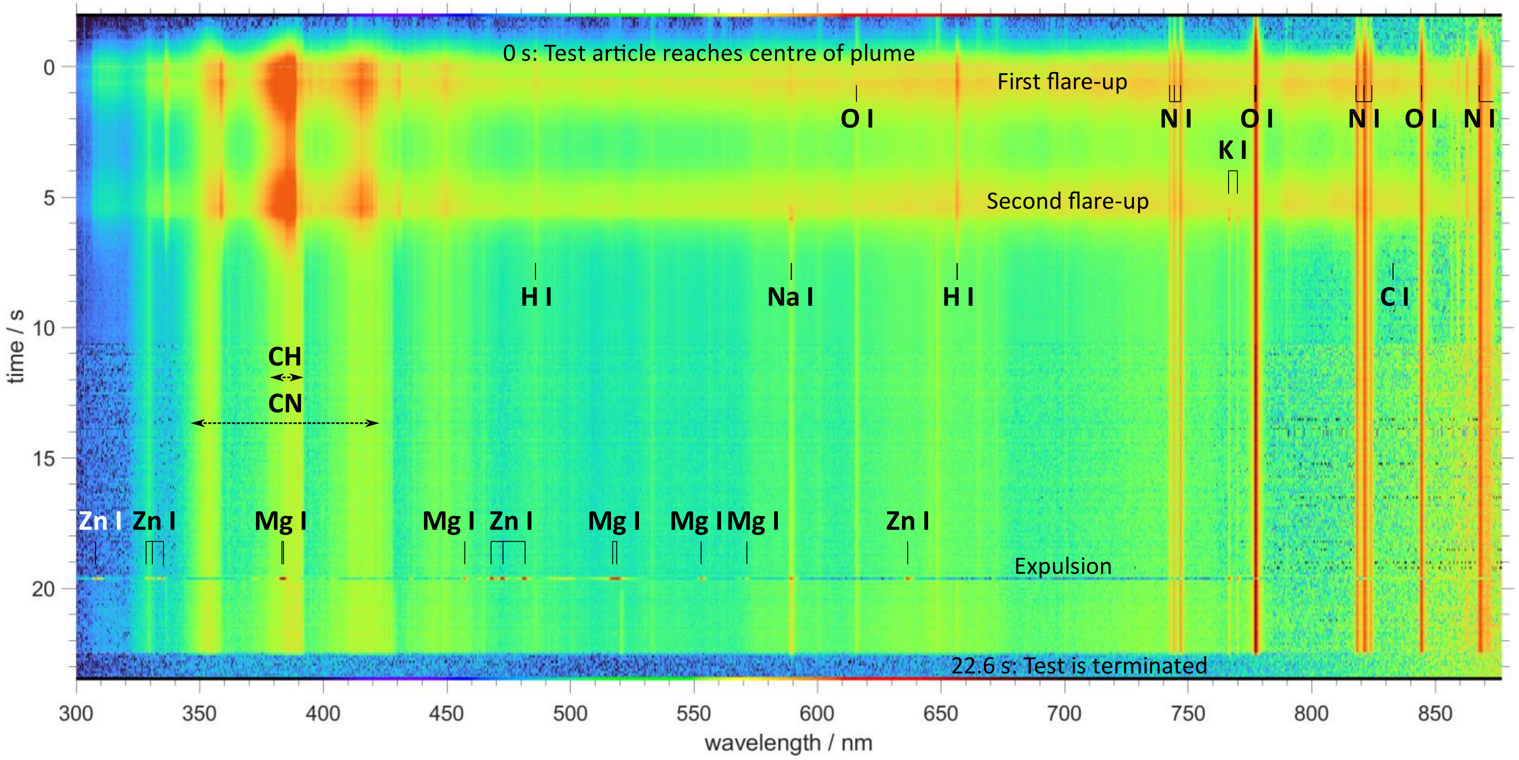


Phase A: Material Tests

AA7075 w/ Aeroglaze coating #42 (Max-H)

- Aeroglaze coatings (primarily carbon) appear to extend survivability of metallic samples by 10%-20%.
- Two successive flare-ups near start of exposure typical for organic compounds (e.g. CFRP): **CH, CN, H I, C I**
- Super-heated droplets betray type / composition of alloy (here: **Mg I, Zn I**)
- Similar to the stainless steel material test

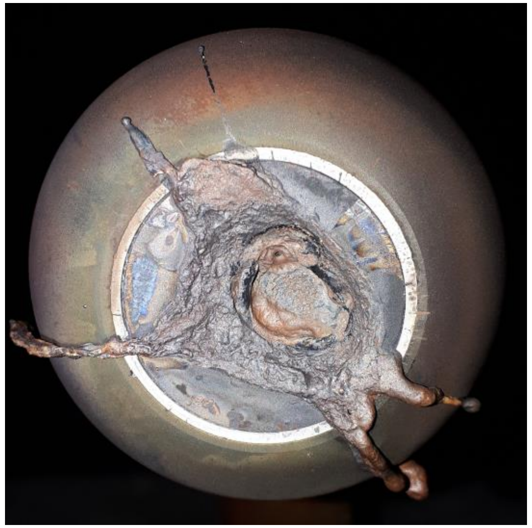


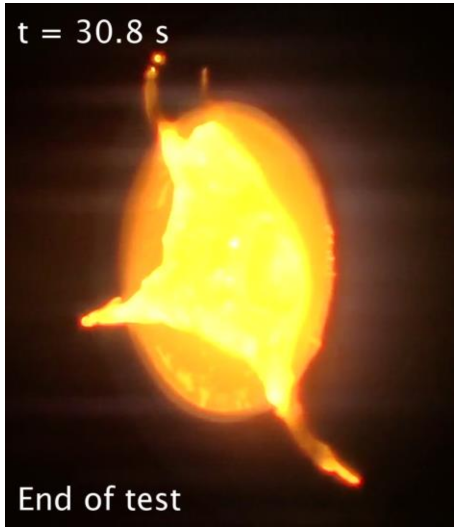


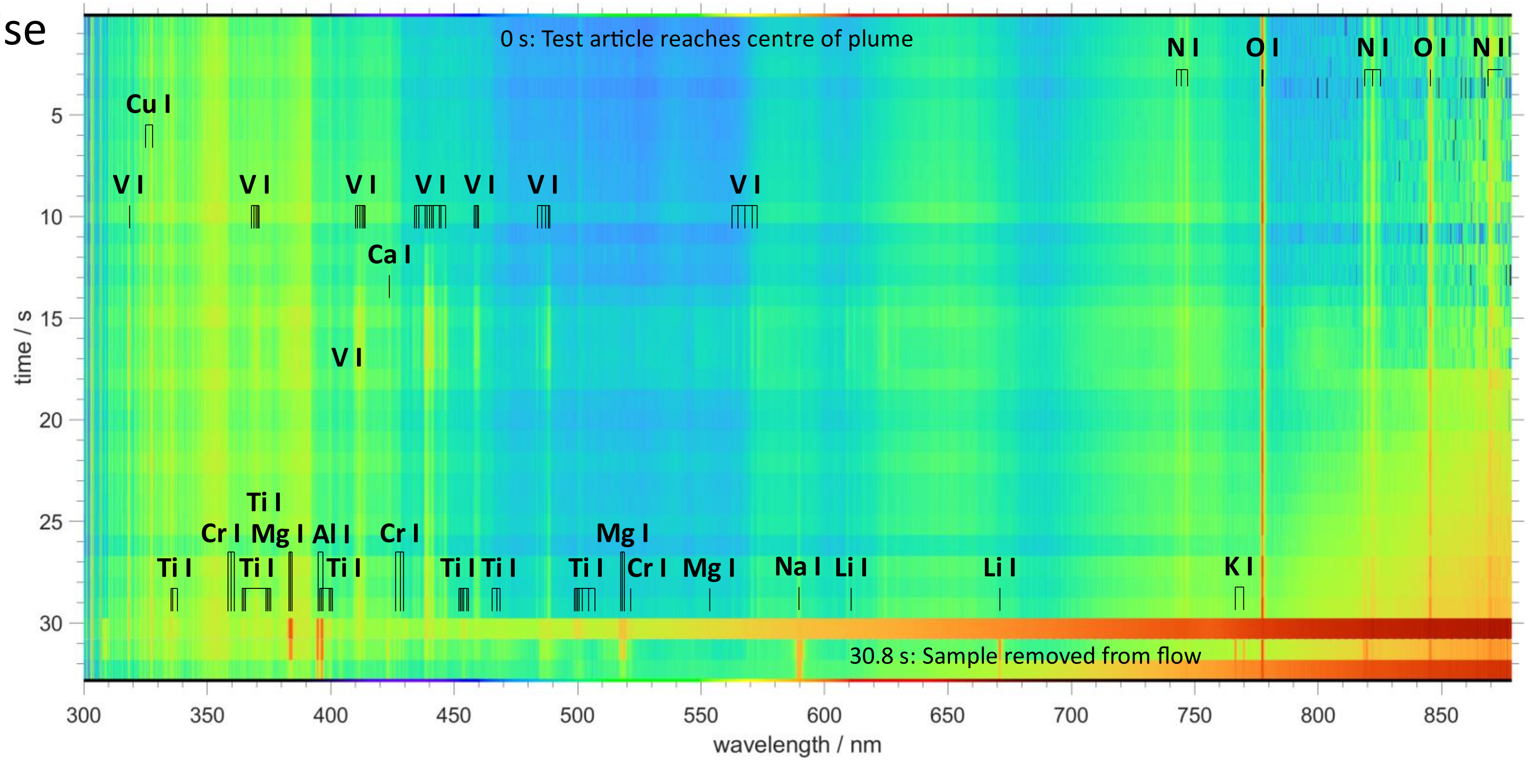
Phase A: Material Tests

Ti6Al4V #27 (Max-Q)

- High-temperature alloy with high relevance in spaceflight; high demise threshold
- Samples emissions differ over phases of heating:
  - **V I**: “active oxide layer” phase
  - **Na I**, **K I** and **Li I**, i.e. alkali metals clearly indicate demise
  - **Ti I, Al I, Mg I**, etc.: Occur only once sample actually melts
  - **Ti I** (primary constituent) emissions require high energy densities







Phase A: Summary

- Five different key aerospace materials were subjected to destructive testing in PWT
- Samples exposed to high mass-specific enthalpy **and** heat flux conditions leading to partly gaseous, highly excited outflow with distinct spectral emission signatures
  → Relevant for wake flow of debris during re-entry
- Aluminium alloys and coated steel show formation of a retaining oxide layer causing a rapid expulsion event, mainly alkaline emissions during heat-up phase
- Only the super-heated droplets betray the type / composition of the alloy after expulsion
- Demise of CFRP confirmed to be accompanied by primarily **CH**, **CN**, **NH**, and other **C-** and **H**-based diatomic species. Distinction between different types of polymers unlikely.
- Aeroglaze coating on metals shows characteristic time-variant signature with typical carbonaceous emissions (**CN**, **CH**, **H**). Slight (≈10%) increase of sample survivability.

Phase A: Conclusion

- Material **emissions** can **identify materials** (for correspondingly homogeneous objects)
  - Works well for metal alloys, if heating rate and enthalpy is sufficiently high
  - Organic polymers (e.g. CFRP or epoxy) appear fairly uniform in their qualitative emissions (dominating CN band)
- Material-specific emissions require sufficiently **high energies** resulting in excited droplets also for low-temperature materials → **Wake flow** as promising **source of emissions**
- Material **emissions** can **indicate state of** actively **demising** material (heating/oxidation phase, melt, droplets). Presented example: Ti6Al4V
- Certain **alkalines** (**K I** & **Na I**, sometimes Li I) appear to be ubiquitous (associated with impurities originating from machining and/or handling?) but are **good overall indicators** for onset **of demise** even at low temperatures

Results and Discussion

Phase B: Components & Structures

Phase B: Component Tests
Overview

- Structural and component samples of crashe
(Ariane V maiden launch) were provided by
- Two structural samples:
  - Inner Equipment Platform Bracket (including CFRP/Al honeycomb, CFRP struts and Al bracket)
  - Aluminium Honeycomb
- Four components from Cluster Battery Regulator Box (BRB):
  - Two instrumented Printed Circuit Boards (PCB)
  - One Swagelok fluid connector (mainly stainless steel)
  - One D-Sub data connector

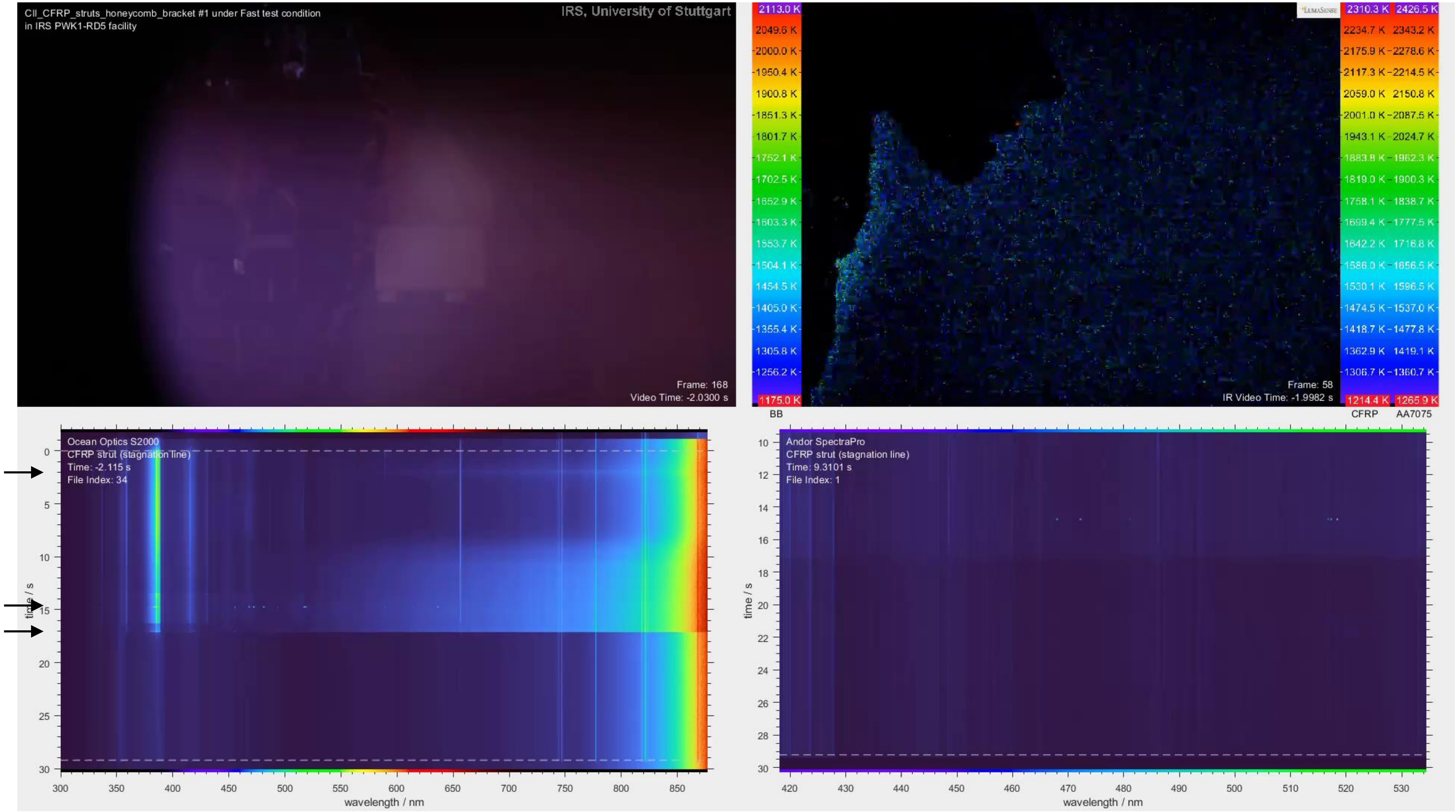
Phase B: Component Tests

Cluster IEP bracket

Minor UV flash event

Green flash event

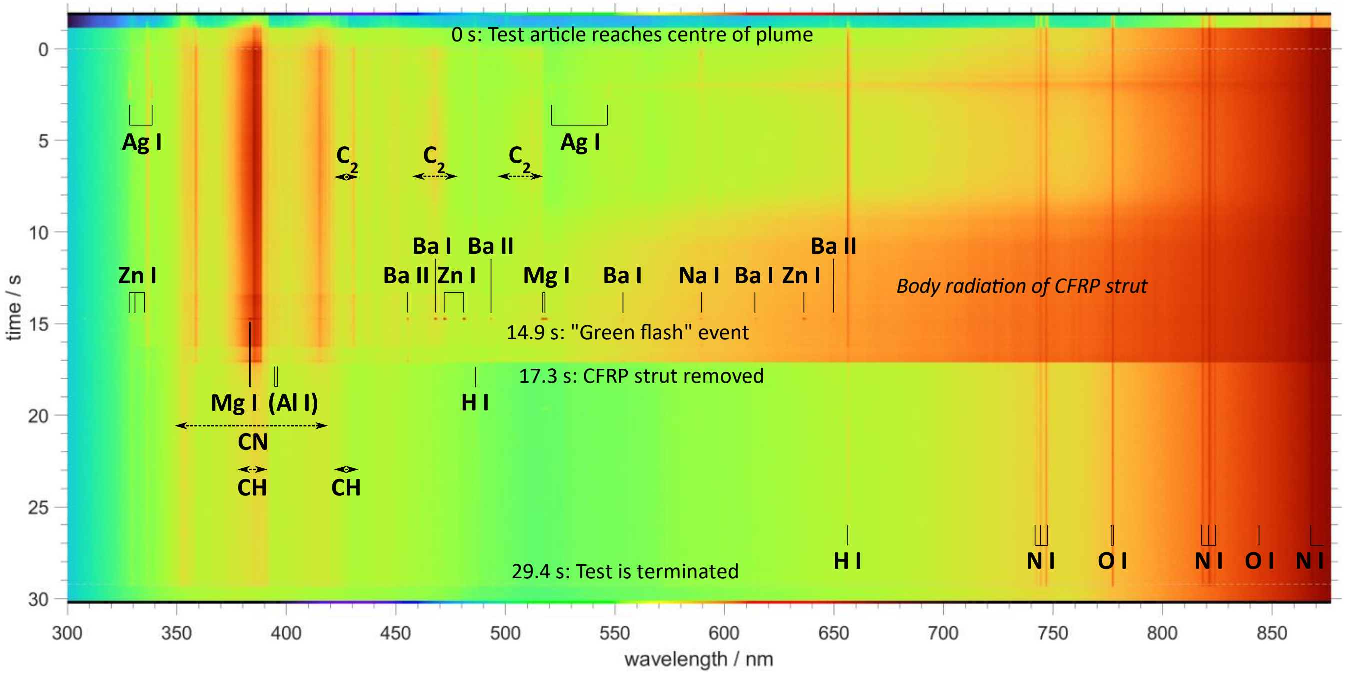
CFRP strut break-off



Phase B: Component Tests

Cluster IEP bracket

- Composite materials are generally hard to distinguish by spectrum
- C_2 bands appear only at low heating rates
- “Green flash” events appear to be typical for composite structures featuring Al alloy and organic adhesives / resins (**Mg I** dominates)
- Blue flashes also observed (**Zn I** or **C_2** dominates)
- Separation of CFRP associated with subtle flare of ionic **Ba II** and **CH**



Phase B: Component Tests

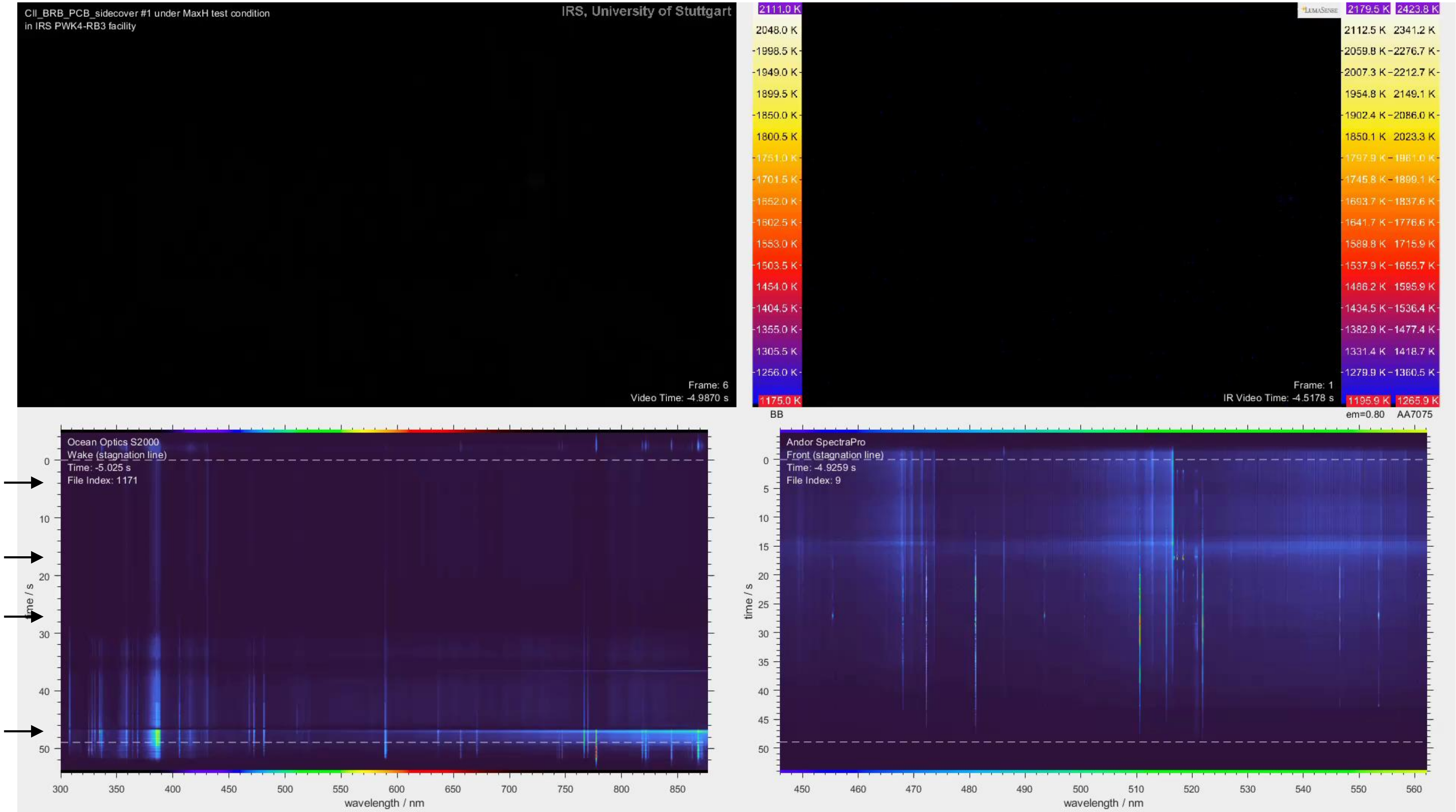
Cluster BRB PCB (Side Panel)

Removed coil cover →

Break-off of coil →

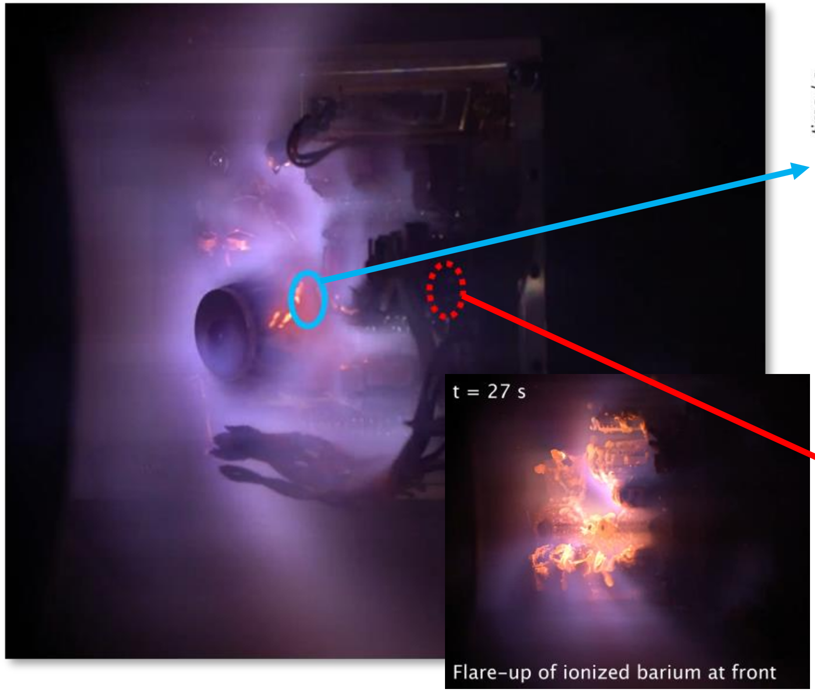
Ba II flare-up at front →

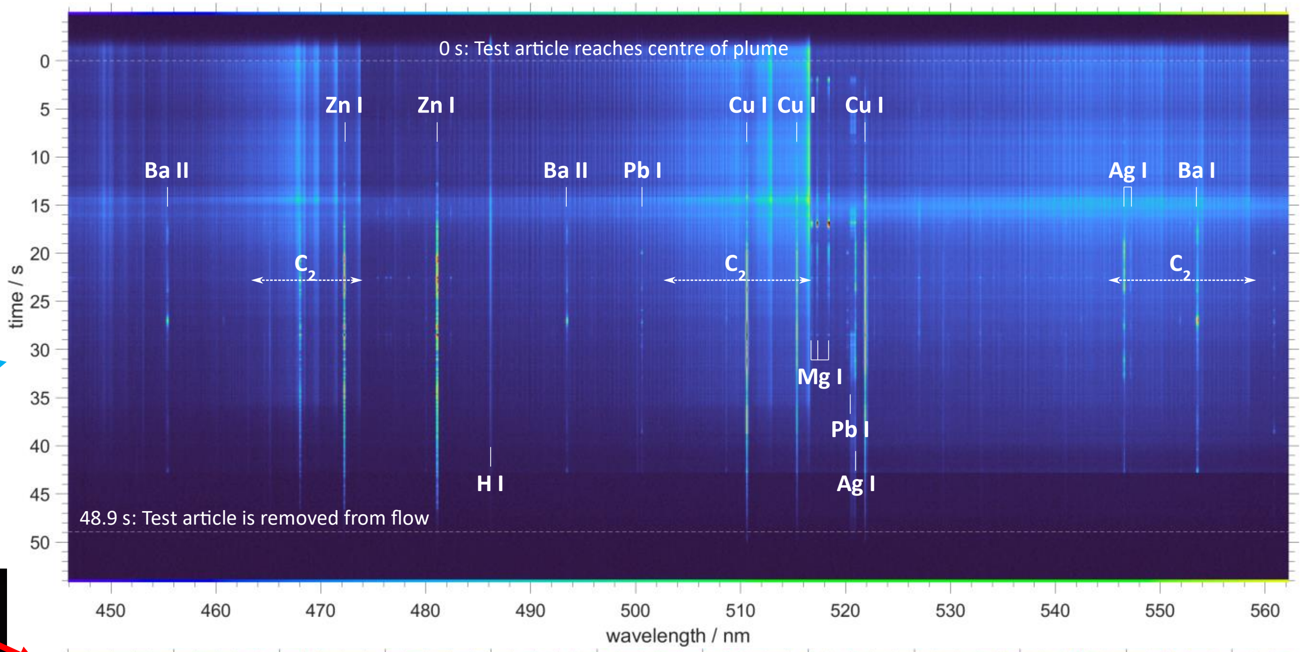
Partially occluded wake →

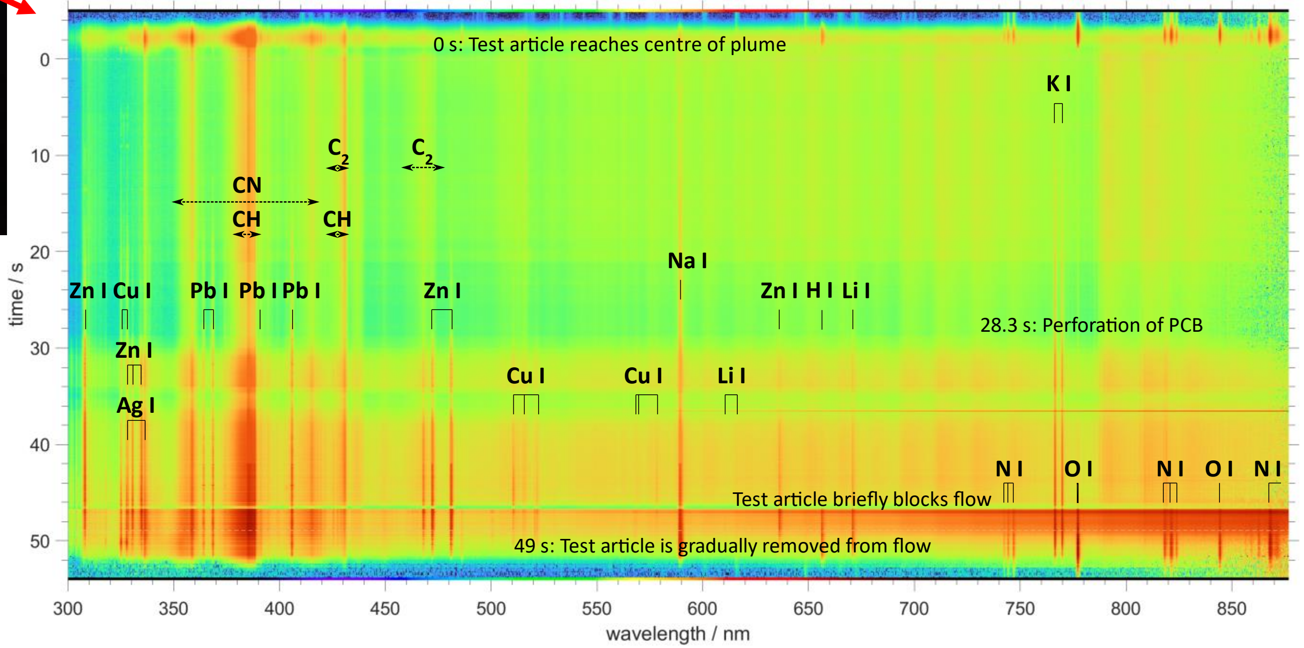


Phase B: Component Tests

Cluster BRB PCB (Side Panel)



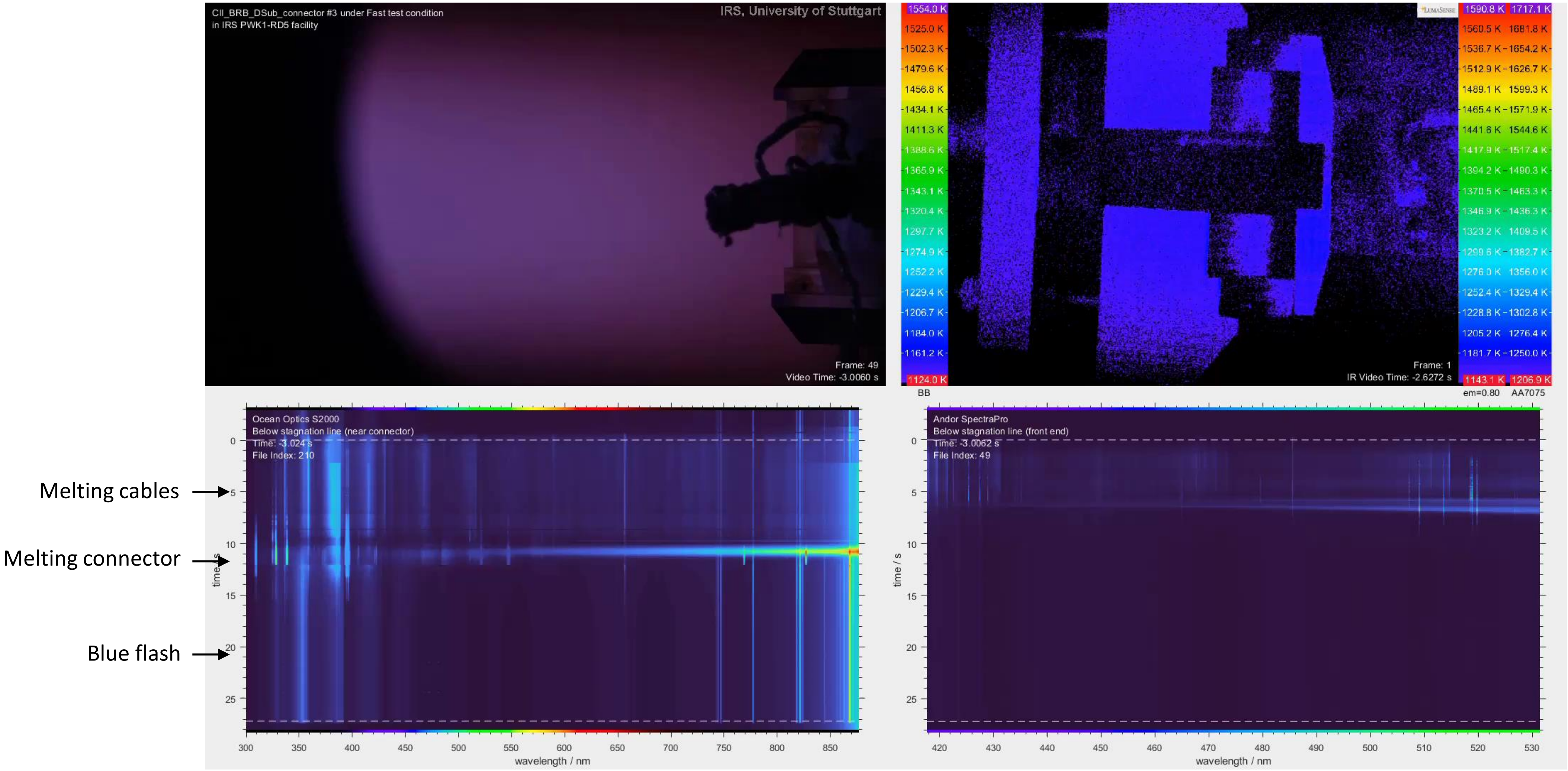




- Very rich emission spectrum, hypothetically permitting identification of individual mounted components (not realistic for remote observation)

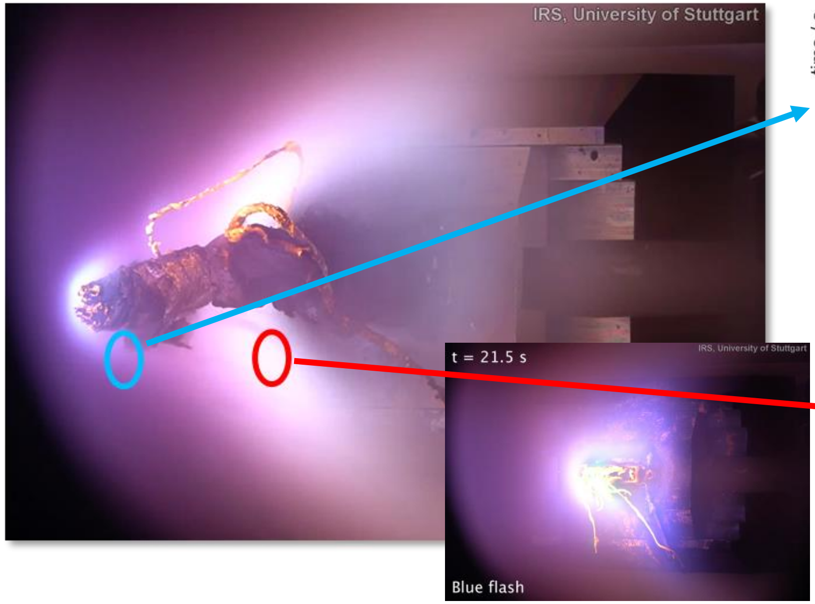
Phase B: Component Tests

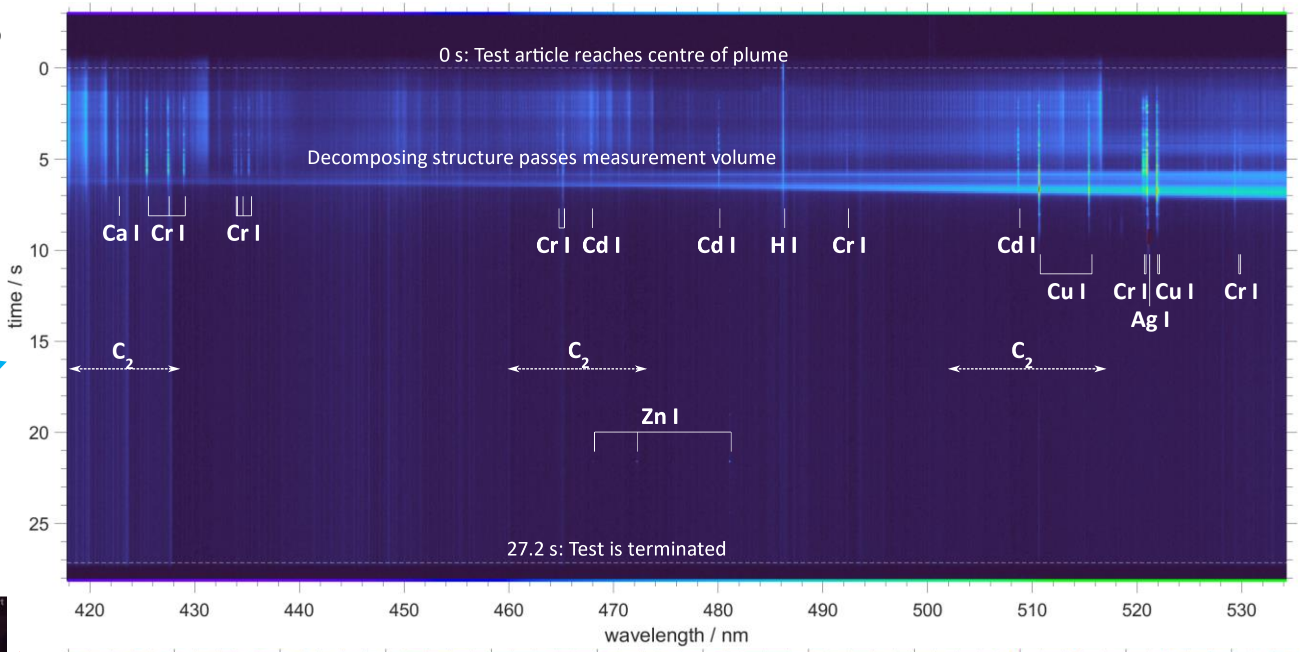
Cluster BRB D-Sub Connector

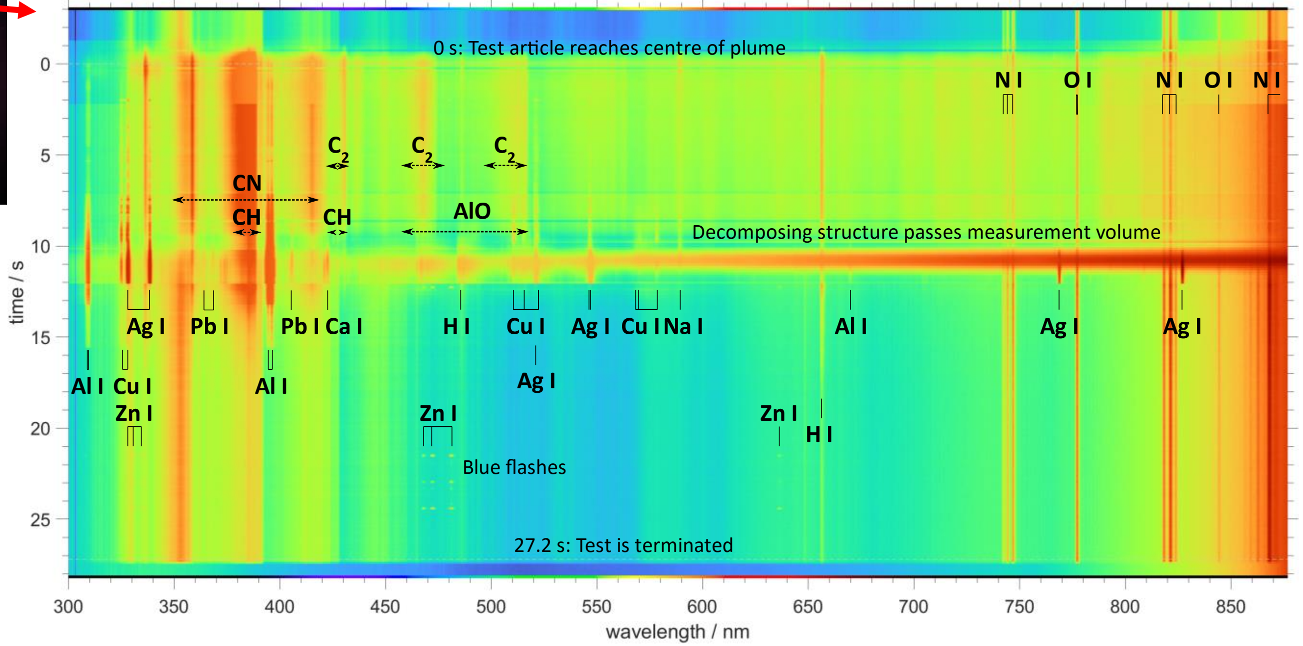


Phase B: Component Tests

Cluster BRB D-Sub Connector







- Typical organic diatomic species and **AlO** identified
- Forward area (cables) dominated by **Cr I, Cu I, Ag I, H I, Ca I**, and **Cd I**
- Base area dominated by **Al I, Ag I, Cu I, Pb I, H I**
- Blue flashes are expulsions of **Zn I**

Phase B: Summary

- Heterogeneous composition with accordingly rich emission signatures during demise
- Spectral baseline signature of PCBs and CFRP parts reflects the demise of their polymer components with diatomic emissions (**CN, CH, C2, NH**) and atomic lines of **H I, Na I** and **K I**
- PCBs shows **Cu I** and **Pb I** as internal conductive pathways and solder dissolves
- CFRP/Al-honeycomb structures show typical emissions associated with **Al** demise
- Green (and some blue) flashes may be linked to a characteristic atomic emission signature of aluminium-epoxy joints, with strong lines of **Zn I, Mg I, Na I, Ba I** and **Ba II**
- Separation event (CFRP struts from Al bracket) indicated by very subtle flare-up of **Ba II**, perhaps linked to adhesive.

Phase B: Conclusion

- Tests illustrate **difficulty in distinguishing** between different polymers (CFRP makes, epoxy adhesives) by their **emission spectra** (typical carbonaceous/organic material emissions)
- However, **green and blue flashes** observed in tests of Al honeycomb and IEP bracket indicate **origin in adhesives** used to bind aluminium to polymers
- Very weak (Ba II) signature observed for separation of Al and polymeric structure → Impractical for remote observation, otherwise no particular emission signature
- An **identification of** individual small **sub-components** (e.g. PCB mountings, different steel alloys in fluid connectors) might be possible **from spectral analyses** → However, probably impractical due to mass/length scales during remote observation

PRODUCERS: Summary of Experimental Findings

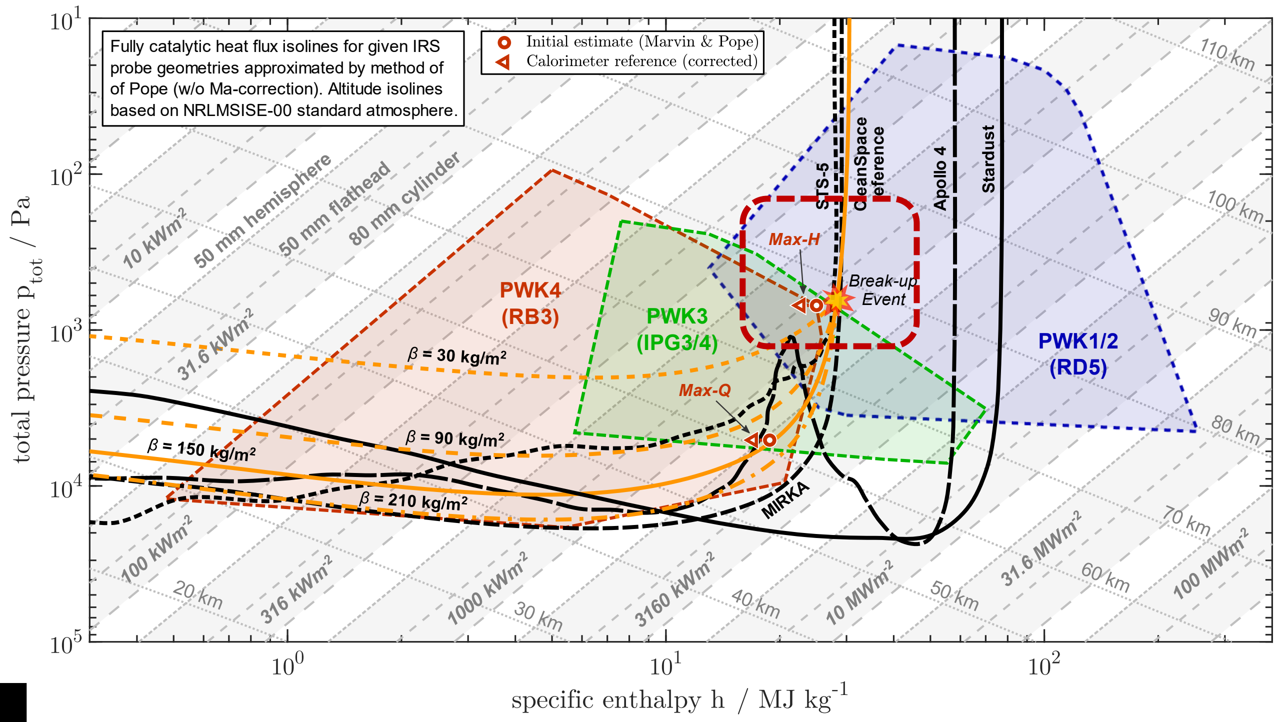
Results and Discussion

Phase C: Splitter Probe

Phase C: Experimental Method

Test Condition and Matrix

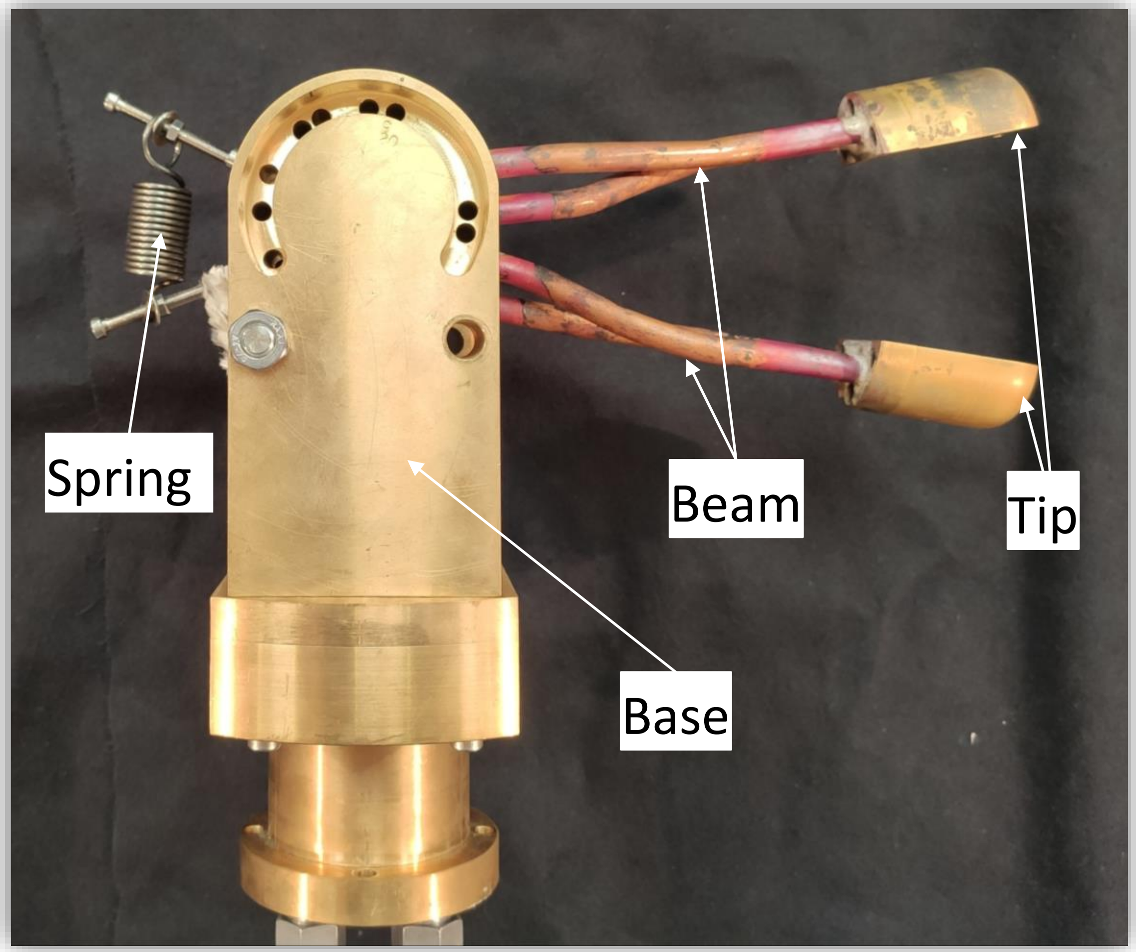
Parameter	Unit	Max-H
Axial position $\boldsymbol{x}$	mm	135
Reference heat flux $\dot{q}_{\mathrm{CuO,cw}}$	$\mathrm{kWm^{-2}}$	790
Reference heat flux $\dot{q}_{\mathrm{CuO,fc}}$	$\mathrm{kWm^{-2}}$	790
Stagnation pressure p_0	Pa	655
Mass-specific stagnation enthalpy h	$\mathrm{MJkg^{-1}}$	25
Mach number reference $\mathbf{Ma}$	–	4.72

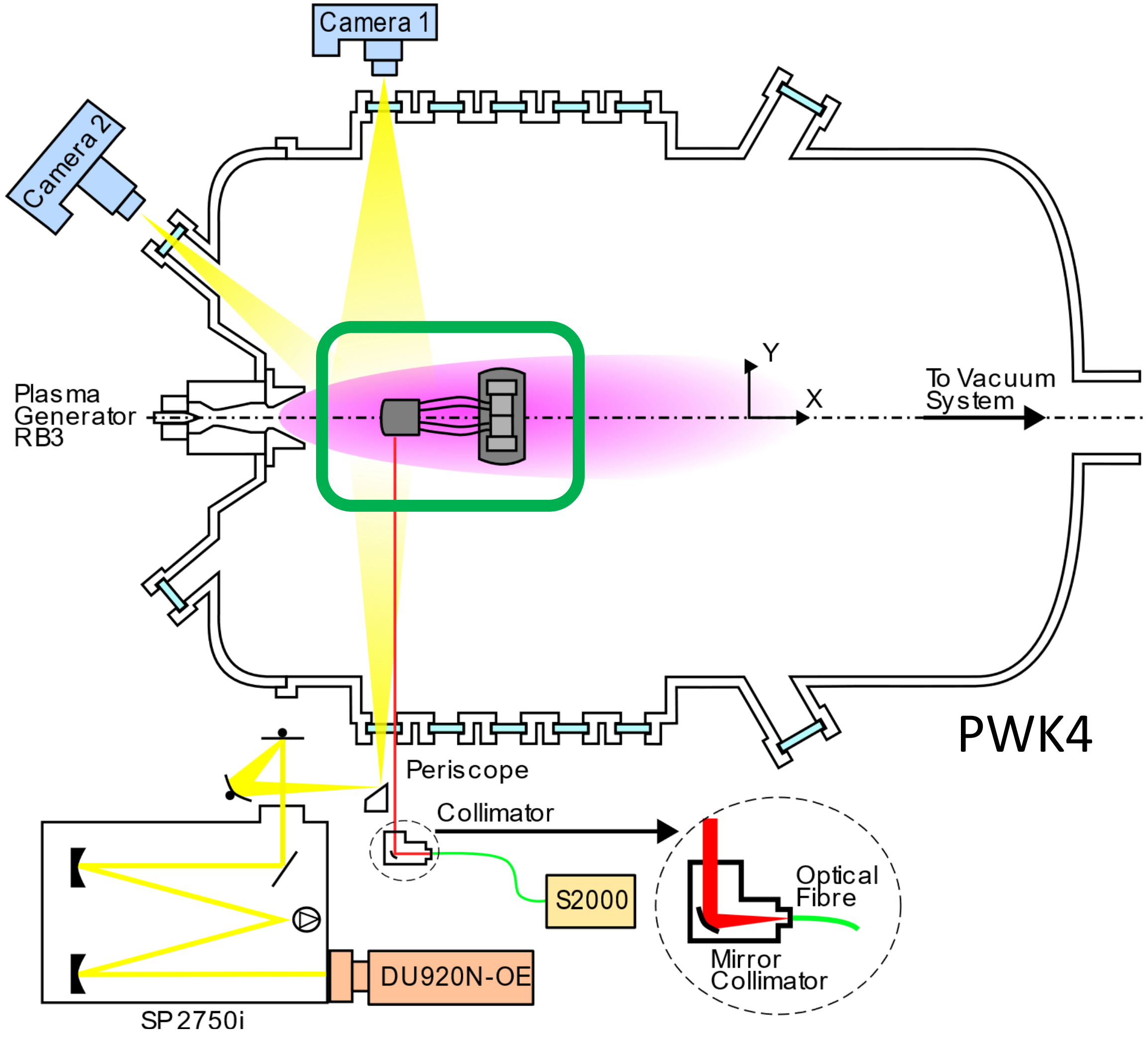


Test ID	Sample	Purpose	Angle
C1	Al 7075 flat coin	Angle 1	6.5 deg
C2	Al 7075 flat coin	Re-run Angle 1	6.5 deg
C3	Al 7075 flat coin	Angle 2	16.7 deg

Phase C: Experimental Method

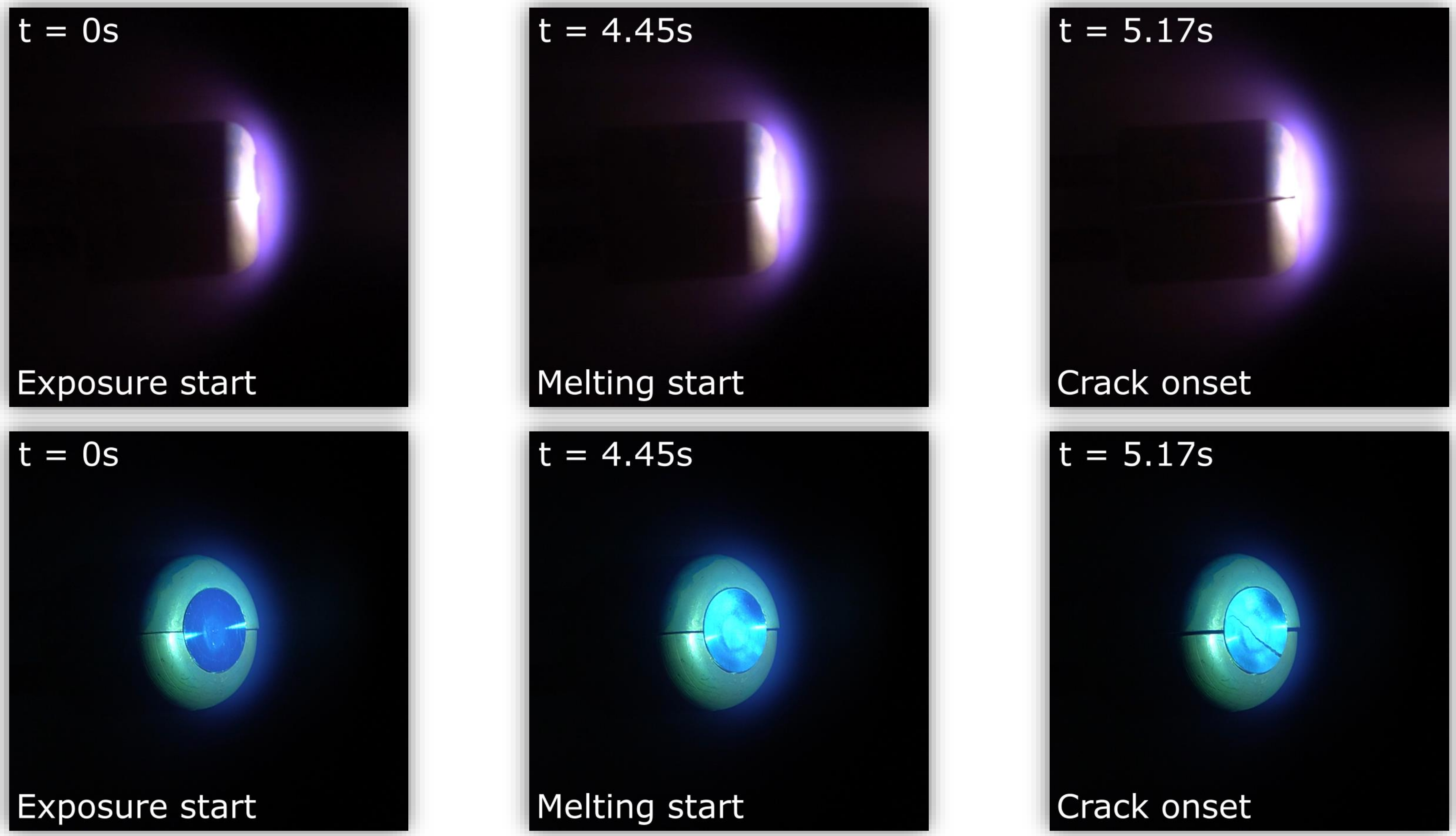
Splitter Probe





Phase C: Results and Discussion

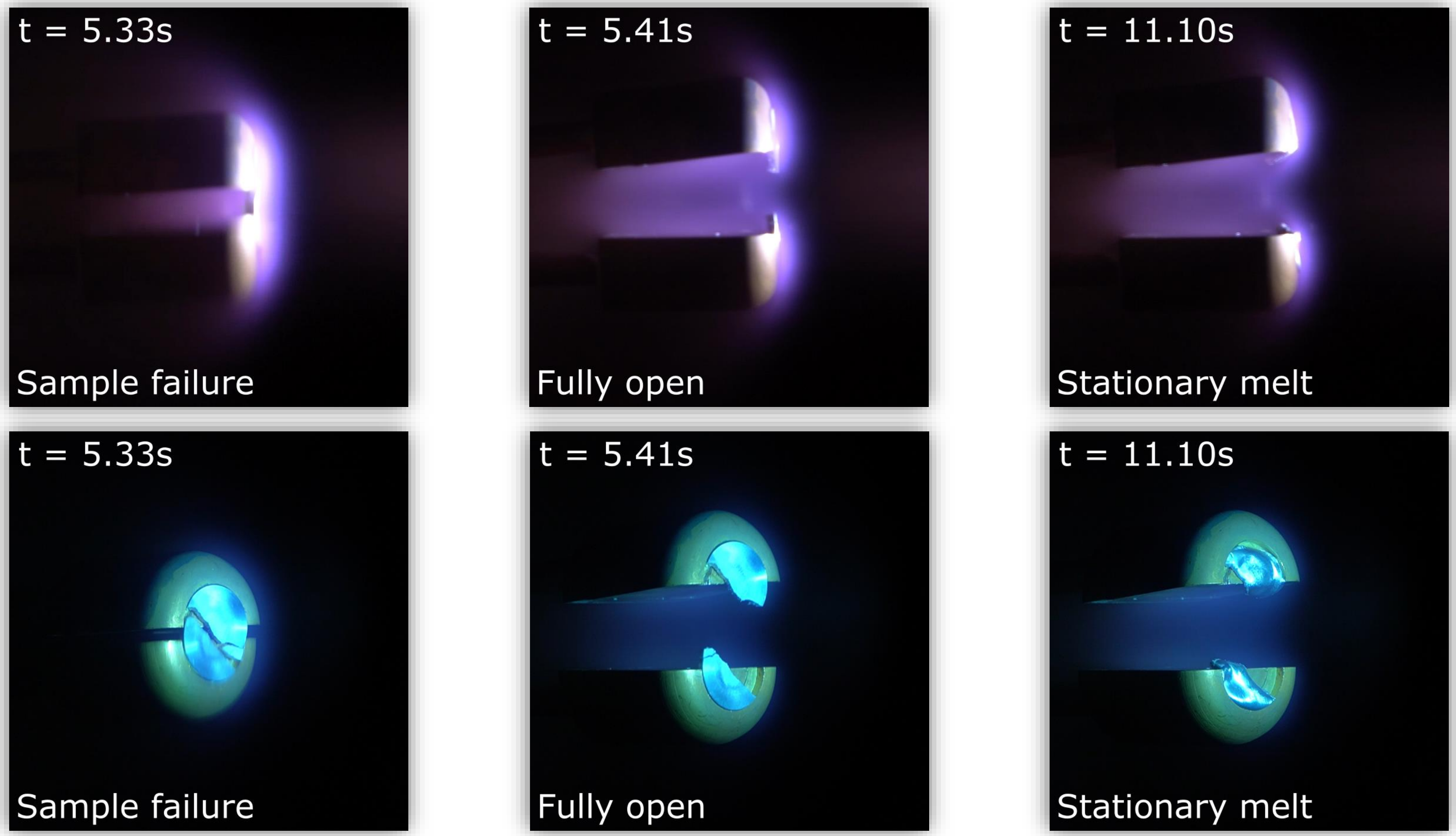
Failure Behavior



- Camera 1
- Camera 2

Phase C: Results and Discussion

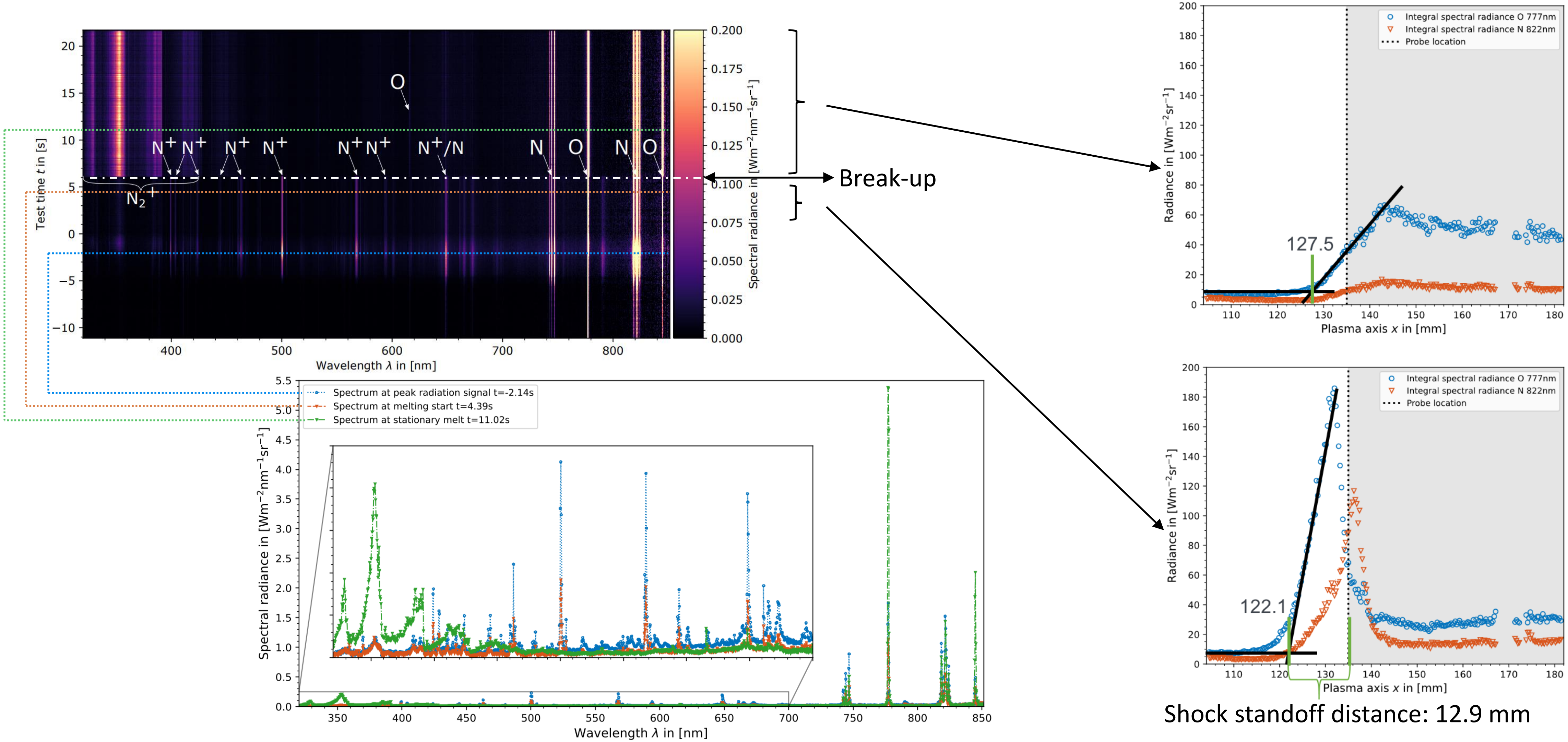
Failure Behavior



- Camera 1
- Camera 2

Phase C: Results and Discussion

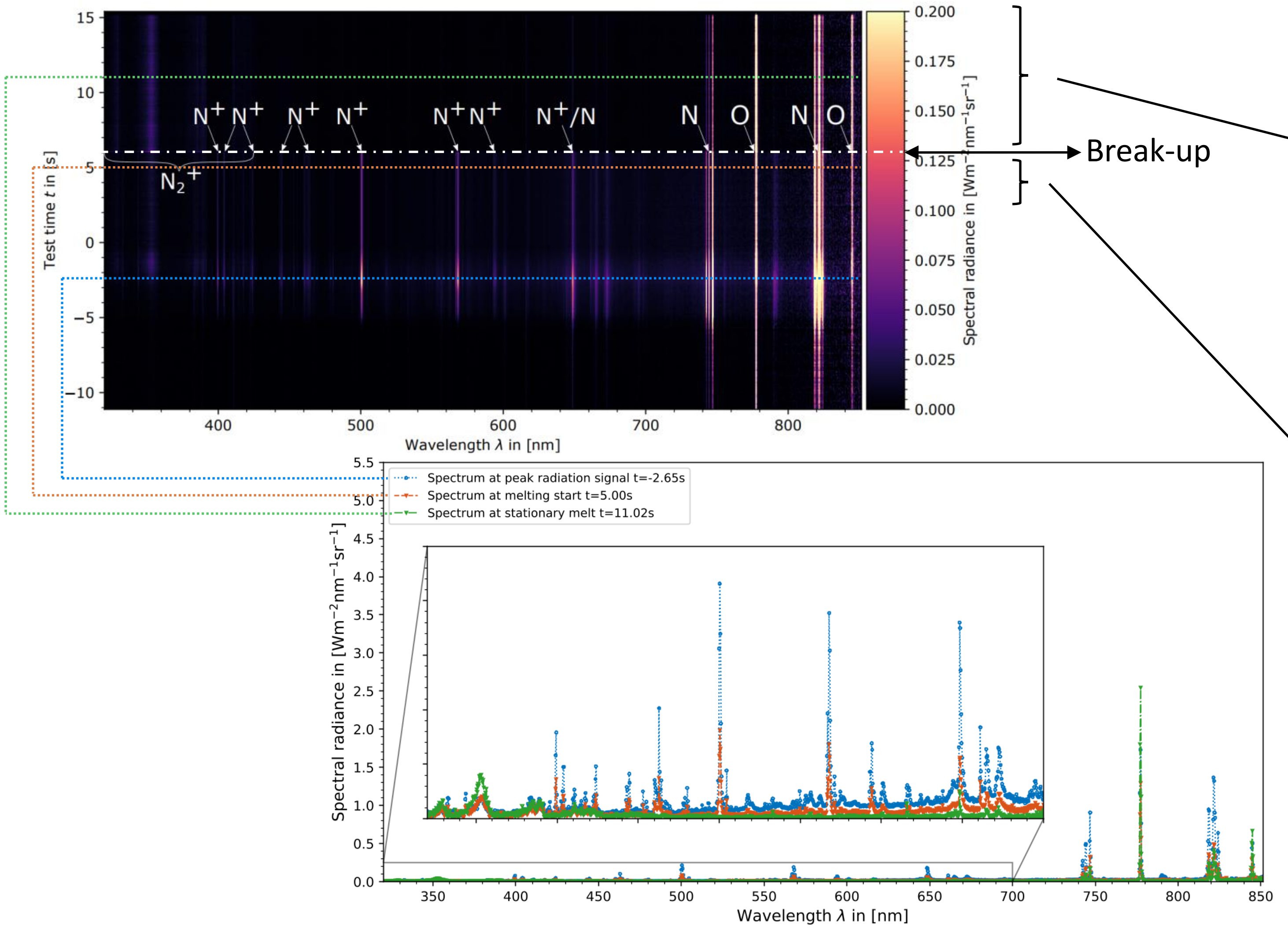
Radiation Marker and Shock Identification at Opening Angle: 6.5 deg

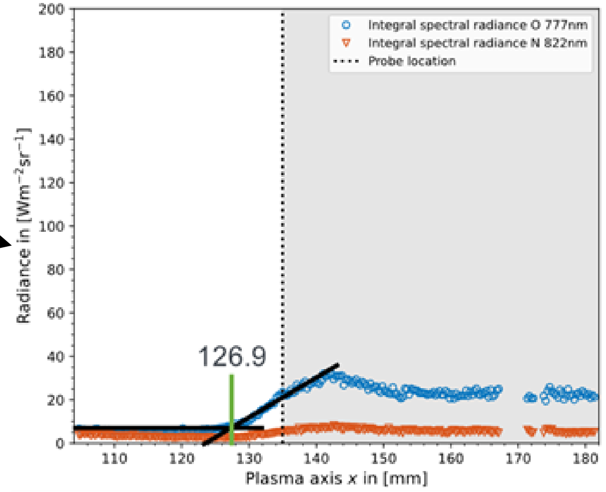


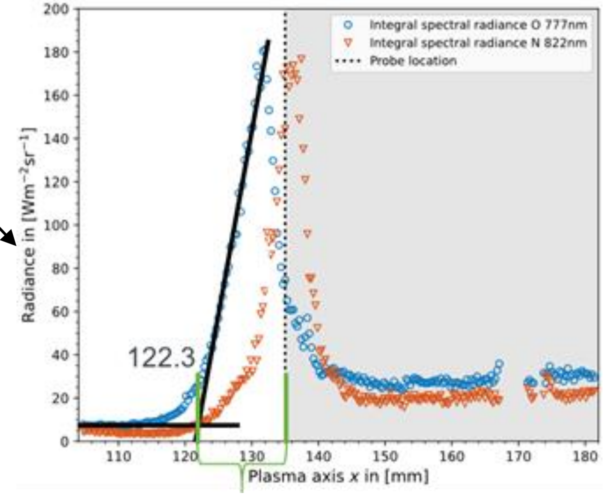
Shock standoff distance: 12.9 mm

Phase C: Results and Discussion

Radiation Marker and Shock Identification at Opening Angle: 16.7 deg







Shock standoff distance: 12.8 mm

Phase C: Summary

- Dedicated **Splitter Probe** designed to simulate low-level break-up during re-entry for understanding separation events.
- Al 7075 alloy sacrificial coins tested in Max-H conditions using a splitter probe and observed with UHD cameras, OES S2000, and OES SP2750i.
- Oxygen triplet emissions used to analyse **bow shock** and **shock structures** during probe opening.
- Spatial integration of OES SP2750i spectra showed a decrease in radiation (-24% to -80%), with reductions in oxygen triplet peak radiation, but no conclusive evidence for increased brightness.
- OES S2000 spectra revealed changes in **spectroscopic markers** after probe opening, with disappearance of N+ radiation markers and appearance of N2+ bands and increased N and O radiation. N+ emissions were suspected to originate from reflections on the probe tip's corner within the plasma generator. No markers related to sacrificial coins due to effective cooling.

Phase C: Conclusion

- **No conclusive evidence** supporting the hypothesis of increased apparent brightness during re-entry due to limited observation of the whole shock structure volume.
- **Radiation marker** identification of low-level break-up event:
  - Significant increase in N2+ band emissions
  - Especially in the merging point of two bow shock layers
  - **N2+** as **potential candidate** for a radiative marker
- Detailed analysis of **shock structures** using spatially resolved spectra offered valuable insights into bow shock and probe-induced shock structures:
  - **Oxygen triplet** at 777.34nm as excellent radiation marker
  - Study of shock layer thickness and location with **spatially resolved OES**

PRODUCERS: Summary of Experimental Findings

Conclusions

Conclusions

- Established an **extensive experimental database of spectroscopic markers** for a range of materials, surface coatings, functional and structural components **relevant to** the Cluster-II re-entry and **destructive re-entries** of spacecraft in general.
- Associated specific markers with certain events in timeline of demise of materials and decomposition of components and structures.
- Experimentally assessed effects of object separation on shock structure and optical emission behavior.
- Assessed **implications on remote observation** campaign designs and ground-to-flight read-across potentials and limitations.
- Observed a connection between the **accumulated energy density**, i.e. local heat flux, as considerably **affecting the resulting spectrum**, e.g. with primary alloy constituents in **metallic alloys** generally becoming **visible only** as droplets become **superheated in wake flow** during flight. Emulating this in ground testing environments via dedicated sample design or extreme overheating is considered challenging but feasible.

Overview of PRODUCERS modelling software

Software Requirements

- Identify radiating species
  - Based on components being heated/ablated
- Identify relevant flow conditions
  - Capture magnitude of emission
- Identify break-up events
  - Brightness changes?
- Take output from re-entry tool (DRAMA) and construct inputs to drive a radiation tool (PARADE)
  - Linking existing ESA tools

Physics Model Design

- Limited information from DRAMA (or any destructive re-entry tool)
  - No flowfield representation, limited material representation
- Flowfield model
  - Emission from air chemistry
    - Primarily N2+
    - Require estimation of number density and temperature
  - Emission from ablation products
    - Spacecraft materials gaseous emission in boundary layer
    - Require estimation of number density and temperature
- Particle model
  - Small droplets/particles are released in ablation
  - Boundary layer gaseous emission
  - Molten droplet ablation

Physics Model Design

- Radiation production
  - Which component produces which emitting species
    - Markers; species mapping
  - Grey body radiation from hot surfaces
    - Large bodies and droplets
  - Brightness flashes
    - Evidence of fragmentation postulated
    - No evidence of mechanism from test, not included
- Radiation transport correlation
  - Remote observers
    - Aircraft (10km altitude, interpolated movement)
    - Ground (static)

Flowfield Model

- Emission from air species
  - Dominated by N2+
  - Emitted from shock layer and from post shock region
- Equilibrium shock layer
  - Only a simple approximation can be justified from basic data available
  - Know density, velocity
  - Construct equilibrium look-up (via CEA data) for shock temperature and density
  - Correlations for shock standoff (Lobb)
  - Assess N2+ using equilibrium value (correlated CEA data)
    - Supported by CFD runs
    - Tests suggest that emissio
      - Use fraction of shock te $T = C\left(\frac{\frac{1}{2}v^2}{1005}\right) + (1 - C)T_{shocklayer}$ m shock layer temperature

Flowfield Model

- Uncertainties
  - Shock layer conditions
    - CFD support shows that the shock/boundary layer may be non-equilibrium
    - Small shapes (0.2m) at high altitude (80km) will be non-equilibrium
    - Larger shapes (2m) equilibrium at 80km
    - Small shapes (0.2m) close to equilibrium at 65km, larger (1m) equilibrium
    - There will be significant uncertainties in the air species radiation
      - Temperature profile will not be predicted well, T^4 dependency
      - Boundary layer species temperatures are likely to be better
      - Uncertainties should be considered at order of magnitude for intensity
      - Quality is approximately 'marker' level
  - Shape factor for shock standoff
    - Uncertainties in conditions dominate, sphere model considered in first version
- Better than an order of magnitude is good

Boundary Layer Ablation

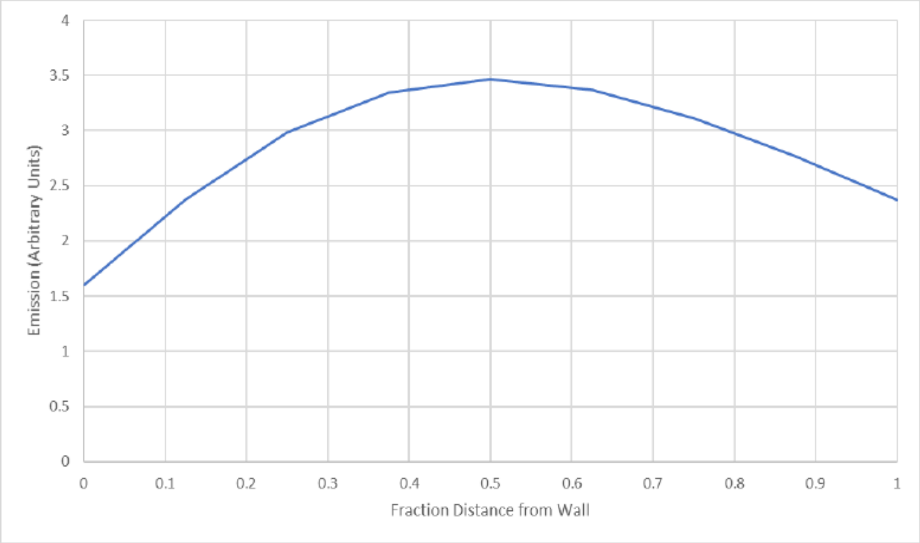
- Significant CFD support has been provided here
  - Correlations are highly approximate
  - Gas phase radiation from surface of component vs. from shed particles/droplets
    - Large unknown; use model constant to give proportionality
      - See FGE test analysis / interpretation
    - Will be an input in the software
- Flow conditions
  - Set of CFD simulations at 80km and 65km, two model sizes
  - Assess length scales of diffusion and temperature rise from surface
- Gaseous ablation products
  - Species considered: Al, AlO, V, Cu, Li, CN
  - Highly consistent behaviour (transport properties?) for given B' value
    - Surprising, but useful for building simple correlations

Boundary Layer Ablation

- Radiation profile across boundary layer
  - Pseudo-constant; becomes small quickly outside fast temperature rise region
  - Approximate curve of concentration x T^4 constructed; 3% concentration at edge
  - Capture approximate level; values which give good estimate
    - Temperature: $T_{abl} = 0.25T_{wall} + 0.75T_{shocklayer}$ tuned to testing results
    - Concentration: $\frac{B'}{(B'+1)}$ B' film coefficient blowing parameter
- Two model constants

$$\psi = \frac{Mass\ released\ as\ gas\ at\ the\ surface}{Mass\ released\ as\ liquid\ at\ the\ surface}$$

  - B' for gaseous species
- Grey body radiation
  - At surface temperature
  - Large contributor of radiation



Molten Droplet Ablation

- Melt ablation products
  - Droplets removed from surface of melting component
  - Likely secondary break-up
    - Consistent with meteoroid modelling approaches
    - Standard spray modelling correlations used for secondary breakup
      - Weber number based
  - Small particles will heat and slow quickly
    - Hand calculation suggests using oxide melt temperature
      - Short timescale for heating relative to slowing
    - ODE solution for residence time at high speed (>2km/s) calculated
  - Radiation calculation: two sources (both high contributors)
    - B’ model with boundary layer used in dispersed mode
      - Velocity scaled by factor 2 in B’ calculation for rapid deceleration
    - Grey body radiation
      - Oxide melt temperature and emitting area calculated
- Model suggests that droplet/particles are major radiation source

Radiation Production

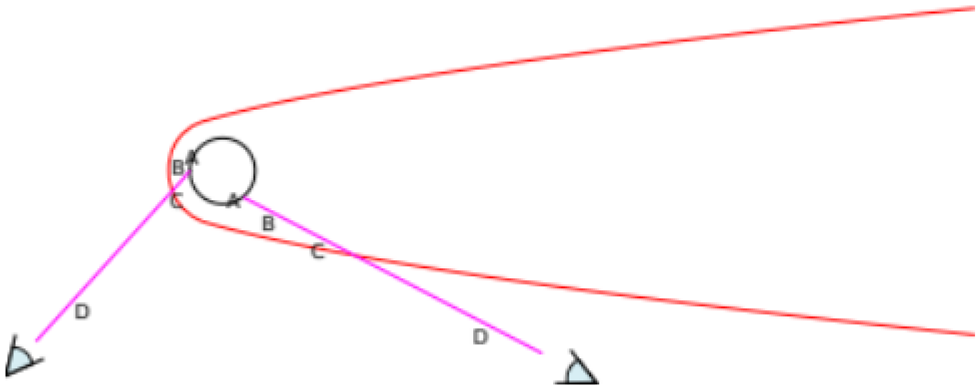
- Radiating species set
  - Suggestions from previous testing
  - Implication from PRODUCERS test campaign

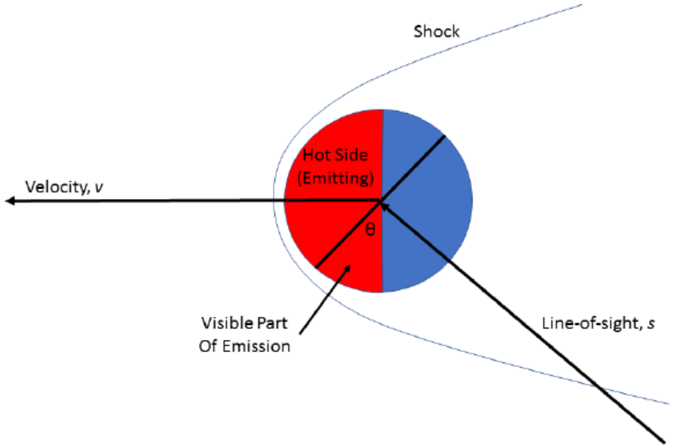
Observed Spectra	Source	Mapping Requirement	Notes
N_2^+	Air chemistry	No	
CN violet	CFRP material	Yes	
Li	Li-ion Battery	Yes	Cells can be modelled as steel cans Cannot be identified from material
Cr	Steel	Yes	Emitted before melt
Cr	Paint	Yes	Cannot be identified from underlying material
Fe	Steel alloy	Yes	
V	Titanium alloy	Yes	Emitted before melt?
Ti	Titanium alloy	No	
TiO	Titanium alloy	Yes	Unconfirmed
Xe	Propellant tank	Yes	Specific object; tank rupture
Al	Aluminium alloy	No	
AlO	Aluminium alloy	Yes	
Zn	Aluminium alloy	Yes	
Zn	Paint	Yes	Underlying material?
Cu	Harness, Electronics	No	Electronics model?
Ni	Inconel, Invar	Yes	
Ca	Uncertain	Yes	
K	Uncertain	Yes	
Na	Uncertain	Yes	
Mg	Magnesium alloy	Yes	
Mn	Battery?	Yes	

Material	Atomic species	Diatomic species
Plasma wind tunnel species	*N, O*	*N_2, N_2^+, O_2*
AA7075	Al(88.77), Zn(5.9), Mg(2.3), Mn(0.3)	
AISI316L	Fe(65.56), Cr(17.5), Ni(11.5), Mo(2.25), Mn(2)	
AA2099	Li(1.8), Zn(0.7), Mg(0.3), Mn(0.3)	
Ti6Al4V	Ti(89.13), Al(6.125), V(4)	TiO, AlO
CFRP EX1515/M55J		CN, CH, NH
Aeroglaze coating	*C, H (these species appear at start of test but not at expulsion)*	CN, CH

Radiation Production

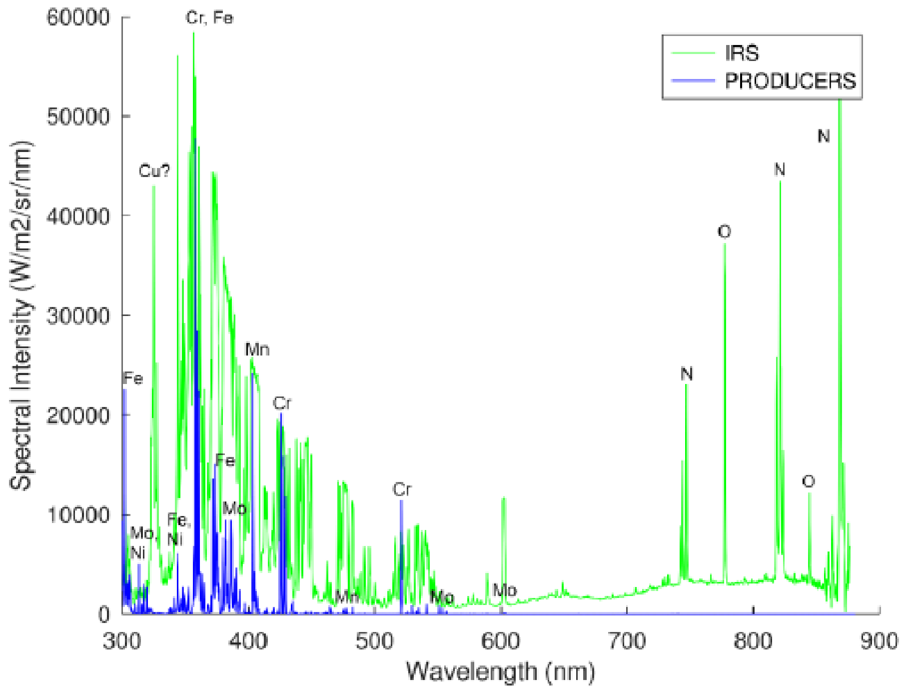
- Location of emission
  - Collect emission
    - Surface
    - Shock layer
    - Boundary layer
    - Particles
  - Emit from two layers per component/object
    - Boundary layer / shock layer
    - Particles in shock layer
    - Distinct sources
  - Transport through air column in PARADE(*)
- Observability
  - Take factor of front half of sphere
  - Changes power
  - Ignore Doppler shift in first version





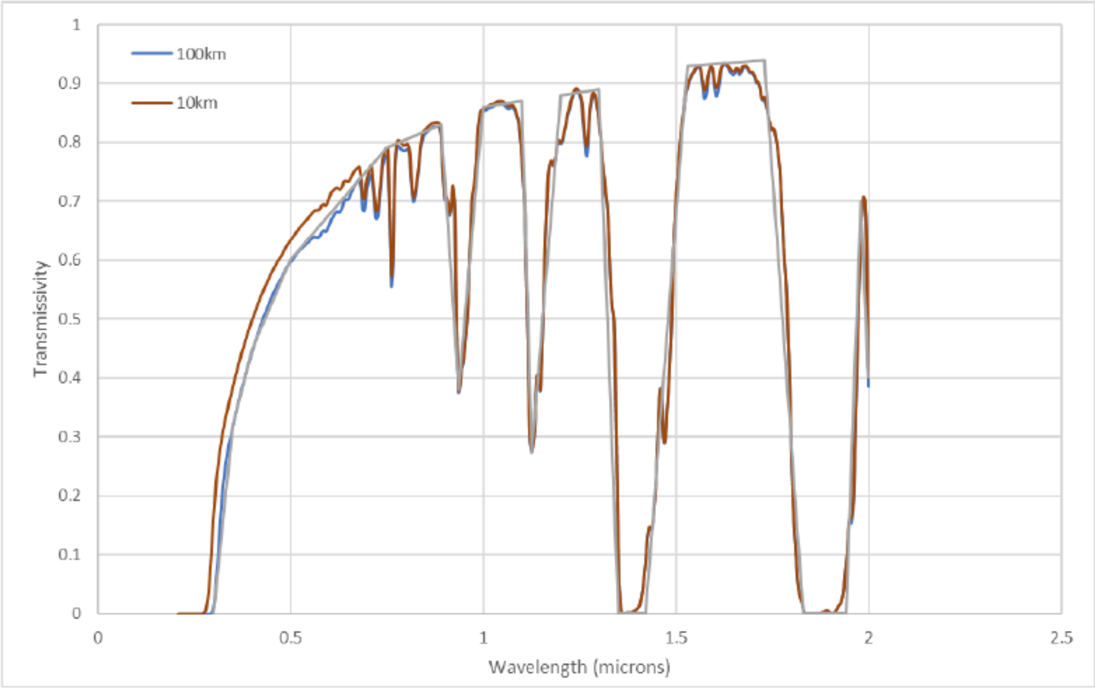
Radiation Models

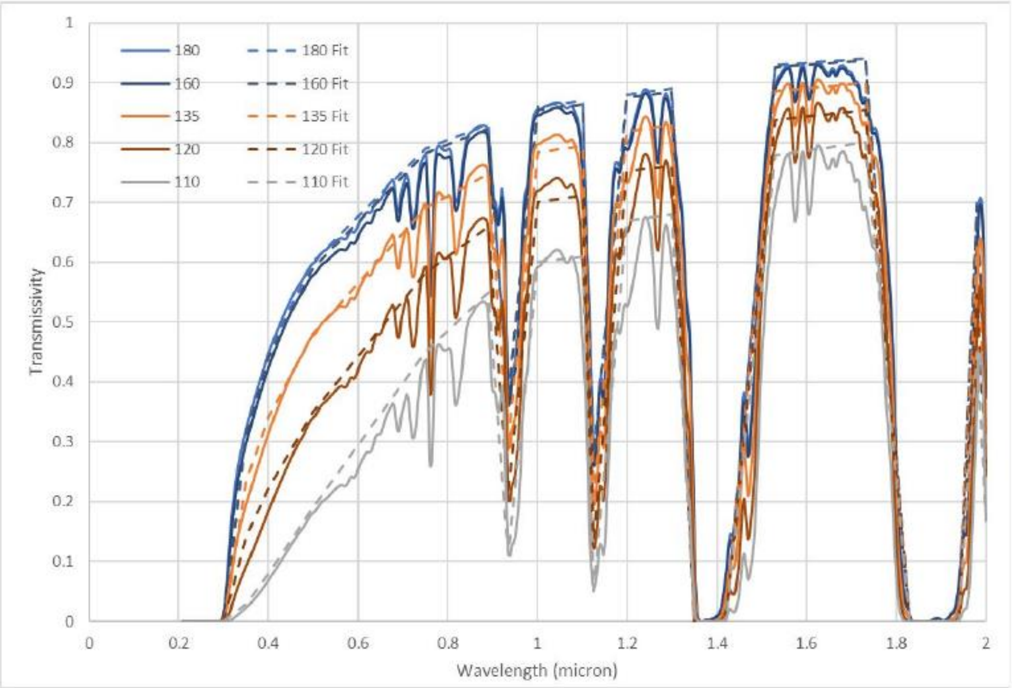
- Quick look correlation
  - Radiative power $P = nT^4$
  - Basic correlation
  - Allows identification of major radiating species
  - Allows assessment of time of major radiation
- PARADE calculation
  - Line-by-line methods
  - Provides radiative signatures



Radiation Transport

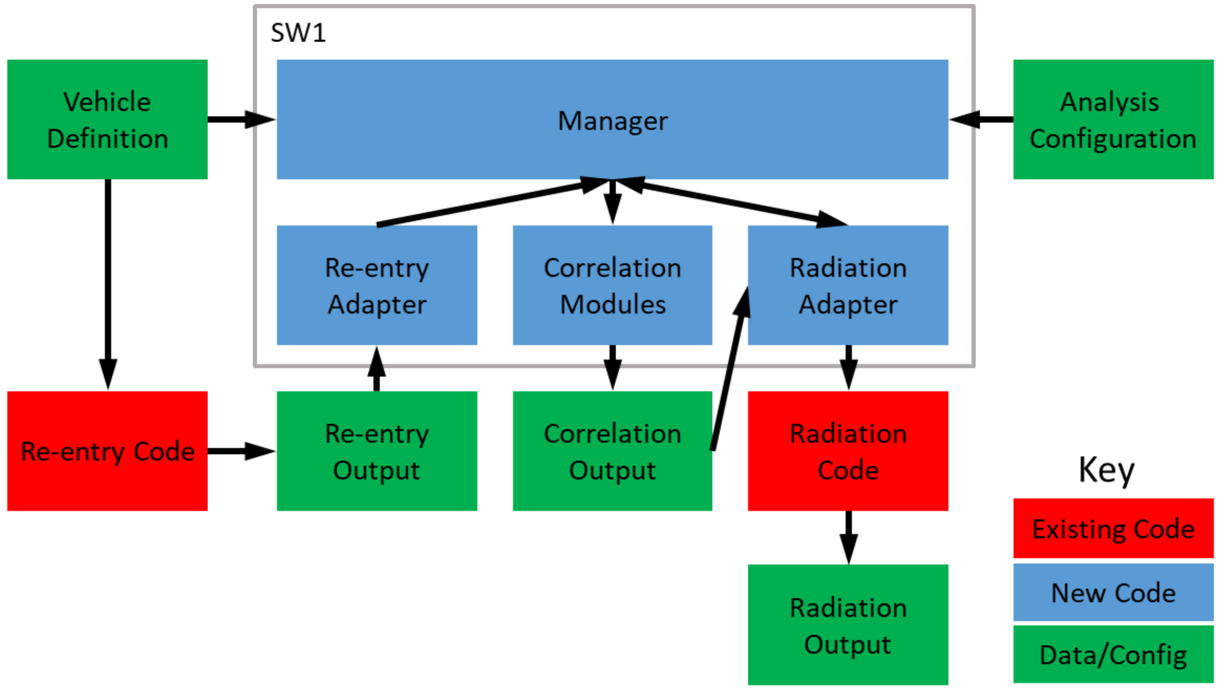
- Key absorbing species are missing in PARADE
  - Implement band model absorption cross-sections for H2O, O3
  - Significant work
- Public MODTRAN data
  - MODTRAN online data tool
    - Transmissivity is a function of altitude, zenith and wavelength





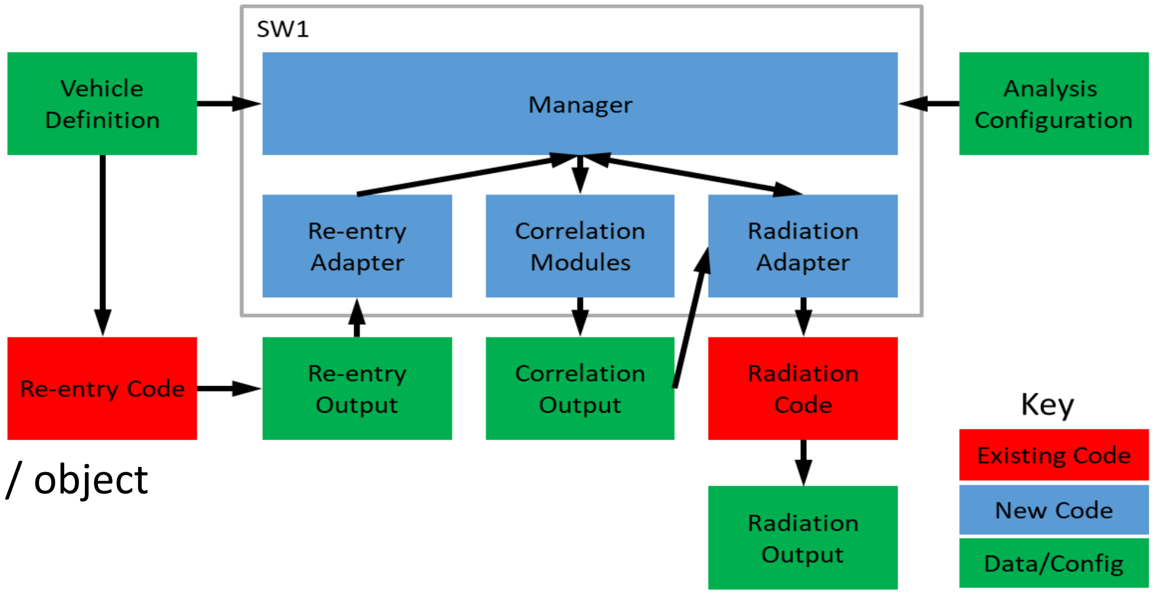
Software Architecture - Overview

- Priorities, simple & extensible
  - Custom Python command line application
  - Output presented as static HTML pages, PNG images and plain text data files
  - Building on infrastructure constructed for PADRE



Software Architecture – Core Elements

- Manager
  - Reads configuration
  - Instantiates analysis tasks
  - Marshals analysis state between tasks
  - Stores analysis state to disk



- Configuration
  - Extended PADRE spreadsheet definition of spacecraft / object
  - Python object graph configuration stored in text file
  - List of analyses, each with independent configuration

- Analysis state
  - Python “Pickled” Data Transfer Object (DTO)
  - Passed between analysis tasks
  - May be read from / written to by tasks
  - Permits re-running of single tasks

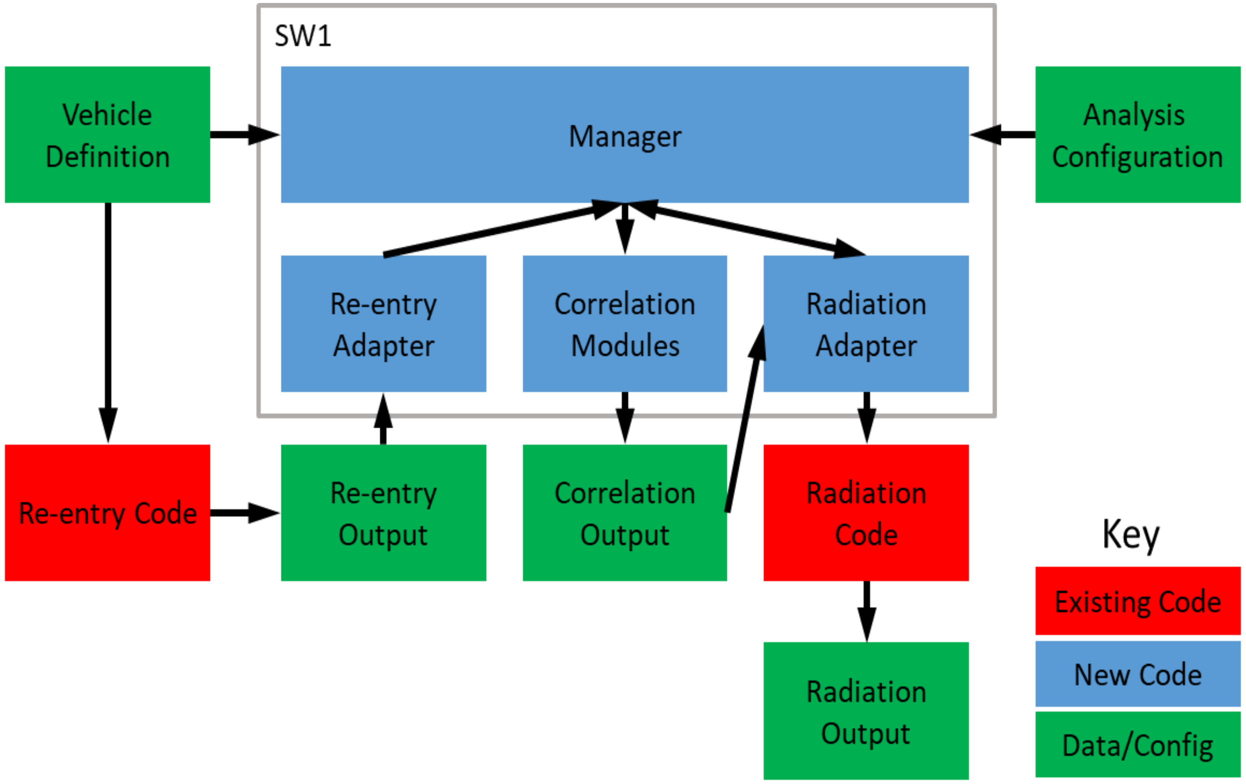
Software Architecture – Configuration

```
{
    "title" : "PRODUCERS Test Analysis",
    "description" : """
        This is a test analysis of the ESA PRODUCERS application.  It is
        designed to predict spectral emissions observed from an entering

        object as it fragments and demises.
    """,
    "outputDirectory" : "Output/Test",
    "tasks" : [ {
        "type" : "loadVehicleModel",
        "vehicleSpreadsheetPath" : "TestScenario/sentinel1DramaV4-20.xlsx",
        "vehicleProfilePath" : "TestScenario/conversionProfiles.xlsx",
    }, {
        "type" : "loadDramaTrajectory",
        "dramaSimulationPath" : "TestScenario/00000",
    }, {
        "type" : "generateTimeline",
    }, {
        "type" : "reportActiveSegments",
        "disable" : False,
    } ],
}
```

Software Architecture – Analysis Tasks

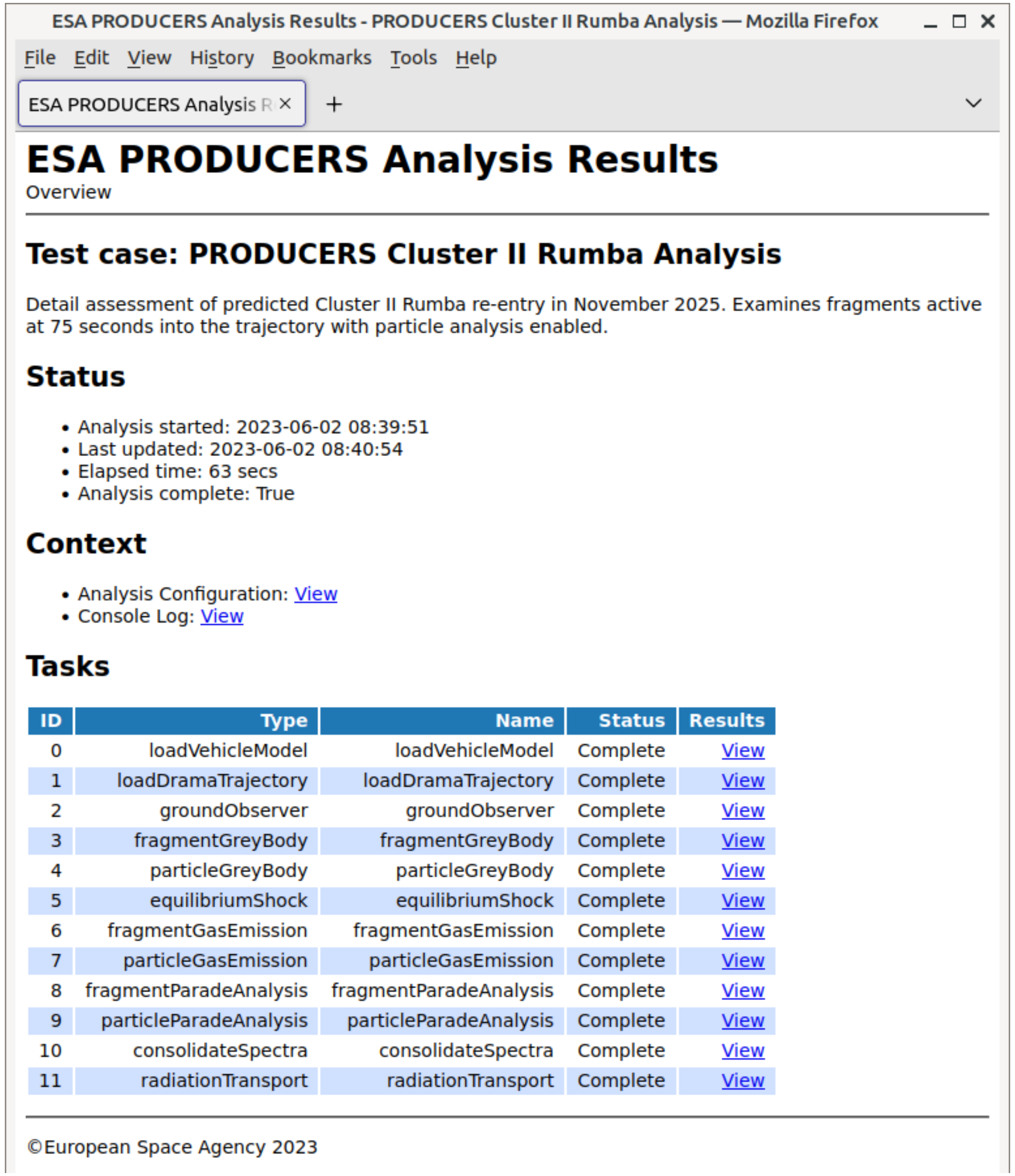
- 15 currently implemented
  - Configuration / Data acquisition
    - Aircraft / ground observer
    - PADRE vehicle model
    - SESAM re-entry analysis
  - Correlation analyses
    - Equilibrium shock layer
    - Fragment / particle grey body radiation
    - Fragment / particle gas emission
    - Radiation transport
  - PARADE analysis / integration
  - Reporting
    - Radiation consolidation
    - Active fragment summary
    - Destructive re-entry timeline
    - Emission source summary



PRODUCERS Analysis Process

- Construct PADRE spacecraft model spreadsheet
- Convert PADRE model to DRAMA
- Execute DRAMA re-entry analysis
- Configure / execute summary PRODUCERS analysis
  - Load vehicle model
  - Load DRAMA results
  - Correlation based analysis
- Review summary results, identify points of interest
- Configure / execute detailed PRODUCERS analysis for points of interest
  - Load vehicle model
  - Load DRAMA results
  - PARADE analysis

Sample Output



ESA PRODUCERS Analysis Results

Overview

Test case: PRODUCERS Cluster II Rumba Analysis

Detail assessment of predicted Cluster II Rumba re-entry in November 2025. Examines fragments active at 75 seconds into the trajectory with particle analysis enabled.

Status

- Analysis started: 2023-06-02 08:39:51
- Last updated: 2023-06-02 08:40:54
- Elapsed time: 63 secs
- Analysis complete: True

Context

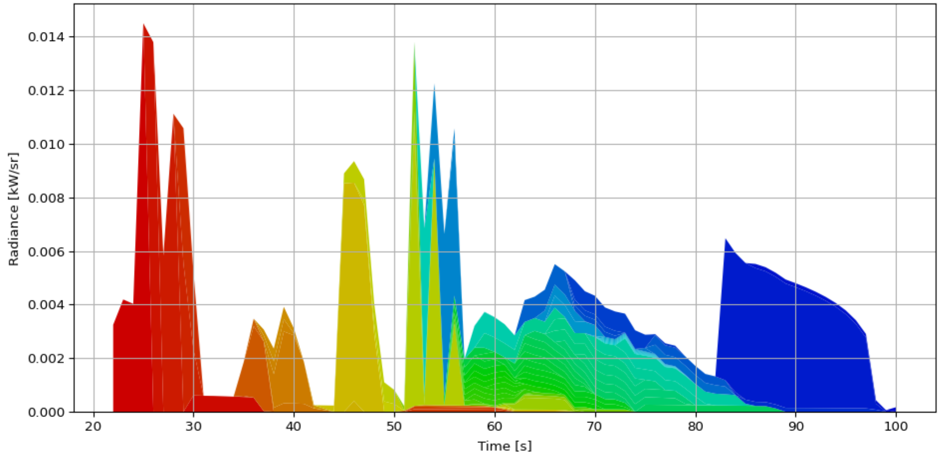
- Analysis Configuration: View
- Console Log: View

Tasks

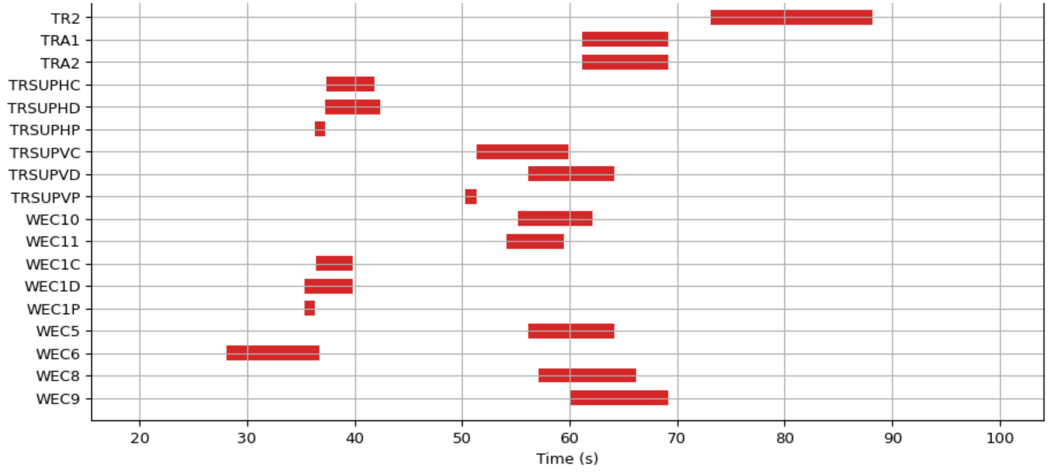
ID	Type	Name	Status	Results
0	loadVehicleModel	loadVehicleModel	Complete	View
1	loadDramaTrajectory	loadDramaTrajectory	Complete	View
2	groundObserver	groundObserver	Complete	View
3	fragmentGreyBody	fragmentGreyBody	Complete	View
4	particleGreyBody	particleGreyBody	Complete	View
5	equilibriumShock	equilibriumShock	Complete	View
6	fragmentGasEmission	fragmentGasEmission	Complete	View
7	particleGasEmission	particleGasEmission	Complete	View
8	fragmentParadeAnalysis	fragmentParadeAnalysis	Complete	View
9	particleParadeAnalysis	particleParadeAnalysis	Complete	View
10	consolidateSpectra	consolidateSpectra	Complete	View
11	radiationTransport	radiationTransport	Complete	View

Sample Summary Output

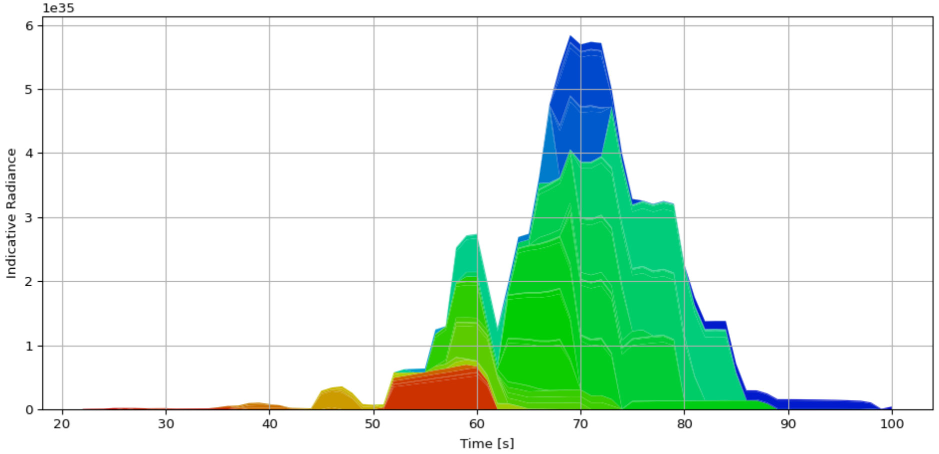
- Grey body emission



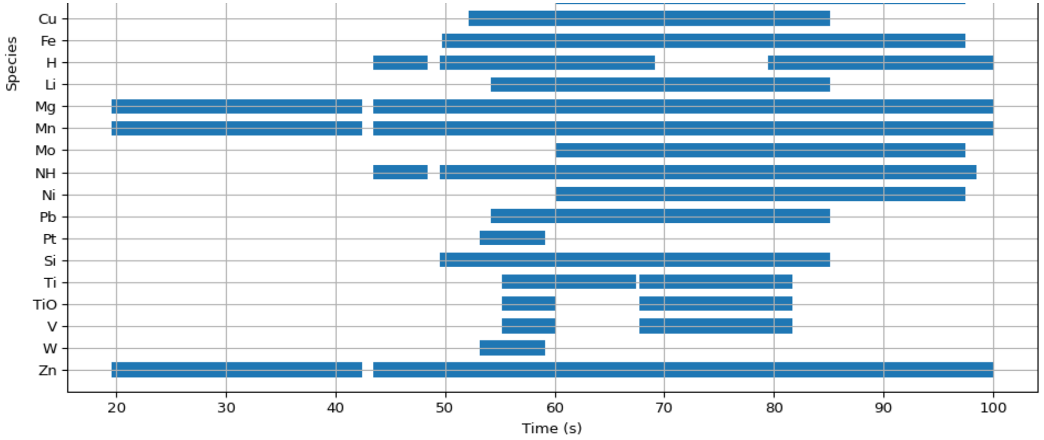
- Object demise



- Indicative radiance

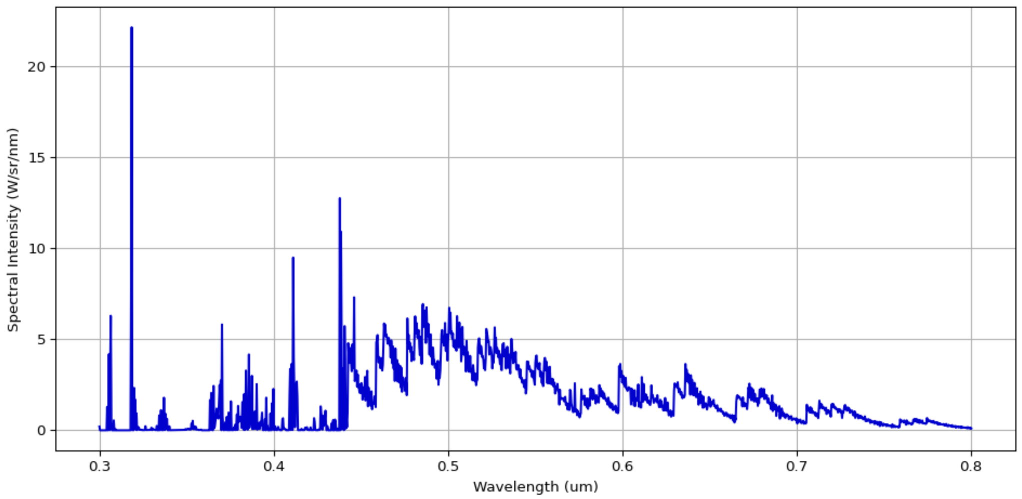


- Species emission

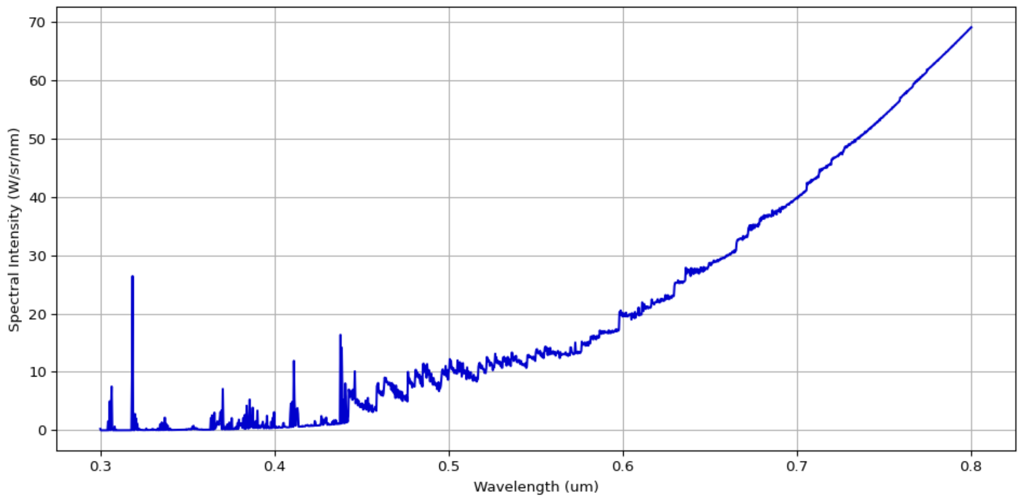


Sample Detail Output

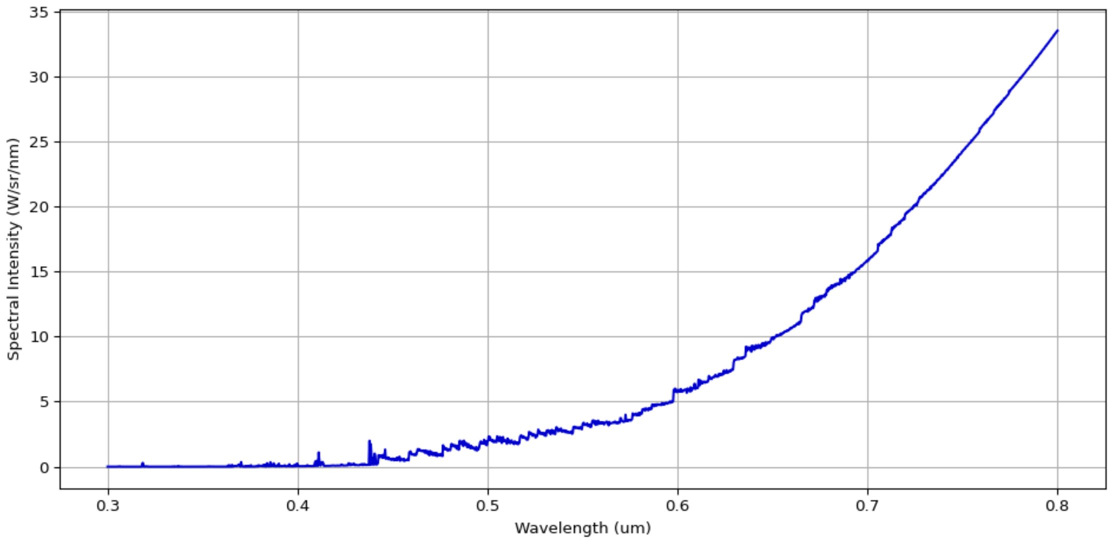
- PARADE spectrum



- Consolidated spectrum



- Observed spectrum



SESAM alterations / enhancements

- Small changes required to:
  - Add output not currently reported
  - Improve consistency / ease of programmatically reading output
  - Changes are additive and to not interfere with wider DRAMA use

- Addition of atmospheric density to trajectory output
  - Freestream density required by correlations
- Addition of average projected area to sesam.log
  - Fragment size required by grey body radiation correlation
- Addition of structured events to sesam.log
  - Parsing of existing log strings is fragile

Software Status

- Preliminary implementations of all components complete
  - Manager
  - Analysis tasks & state
  - SESAM enhancements
- Rebuild of test results completed by FGE
- Cluster II test case executed by BRL

Software Verification

Overview

- Summary of testing methods
  - Wind tunnel test (WTT) re-builds
  - Validation of PRODUCERS against TINA/PARADE
  - ATV Re-entry observation rebuild
- Issues encountered and software updates implemented
- Conclusions

Test Methodologies

1. Emission spectra for 5 metal alloys and 1 CFRP obtained from wind tunnel tests performed by IRS replicated using PRODUCERS
   – A set of fitted Ψ values were produced to generate estimated spectra via PRODUCERS that matched within 1 order of magnitude of measured spectra from wind tunnel tests
2. Results from TINA/PARADE for blown species were compared against spectra generated using PRODUCERS
3. Emission spectra were generated for the ATV-001 Re-entry spacecraft using DRAMA and PRODUCERS' 'AircraftObserver' mode

Wind Tunnel Test Re-builds

Background

- The following materials were investigated:
  - AA7075
  - Ti6Al4V
  - AISI 316L (uncoated &coated in Aeroglaze)
  - AA2099
  - CFRP EX1515/M55J
- PRODUCERS was used to simulate wind tunnel tests (WTT) under two main conditions: Fast & Max-H
  - Exception: Ti6Al4V tested under Max-H and Max-Q conditions
  - Exception: uncoated AISI 316L tested twice under Fast conditions
- Tuned ψ values were sought for each material to match the PRODUCERS spectral output to WTT data for each test condition
  - $\psi = \frac{mass\ released\ as\ gas\ at\ the\ surface}{mass\ released\ as\ liquid\ at\ the\ surface}$

Wind Tunnel Test Re-builds

Methodology – Materials and selection of spectral markers

- Species identified by IRS from the WTT results serve as spectral markers in PRODUCERS
- The abundance of each species in the metal alloys tested have ben specified as a % weighting
- Un-identified peaks in the WTT results have not been considered in the PRODUCERS models
- Additional species present in the test results are attributed to contamination

Material	Atomic species	Diatomic species
Plasma wind tunnel species	N, O	N_2, N_2^+, O_2
AA7075	Al(88.77), Zn(5.9), Mg(2.3), Mn(0.3)	
AISI316L	Fe(65.56), Cr(17.5), Ni(11.5), Mo(2.25), Mn(2)	
AA2099	Li(1.8), Zn(0.7), Mg(0.3), Mn(0.3)	
Ti6Al4V	Ti(89.13), Al(6.125), V(4)	TiO, AlO
CFRP EX1515/M55J		CN, CH, NH
Aeroglaze coating	C, H (these species appear at start of test but not at expulsion)	CN, CH

Wind Tunnel Test Re-builds

Methodology – Set up of PRODUCERS inputs

- Manual configuration of DRAMA Trajectory Files
  - Data provided by IRS on initial and final sample masses, surface temperature and video recordings of the tests informed the inputs to DRAMA
  - Surface temperature and mass loss with time were input to replicate expulsion events for the metal alloys, and constant steady state mass loss for the CFRP material
  - Assumption that mass loss occurred exclusively in expulsion events, with total mass lost in a short time frame

Wind Tunnel Test Re-builds

Results – Fitted and General ψ values

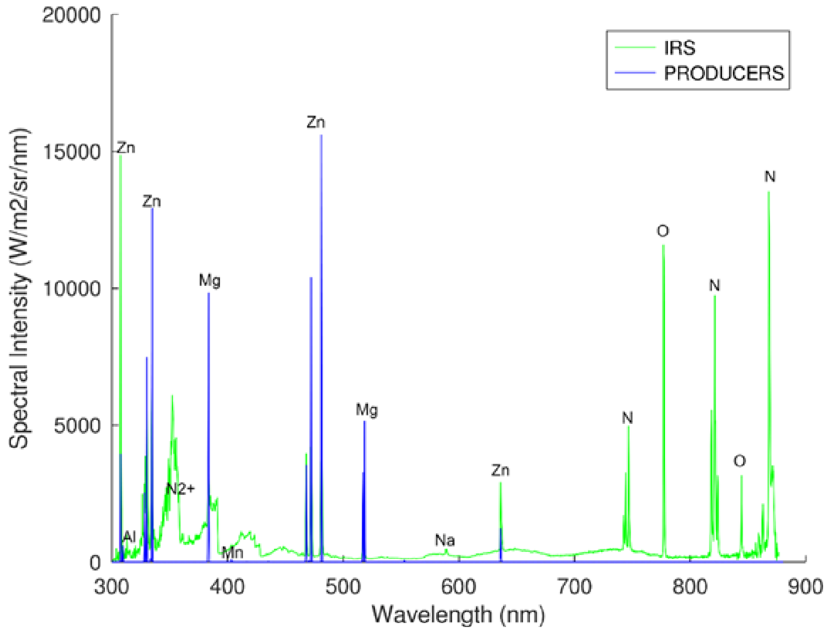
- ψ values for each spectral marker tuned individually to closely match test spectra for each material
- Fitted ψ values have been obtained with the aim to provide reasonable agreement with test results for both Max-H and Fast (or Max-Q) conditions
- A good match is defined as observed peaks aligning at the same wavelength and spectral intensities within one order of magnitude
- For EX1515/M55J and Ti6Al4V, separate ψ values are required for each case as an average fitted ψ value could not be obtained for all present species
- Based on all materials investigated, a series of general ψ values have been obtained
- The general ψ values can be used as a starting point for future PRODUCERS models when material test data is not available

Wind Tunnel Test Re-builds

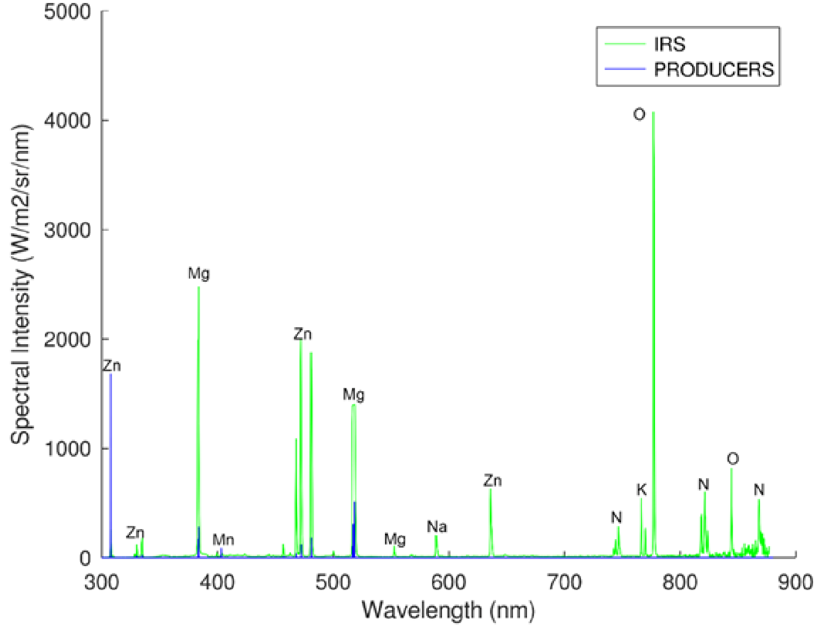
Results – AA7075

- 'Best fit' ψ values generally result in overestimation of Zn and Mg peaks for the Fast case
- Spectral intensities are in within the correct order of magnitude
- Overall using 'best fit' ψ values provide a good estimation of spectral output via PRODUCERS

Fast



Max-H

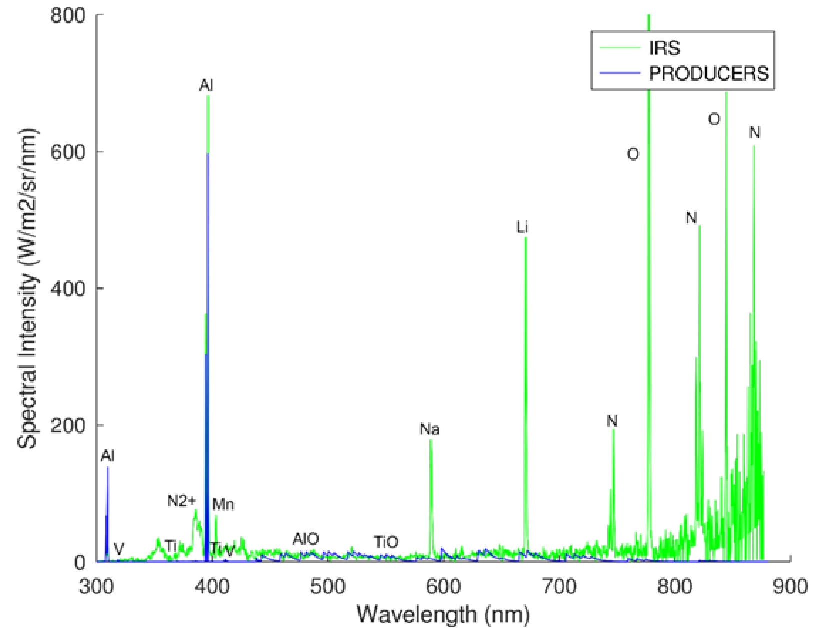


Wind Tunnel Test Re-builds

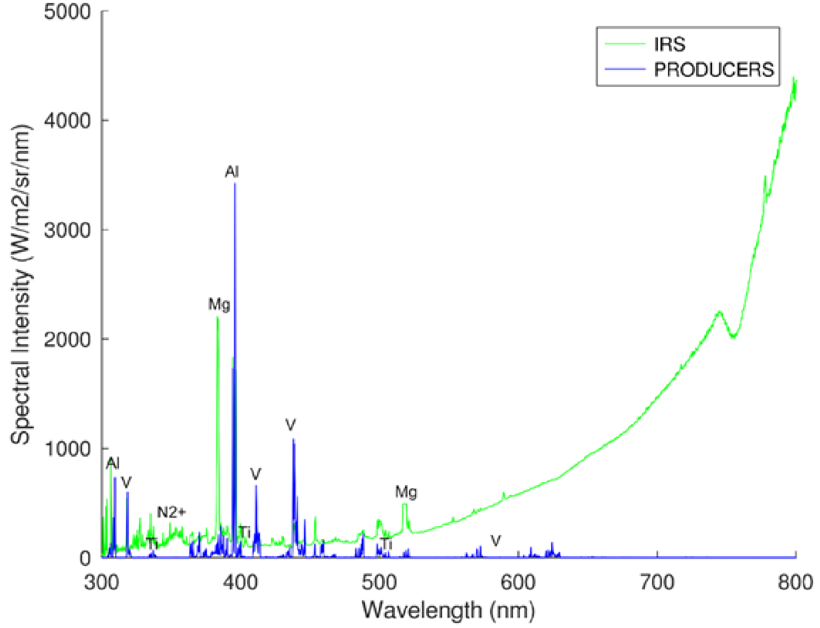
Results – Ti6Al4V

- Tuned ψ values provide PRODUCERS outputs that closely match WTT results
- Fast and Max-Q results require different ψ values as Max-H sample was on borderline demise
  - AlO and TiO only present in Max-H case

Fast



Max-H

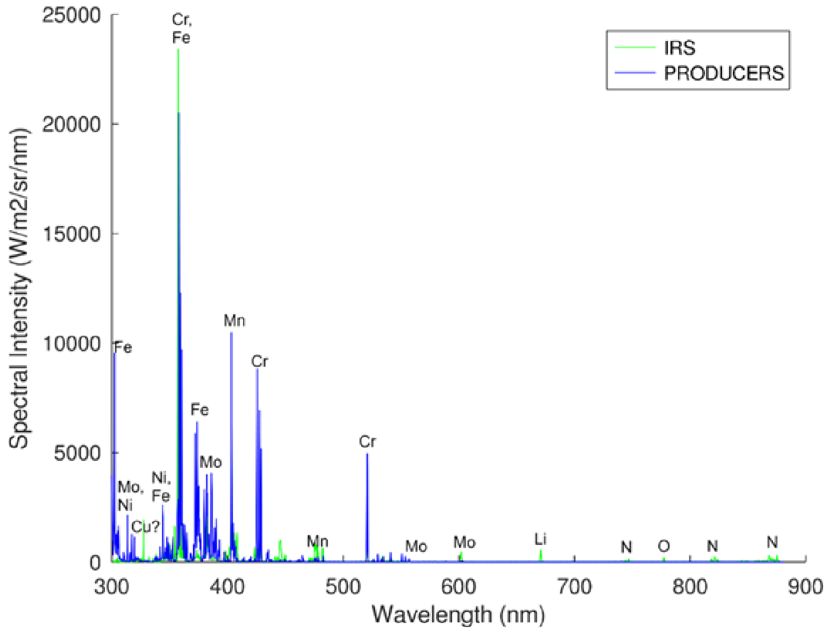


Wind Tunnel Test Re-builds

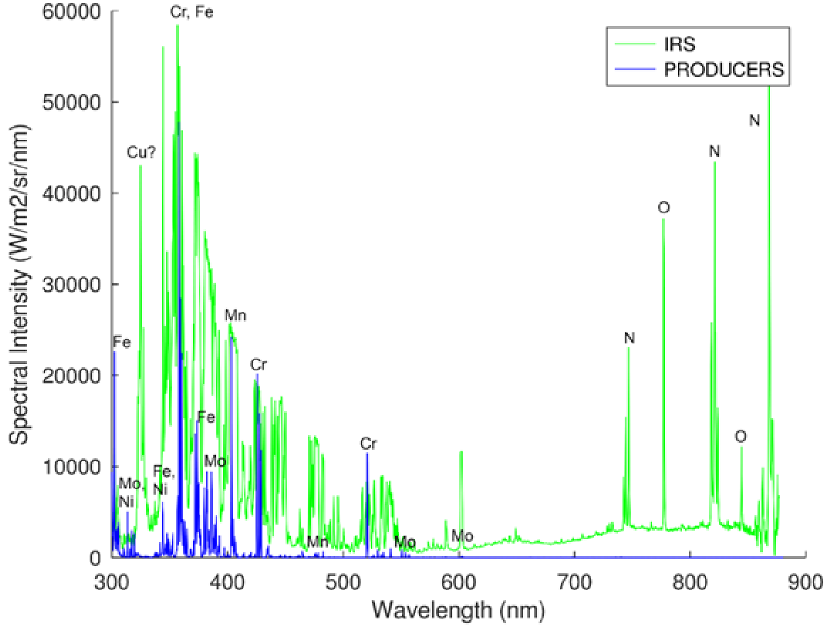
Results – AISI 316L Uncoated

- Tested twice under the Fast condition
- A single set of ψ values obtained for uncoated and coated AISI 316L
- Significant noise due to high N2+ abundance characteristic of the Fast case only

Fast#03



Fast#41

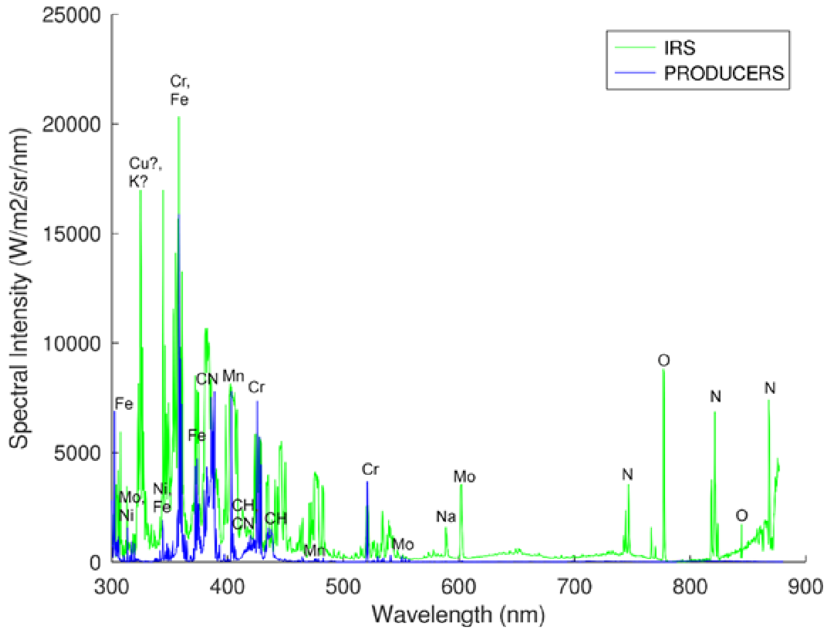


Wind Tunnel Test Re-builds

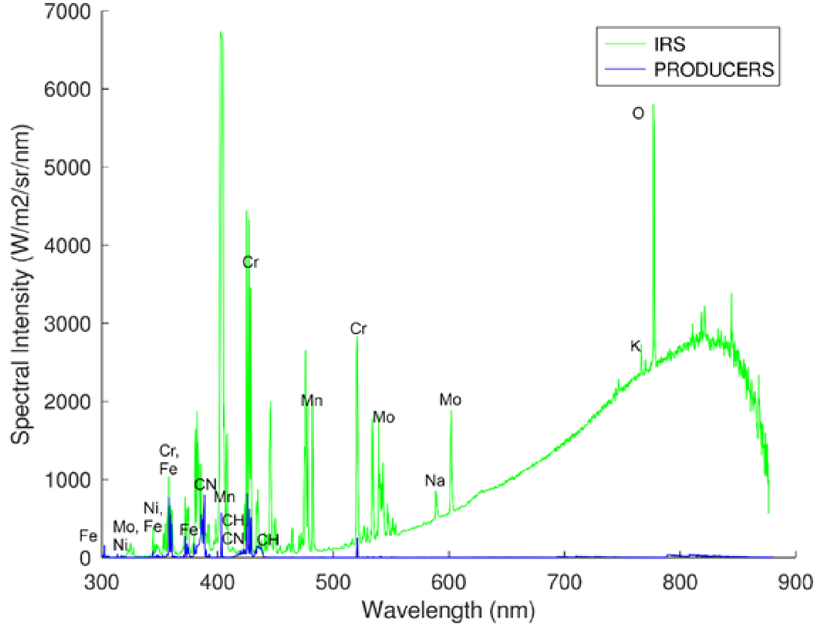
Results – AISI 316L Aeroglaze

- Good agreement is achieved especially in 350–450 nm range for the Fast case
- Underestimation of spectral intensities for the Max-H case
- CH and CN present due to Aeroglaze coating
- Overall, PRODUCERS predictions remain within an order of magnitude of WTT results

Fast



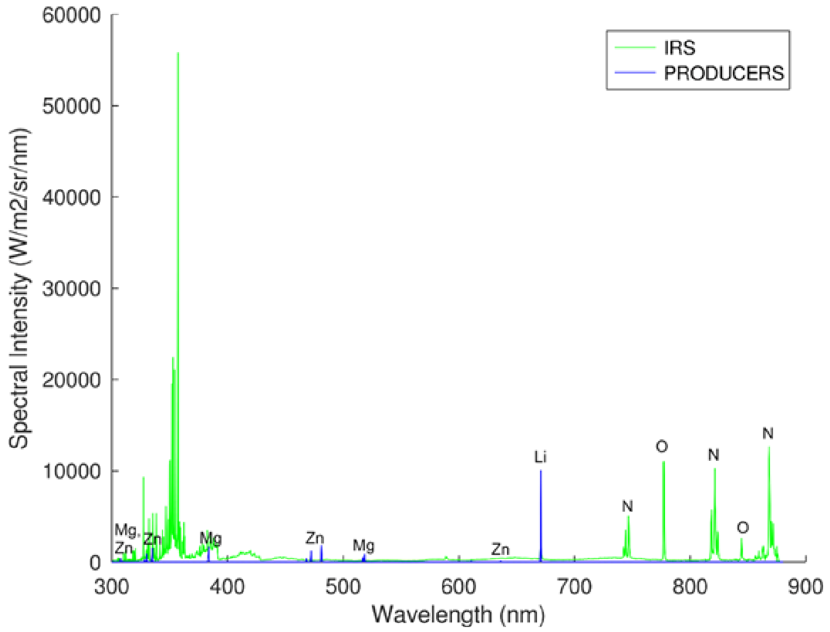
Max-H



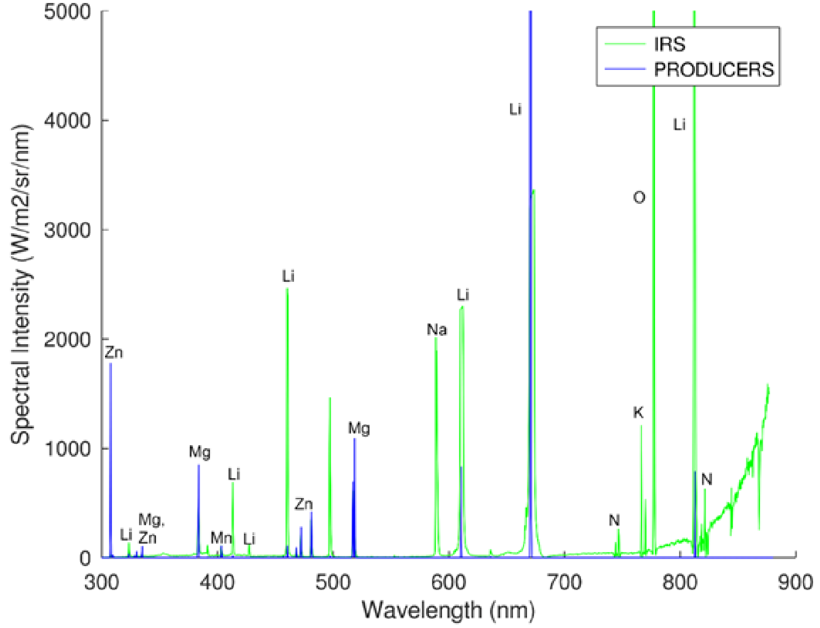
Wind Tunnel Test Re-builds

Results – AA2099

- Identified species overall exhibit good match between intensities predicted by PRODUCERS and WTT results
- Peak ~370 nm seen in Fast WTT results remains unidentified
- Unexpected Li peak at 670 nm with intensity 100 times greater than WTT and other PRODUCERS predictions observed



Fast



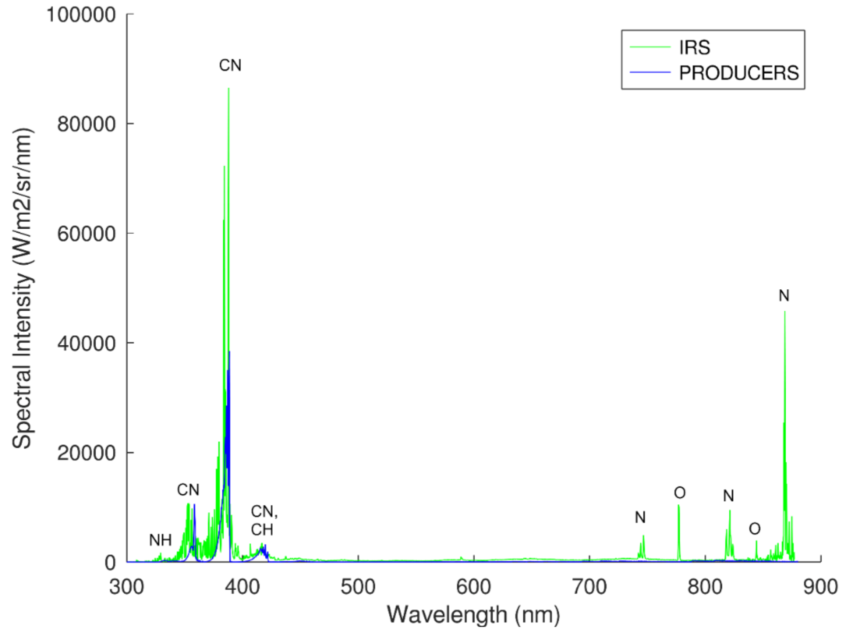
Max-H

Wind Tunnel Test Re-builds

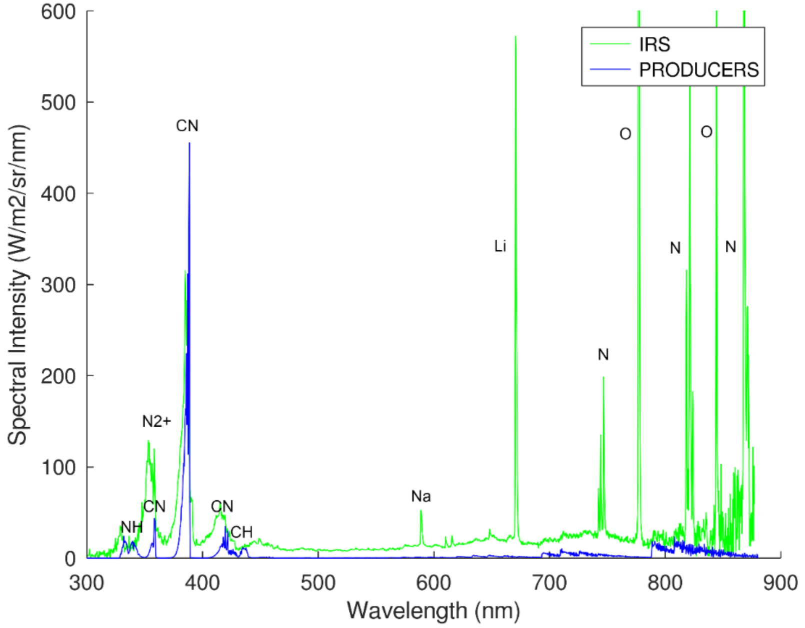
Results – EX1515/M55J

- CN, CH, and NH diatomic species dominate the spectral response of the ablative CFRP material
- Tuned ψ values provide PRODUCERS outputs that closely match WTT results
- Fast and Max-H results require different ψ values for CN due to higher N abundance in the freestream for the Fast case than Max-H case

Fast



Max-H



Validation of PRODUCERS Against TINA/PARADE

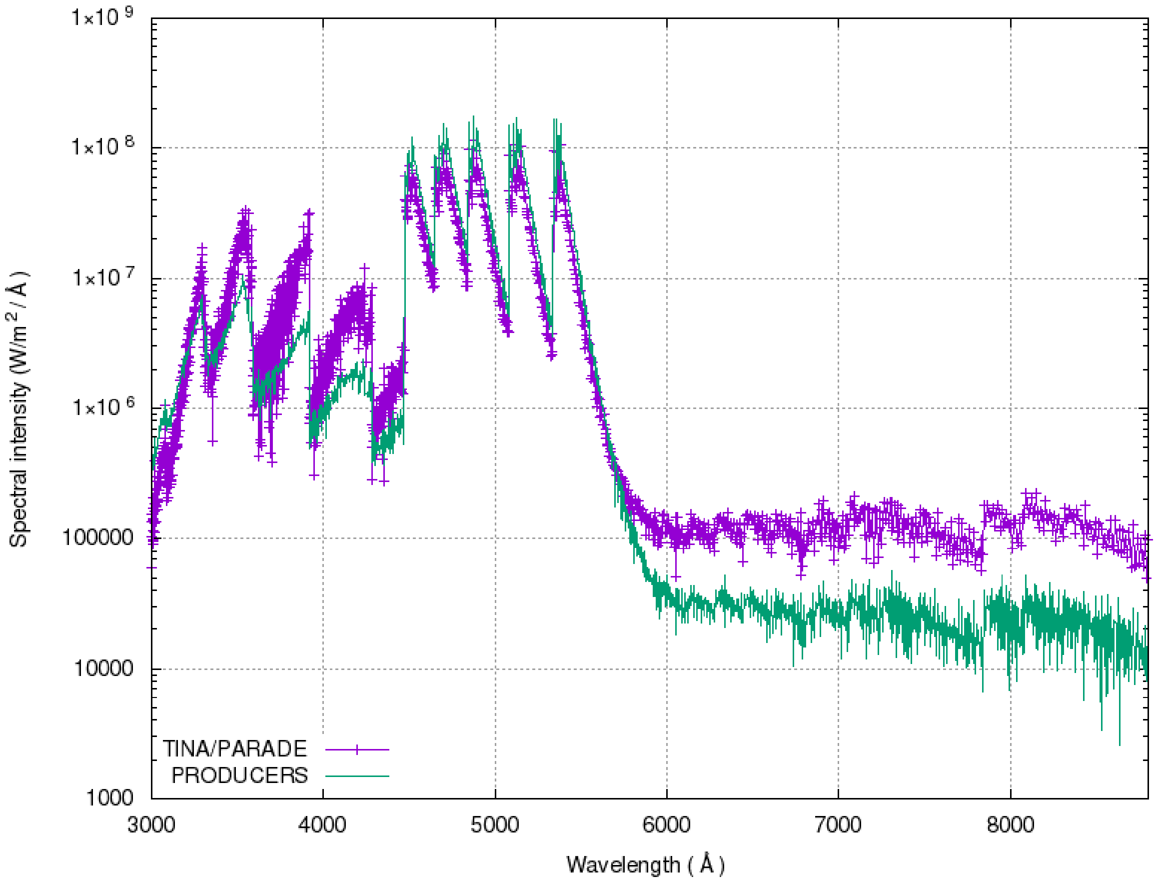
Methodology

- Navier Stokes simulations conducted using TINA and emission spectra obtained from PARADE
  - Simulations were conducted for a 1 m radius Al sphere, with AlO gas blown from the surface at a rate of 4.3e-3 kg/m^2/s
- The original results from the AlO simulations were scaled to other species Zn, Mg, Ti and TiO taking account the composition of AA7075 and Ti6Al4V
- Fitted ψ values for the species of interest from AA7075 and Ti6Al4V were used to scale the AlO simulation to other species
- Comparative models were run in PRODUCERS, and the emission spectra compared with the spectra obtained via TINA/PARADE

Validation of PRODUCERS Against TINA/PARADE

Results

- PRODUCERS spectra consistently lower in magnitude compared to TINA/PARADE results
- Despite magnitude difference, PRODUCERS accurately replicates the shape of emission spectra for all species
- The level of agreement is considered very good given the approximate nature of the PRODUCERS methodology

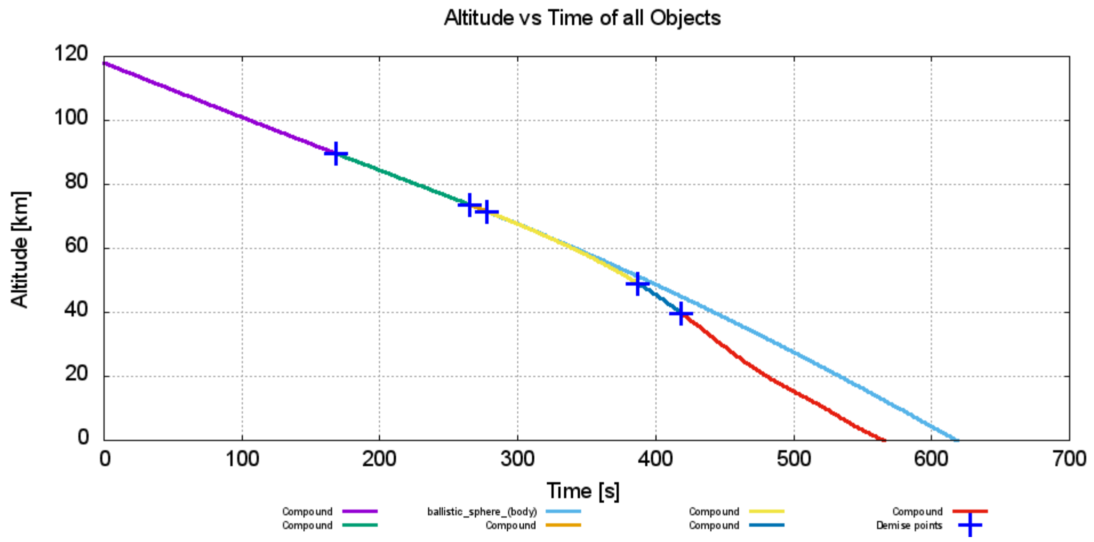


Comparison between intensity from TINA/PARADE simulations and PRODUCERS for AlO at 3000 K

ATV Re-entry Observation Rebuild

Methodology – DRAMA simulations

- Components of the ATV spacecraft were simulated in DRAMA and PRODUCERS analyses subsequently performed on them
- Simplified artificial components specified for each simulation to achieve the same re-entry trajectory as the full spacecraft



DRAMA output showing the re-entry trajectory (and demise) of ATV analogue, components. The ballistic sphere and sections of the RDS docking adaptor survive until ground impact.

ATV Re-entry Observation Rebuild

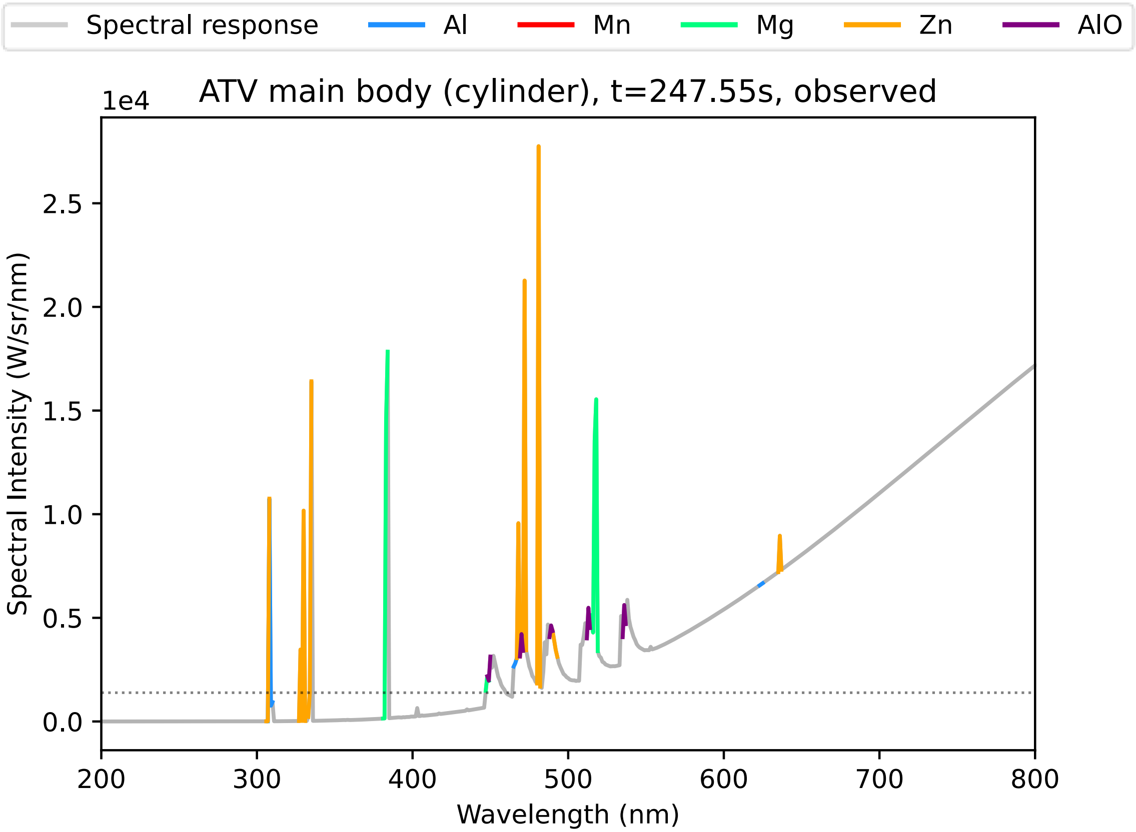
Methodology – PRODUCERS analyses

- PRODUCERS code executed for each re-entry trajectory using ψ values obtained from WTT tuning
- Two ψ values for AlO in the ATV body case
  - Lower value of 1E-10 to effectively disable AlO in certain analyses
  - Higher value of 1E-6 derived from Ti6Al4V demise to demonstrate the effect of inserting additional species markers
- Analysis of demise for three components using different spectral markers based on suspected dominant material
  - ATV Main body case
  - Lithium battery cell
  - Russian Docking System (RDS) docking adaptor
- "AircraftObserver" task used to reconstruct the observation campaign during ATV-001 re-entry
- PRODUCERS analysis for each case was completed with contributions from atmospheric species and grey body radiation enabled

ATV Re-entry Observation Rebuild

Results – ATV Main body, main body emission

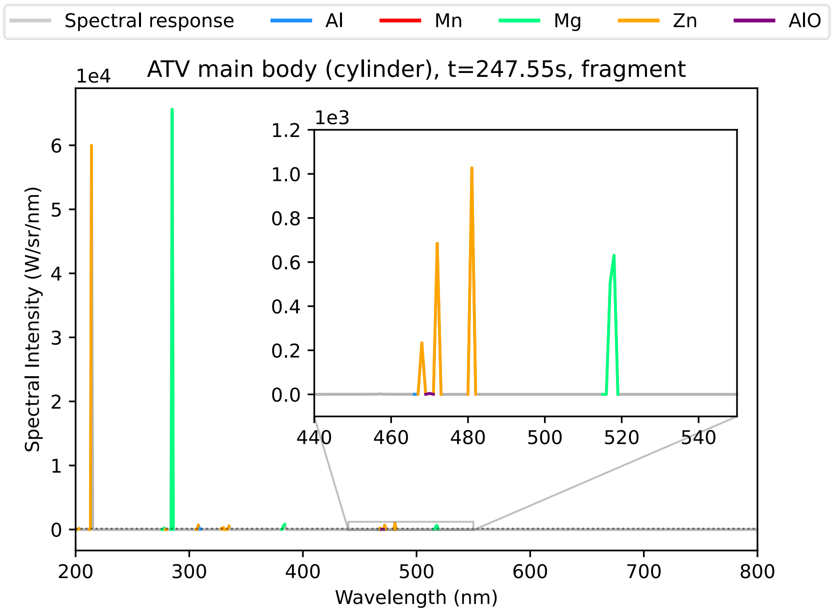
- PRODUCERS analysis of the ATV spacecraft body demise, focusing on demise of AA7075
- Prominent emission lines of Zn and Mg
- A single Al emission line seen just above 300 nm, aligning with WTT observations
- No significant Mn lines visible despite a ψ of 2E-6, likely due to larger ψ values of other marker species
- Demonstrated functionality of seeding fragment and particle marker species separately in PRODUCERS analyses
  - Inclusion of AlO in the “partMarkers” section of the Profile spreadsheet



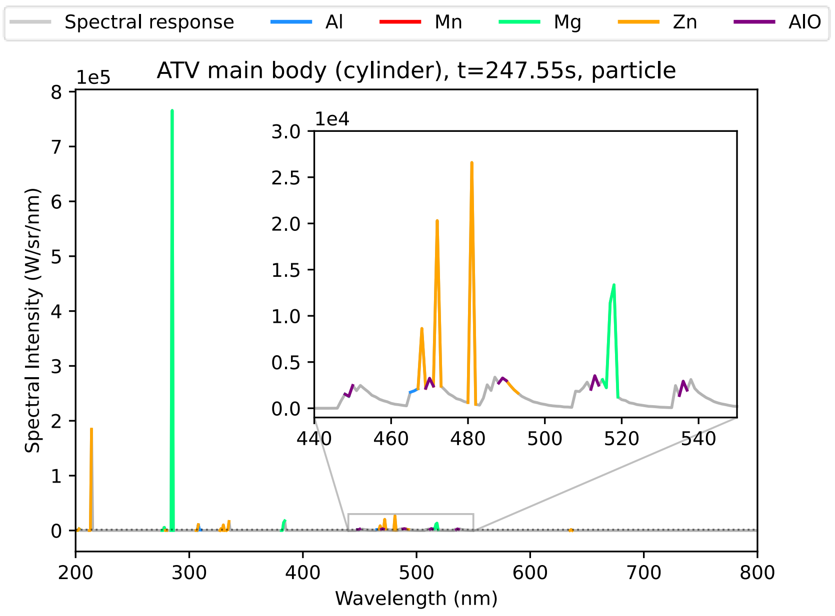
ATV Re-entry Observation Rebuild

Results – ATV Main body, fragment and particle emission

- Demonstrated successful seeding of desired marker species in the particle ejecta through absence of AlO signature in the fragment spectrum and its presence in the particle spectrum



Fragment

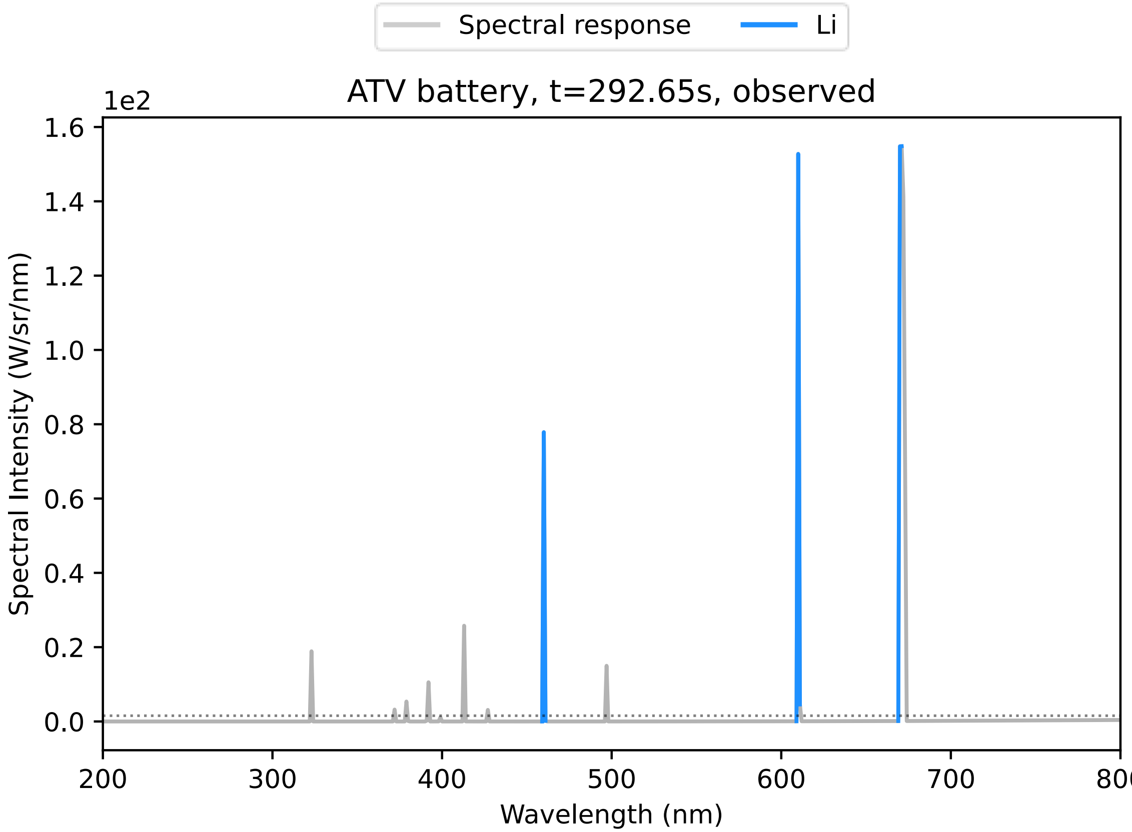


Particle

ATV Re-entry Observation Rebuild

Results – ATV Lithium battery cell

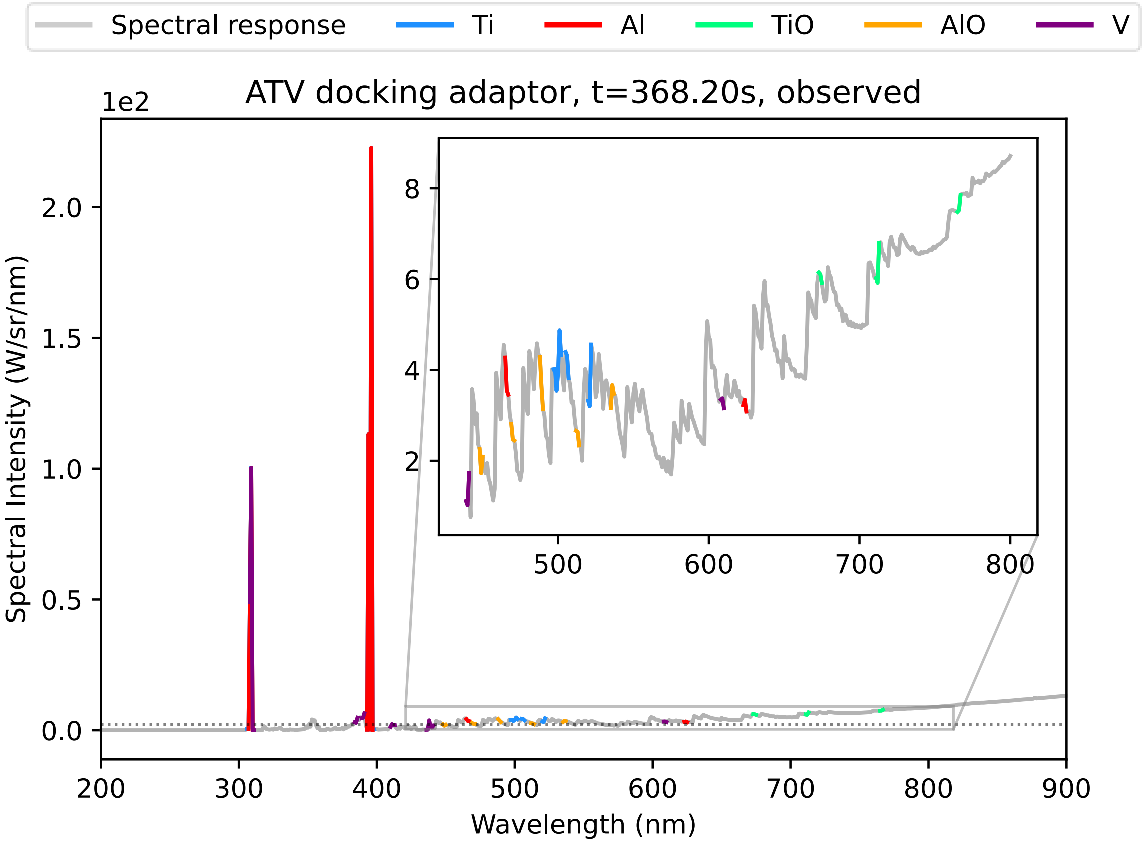
- The battery cell has been modelled as a pure stainless steel cylinder with only the Li species marker added
- Demise of the battery cell occurred over only three DRAMA time steps
- Demonstrates PRODUCERS' ability to generate simulated emission spectra, even with an extremely small melt period



ATV Re-entry Observation Rebuild

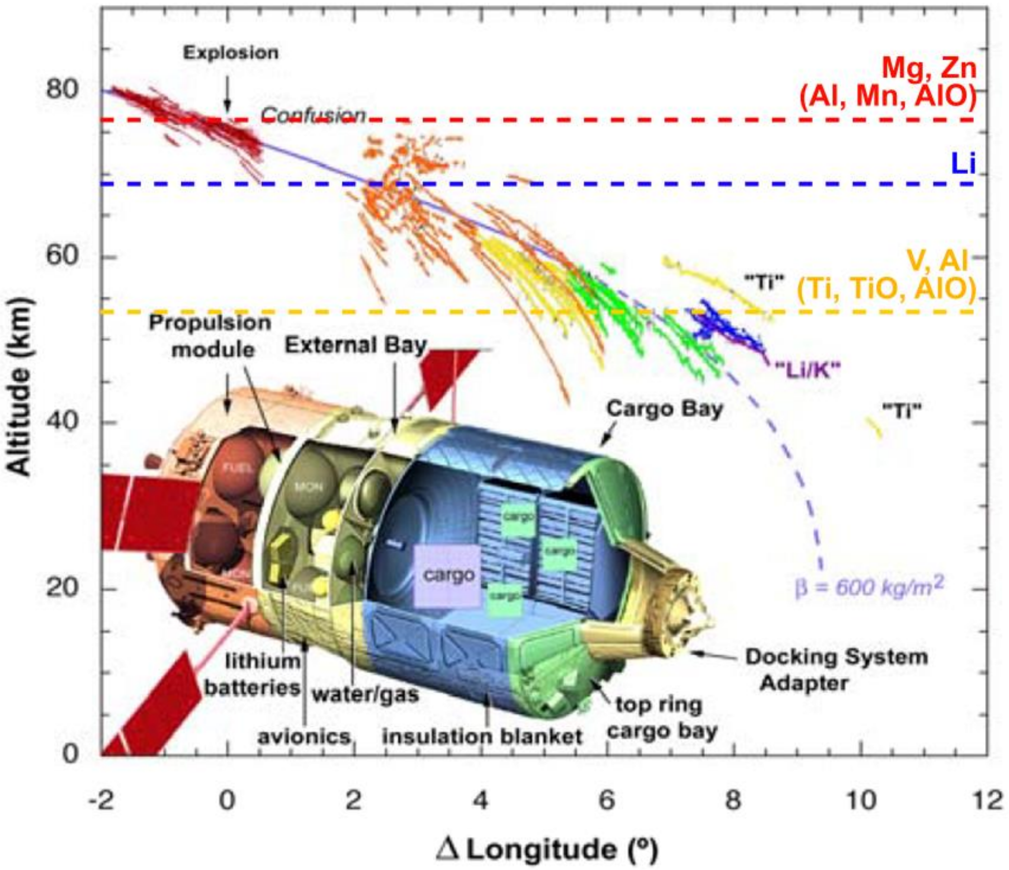
Results – RDS docking adaptor

- Significant emission lines of Al and V are present
- Strong Ti emissions observed during the actual ATV re-entry in contrast to PRODUCERS output
  - Discrepancy attributed to the low value of ψ (1E-7) used in the RDS PRODUCERS simulations, derived from the WTT campaign
- Overall, this analysis demonstrates the capability of PRODUCERS to generate complex demise spectra even for relatively small components like the RDS docking adaptor



ATV Re-entry Observation Rebuild

Results – Comparison of PRODUCERS output to observations



- Li trace from battery cell analysis occurs at a higher altitude than observed, attributed to the simplicity of DRAMA simulations
- Ti and Al alloy traces (Ti6V4Al and AA7075) fall within expected altitudes, matching observation
- PRODUCERS operates as intended, capable of identifying and reproducing calibrated spectra in DRAMA output
- Accuracy relies on the precision of demise trajectories, mass/melt histories, and calibrated ψ values

Issues Encountered & Software Updates Implemented

- Under-representation of ablation species in comparison to TINA/PARADE
  - Ability to define B′ ratio or set B′ to B′/(B′+1)
- Under-estimation of emission temperature
  - Addition of 'boundaryTempRatio' parameter to specify ratio of shock layer temperature and boundary emission temperature, used to define boundary layer temperature
- Under-estimation of air species temperature
  - Addition of 'shockTempRatio' parameter to specify the ratio of the equilibrium shock temperature and frozen shock temperature, used to define shock layer temperature
- Over-estimation of N2+ radiation at lower enthalpies
  - Update to number density tables for air species

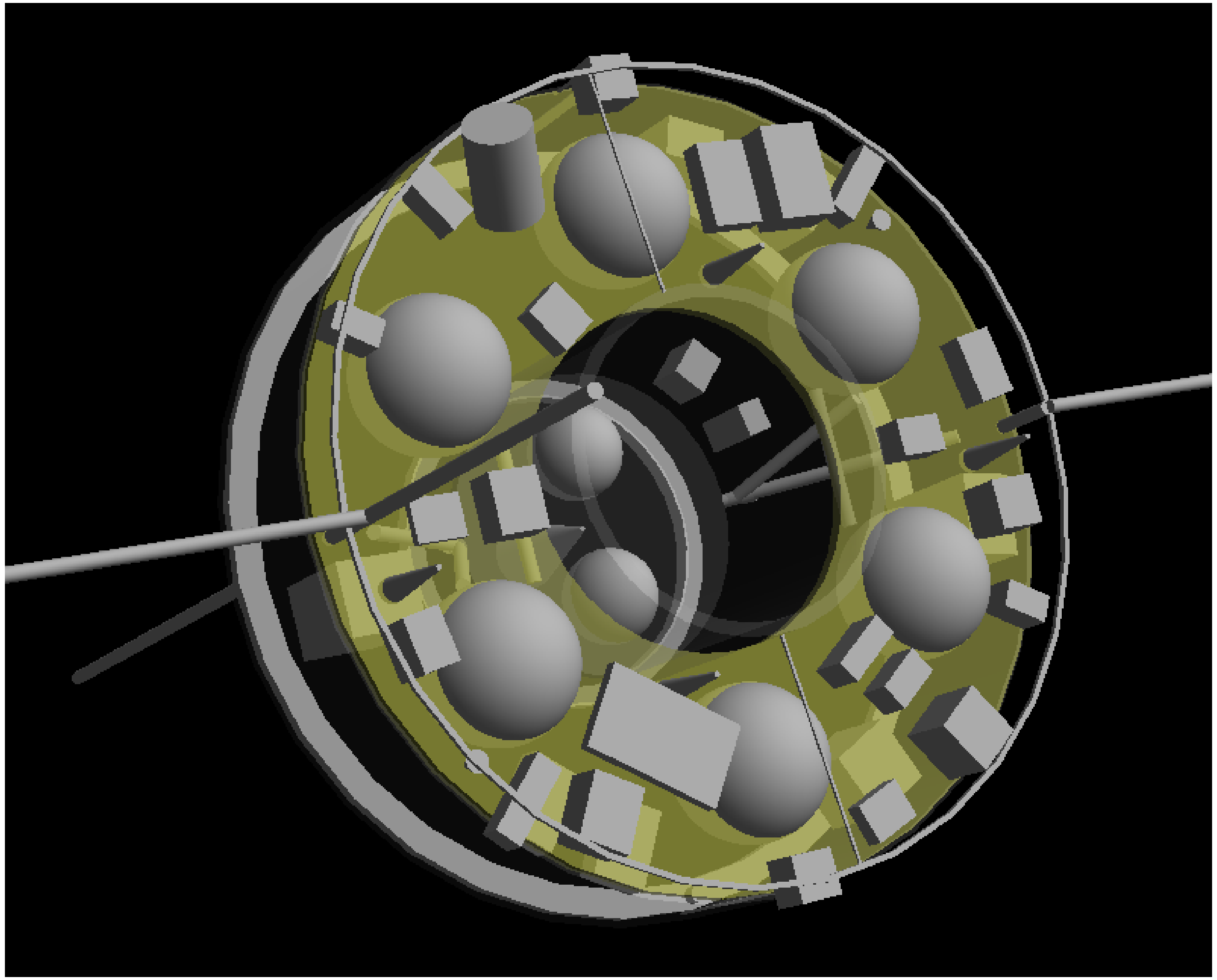
Software Verification Conclusions

- PRODUCERS has been calibrated based on spectra obtained from wind tunnel testing. A set of tuned Ψ values has been generated which can be used for future test and vehicle rebuilds
- The link between the NIST spectral database and PARADE spectral output has been re-established, with the PARADE spectral library updated to contain new atomic species
- Whilst the comparison between PRODUCERS and TINA/PARADE highlighted a difference in magnitude of intensity of predicted spectra, the level of agreement is considered extremely good considering the remit of the PRODUCERS software
- PRODUCERS has been demonstrated to support interpretation of spectral observation data from the ATV spacecraft re-entry. This highlights its potential for use in analysis of future destructive entry events

Cluster Model

Spacecraft Model

- Existing object-oriented model upgraded
- New component-centric model
- 96 primitives
- 50% aluminium by mass



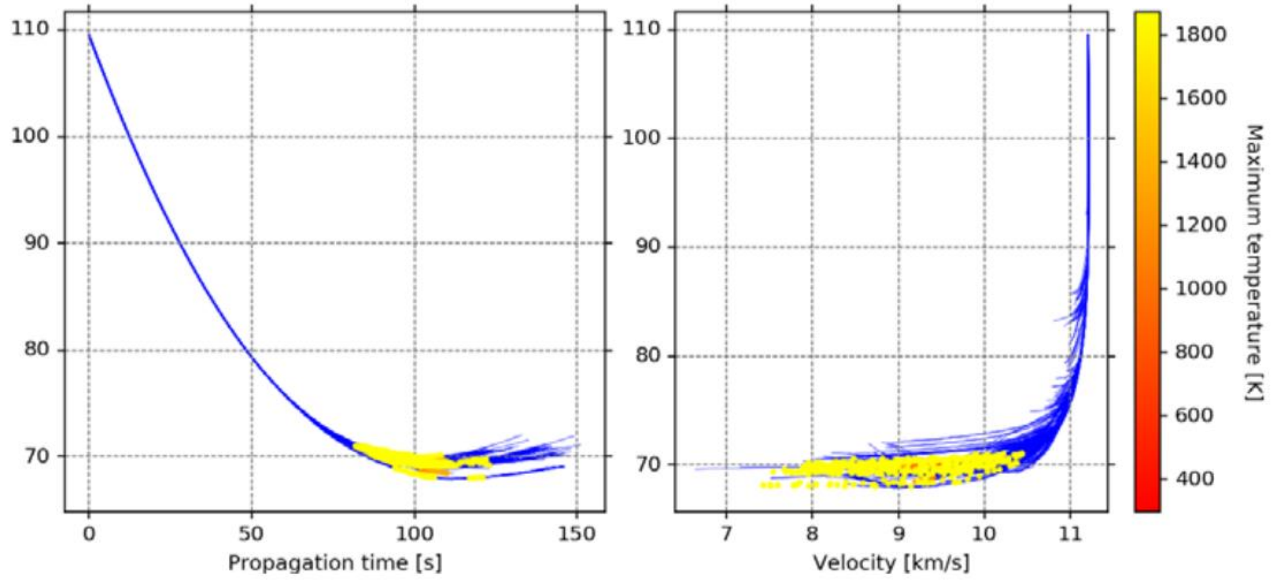
Spacecraft Model

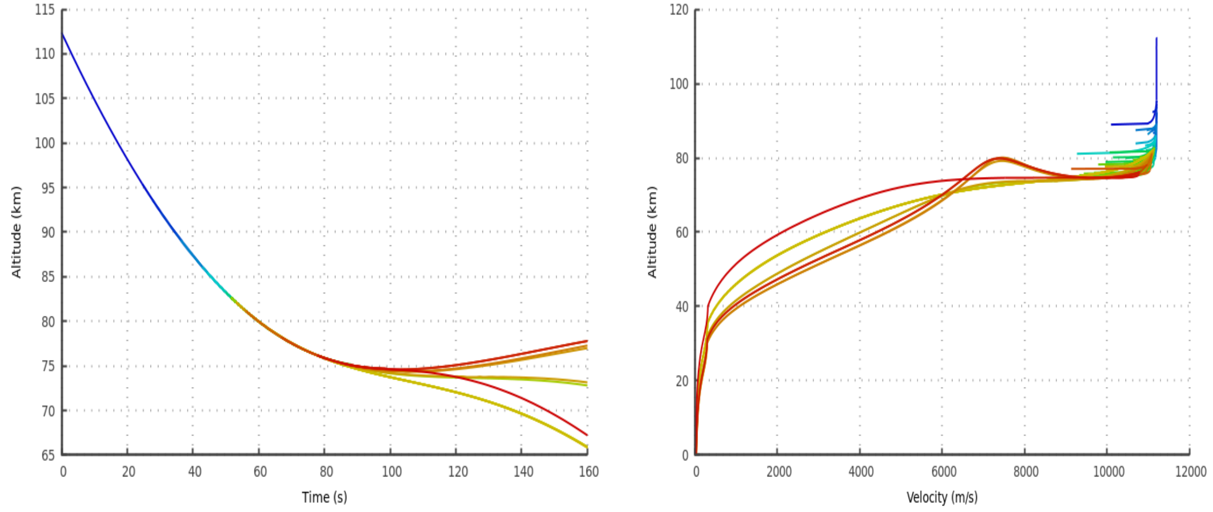
- Materials augmented with spectral markers
- Generic behaviour of 20 components was overridden with specific markers (e.g. solar array)

Material	Fragment Markers	Particle Markers
Aluminium	Al(88.77), Zn(5.9), Mg(2.3), Mn(0.3)	Al(88.77), Zn(5.9), Mg(2.3), Mn(0.3)
Aluminium Honeycomb	Al(88.77), Zn(5.9), Mg(2.3), Mn(0.3), CH, CN, C2, H	Al(88.77), Zn(5.9), Mg(2.3), Mn(0.3)
CFRP	CN, CH, NH, H	
CFRP Sandwich Panel	CN, CH, NH, H	Al, Zn, Mg, Ba, Ba+
Copper	Cu	Cu
Inconel	Ni(60), Cr(20), Mo(10), Fe(5)	Ni(60), Cr(20), Mo(10), Fe(5)
Steel	Mn(2), Cr(17.5), Mo(2.25), Ni(11.5), Fe(65.56)	Mn(2), Cr(17.5), Mo(2.25), Ni(11.5), Fe(65.56)
Titanium	Ti(89.13), Al(6.125), V(4), TiO, AlO	Ti(89.13), Al(6.125), V(4), TiO, AlO

DRAMA Analyses

- Re-entry of all Cluster spacecraft rebuilt in DRAMA
  - Based on 2020 mission extension review
  - Comparison with SCARAB entries good for Rumba / Salsa
  - Less so for Samba / Tango





PRODUCERS Process

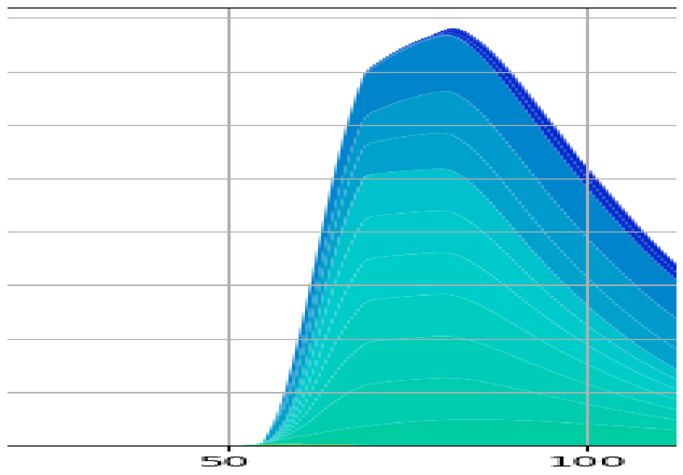
- Phase 1 - Full trajectory summary review of destructive re-entry
  - Rumba and Salsa
- Phase 2 - Detailed analysis of Rumba
  - 75 seconds - emission of titanium markers resulting from the demise of the tanks
  - 90 seconds - demise of the battery (BAT1D) and ENG, CENTCYL, INTEQUIP compound object

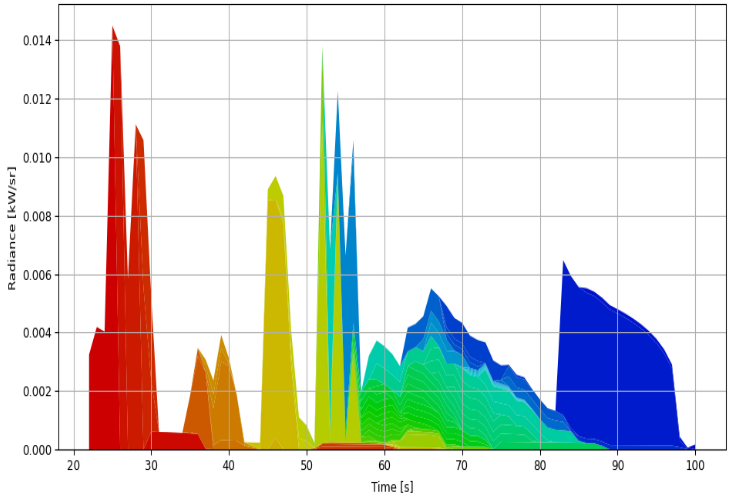
Rumba Summary Results

Fragment Emission

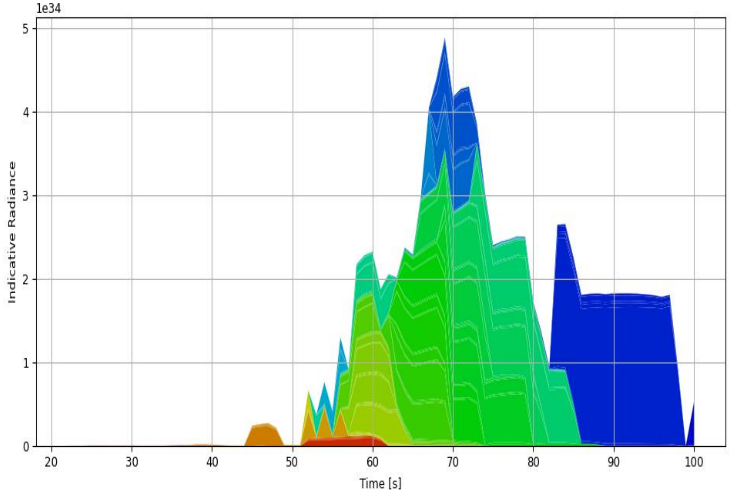
Particle Emission

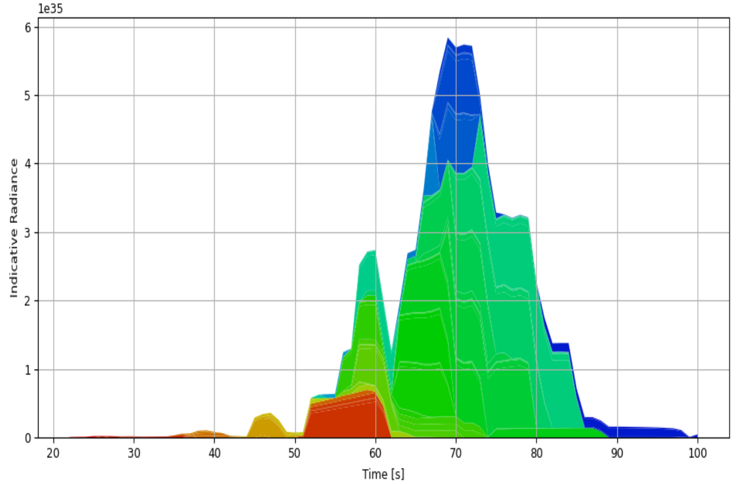
Grey Body Emission





Gaseous Emission



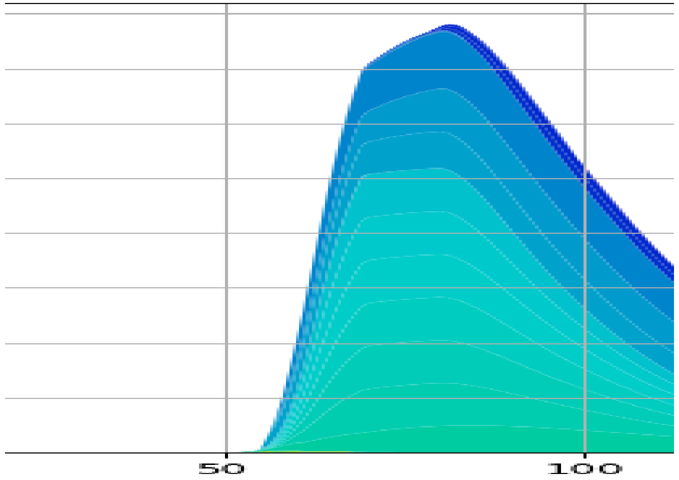


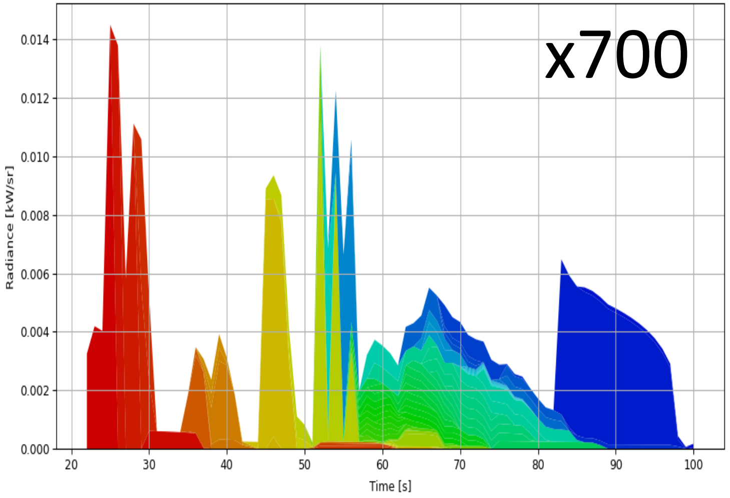
Rumba Summary Results

Fragment Emission

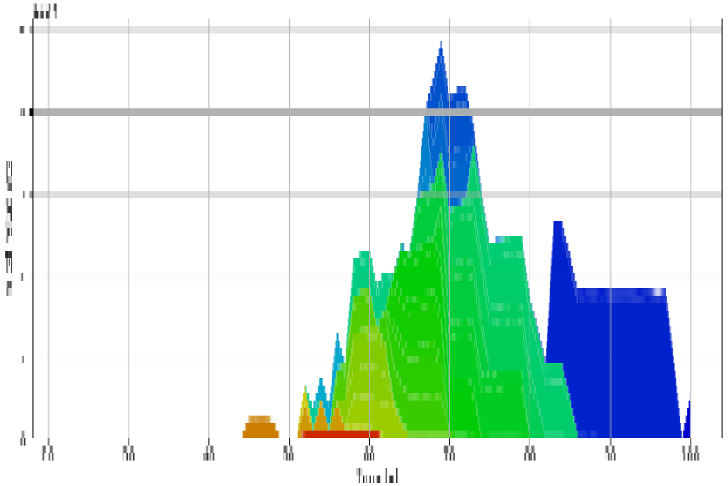
Particle Emission

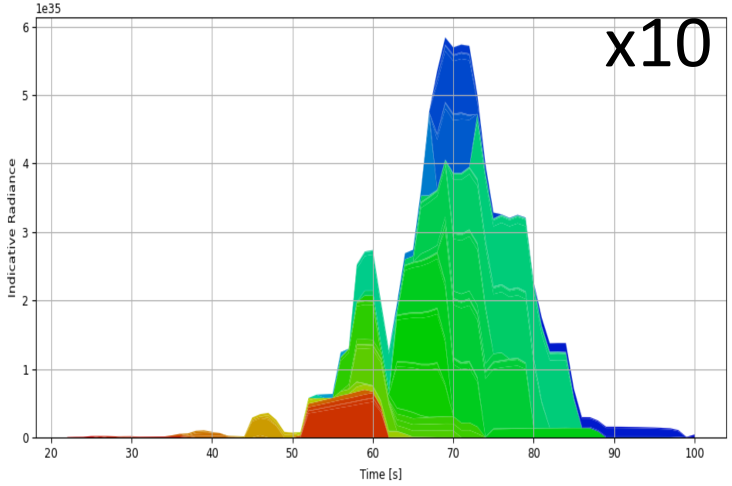
Grey Body Emission



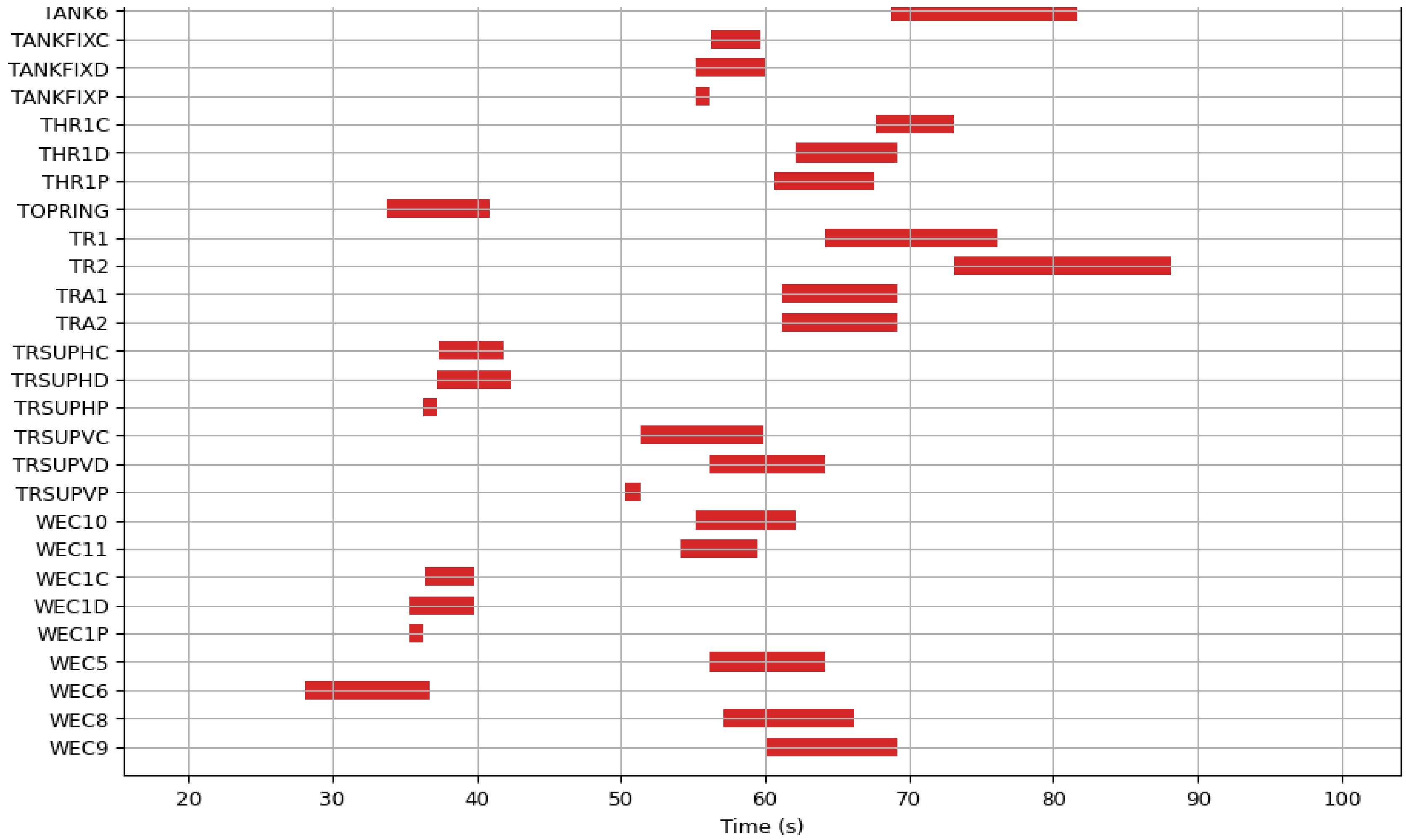


Gaseous Emission

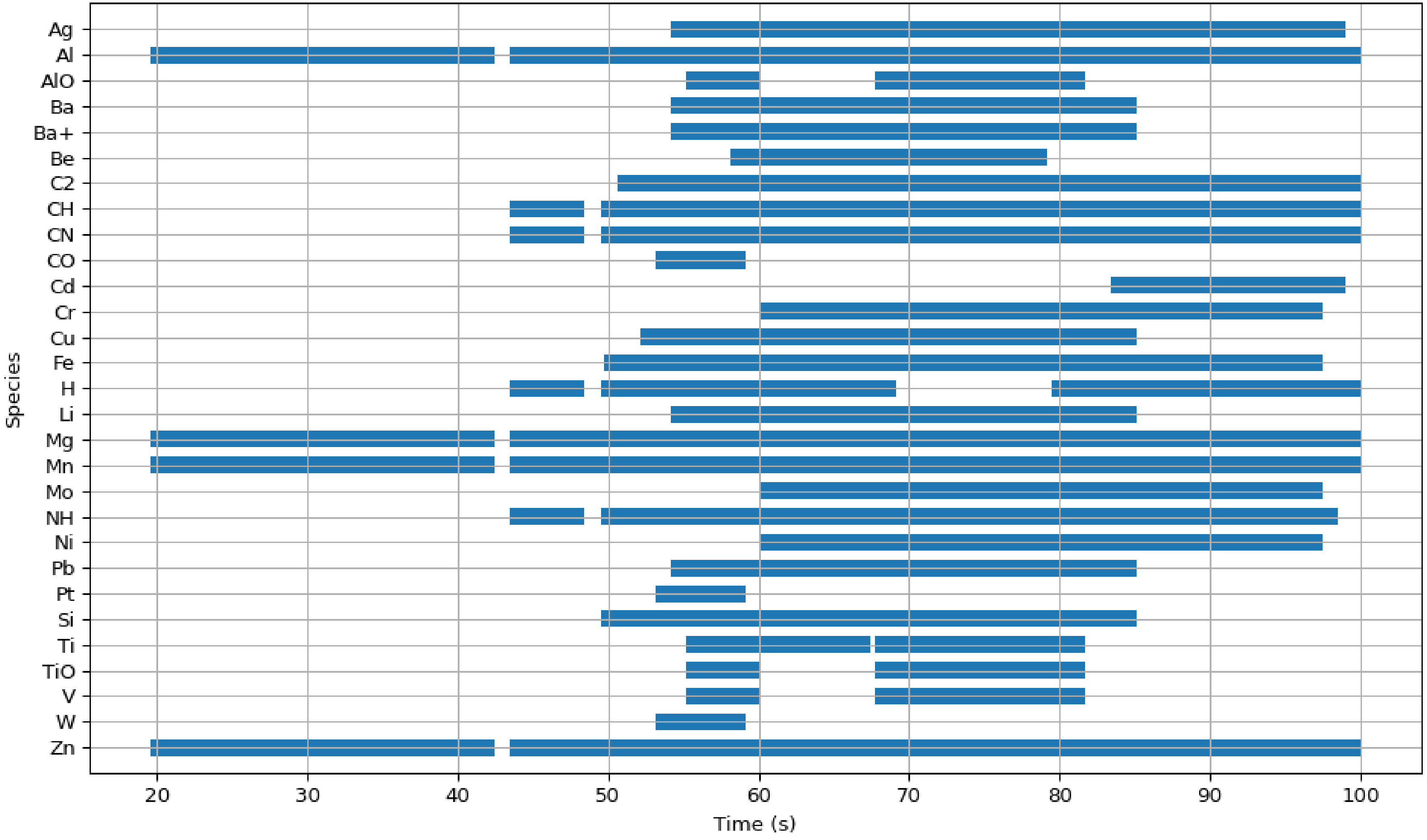




Rumba Summary Results



Rumba Summary Results

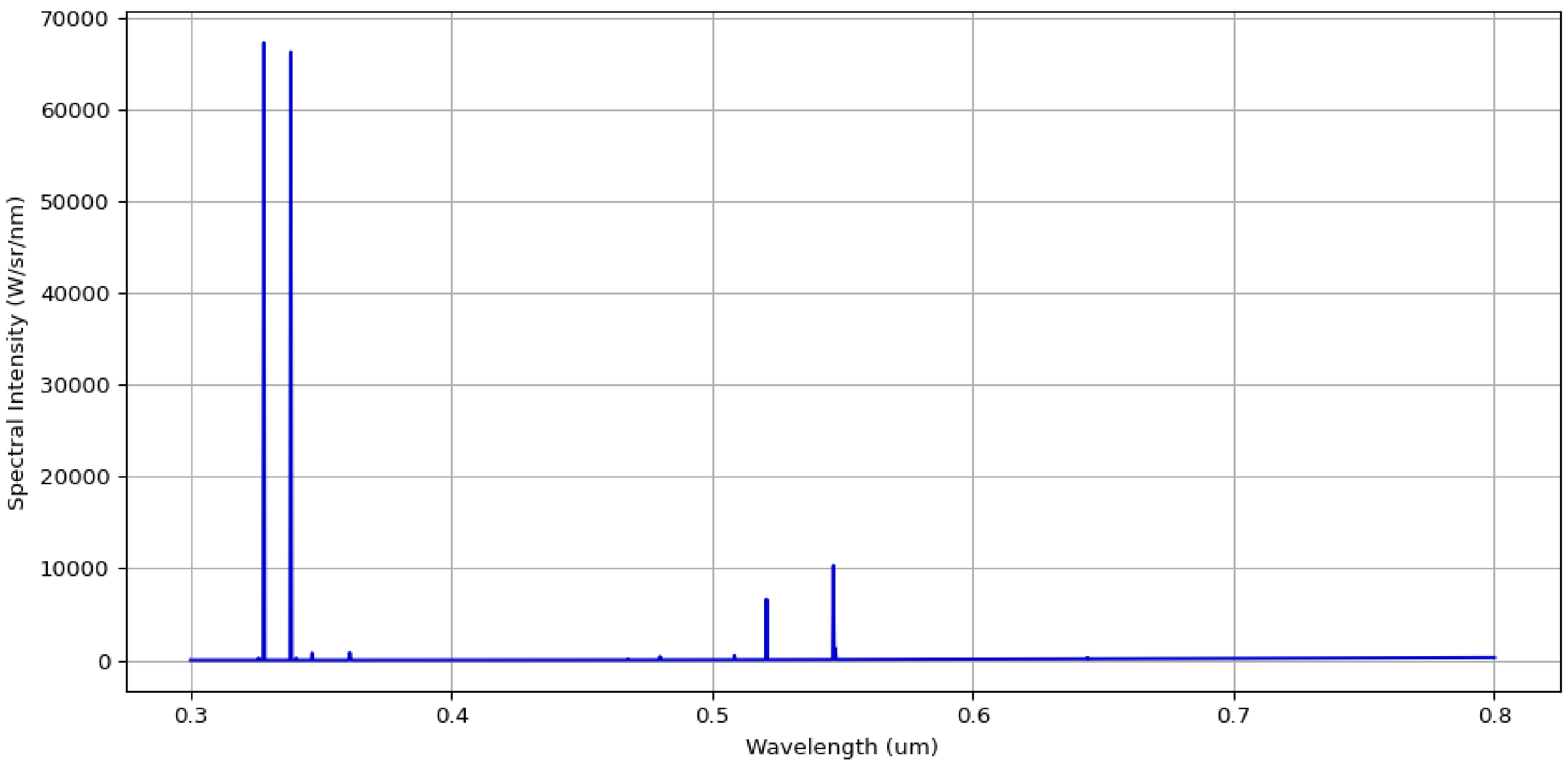


Rumba Detailed Results

- 75 seconds
  - 19 fragments radiating
  - 17 objects demising (aluminium, steel, titanium)
  - All objects are atomic
- 90 seconds
  - 15 fragments radiating
  - 3 fragments demising (batteries & compound)

Rumba Detailed Results

- PARADE spectra generated for each fragment
- Results fall into classes based on material composition
- Example battery emission of Ag & Cd



Tool Assessment

- Tool and methodology appears to work
- Output is highly dependent on quality of inputs
  - Spacecraft model
  - Material demise models
  - Augmentation of markers
  - Marker definitions
- Areas for further investigation / improvement
  - Domination of particle over fragment emission – is this representative?
  - High dependence on ψ values
  - Development of spacecraft modelling guidelines

Future Work – Observations / Experiments

Project Outcomes

Can we use spectroscopic data to unambiguously identify what is happening during re-entry demise?

The software does make reasonable predictions given the challenging simulation task.

It is a useful tool for helping to analyse observational data but with caveats.

The observational data is complex with many things going on.

The software needs better models to increase its predictive reliability and this requires supporting experimental data…

Remote Observation Roadmap

Michael Winter, Neutron Star Systems (NSS)

Purpose of this Report

- Assess general observation strategies to best utilize observation data to support break-up simulations.
- Assess and propose a minimum of different instruments for such an observation and give technical specifications for these instruments.
- Generate a list of additional instruments and experiments with rankings for each experiment.
- Compile a proposed observation strategy for airborne and ground (or ship)-based observation of CLUSTER II re-entries.

- Concept of a Destructive Re-entry Assessment Container Object (DRACO), is considered as well.

Approach

- Illustrate the main challenges and general requirements for individual techniques
- No recommendations of specific hardware (driven by availability of individual hardware and setups, by the chosen approach to select an instrument suite, and by the operation crew).

Remote Observation Roadmap

Michael Winter, Neutron Star Systems (NSS)

Contents

- General Observation Strategies
- Observation instrumentation (focus on airborne)
  - Requirements for Pure Imaging Data
  - Requirements for Imaging Data with Spectral Resolution
- Observation Strategies for Concrete Re-entry Missions
  - Observation of the CLUSTER re-entries
  - Suggestions of Strategies for DRACO

Approach

- Illustrate the main challenges and general requirements for individual techniques
- No recommendations of specific hardware (driven by availability of individual hardware and setups, by the chosen approach to select an instrument suite, and by the operation crew).

Basic Options for Observing a Spacecraft Re-entry

- From ground (for the sake of simplicity observation from any ground-based vehicle, e.g., a ship, is included in this category);
- Airborne from a dedicated aircraft (e.g., the NASA DC-8, or other airplanes, e.g. SOFIA, or even balloons as a possible other option).
- From space (the currently best option is the International Space Station, ISS, but it seems possible to use dedicated satellites, e.g. cube sats or other small satellites in the future);

Lessons Learned

- The last option will most likely not be available for CLUSTER since a coordination of entry location and time with the ISS orbits seems highly unlikely.
- Until the actual re-entry time and location is known with more accuracy than currently available [2], a decision for ground- or ship-based observation is not possible, yet.
- All successful observations were night-time re-entries. day-time observations will generate pointing difficulties (as happened during Genesis) and will generate background emission
  → reduced the signal-to-noise ratio important for weaker emission lines and early re-entry phases.
  → any possibility of a re-entry during night-time will significantly enhance the probability of gathering meaningful data.

[2] Lemmens, S., Merz, K, Funke, Q, Bonvoisin, B., Löhle, S, Simon, H., "Planned yet uncontrolled Re-entries of the Cluster Spacecraft," Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017.

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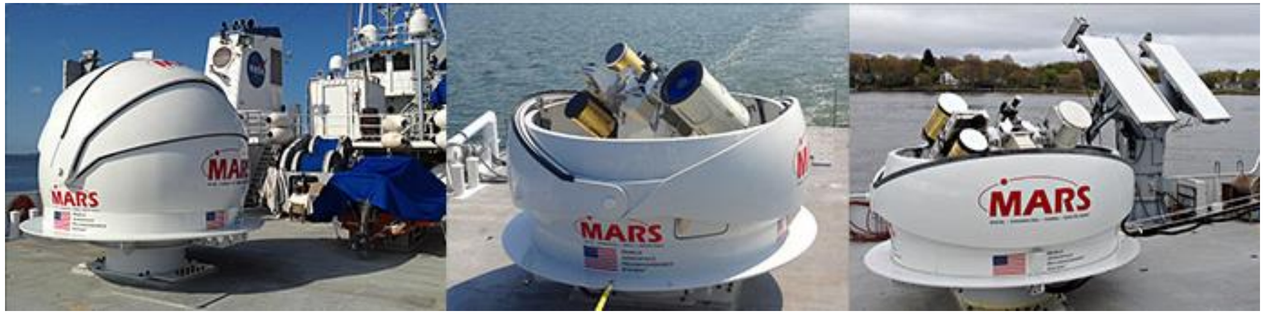
- From space (the currently best option is the International Space Station, ISS, but it seems possible to use dedicated satellites, e.g. cube sats or other small satellites in the future);

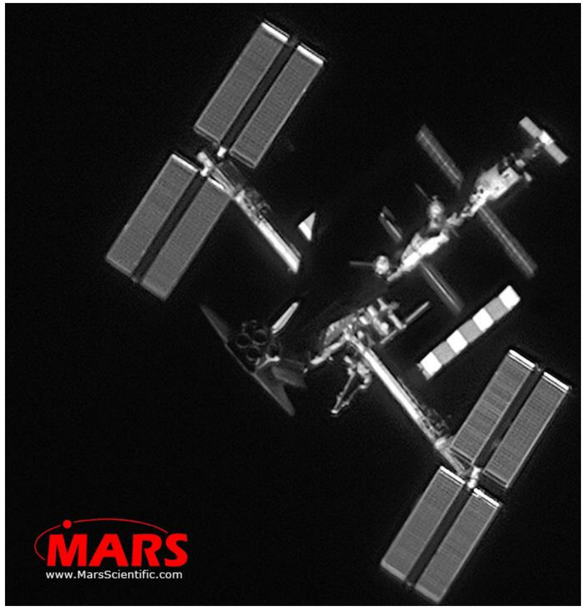
Lessons Learned

- Several airplane observation campaigns enable triangulation of object movement → trajectory data.
  → Observation from at least two separate aircraft at known positions would be advisable.
- Weather independence on airborne observations, instruments restricted in size and weight
  → limited spatial resolution.
  Ground- or ship-based observations highly weather dependent, but enable larger setups
  → spatial resolution significantly improves
- Maximum distance for observing a re-entering object down to 50 km limited by the Earth's curvature to ~800 km. Typical observation distances in past missions were between 100 km and 300 km
- Visible fragment cloud of ATV max up to ~15 deg FOV at ~52 km altitude and 220 km distance to the DC8.
  → fragment cloud extending over a distance of 63 km along the flight path at that altitude.

Instrumentation

- A combination of pure imaging and spectrally resolved data will be needed to be able to:
  a) describe the fragmentation in terms of number of fragments and individual trajectories,
  b) identify individual fragment using spectral markers, and
  c) gather information on aerothermodynamic and thermal properties of plasma and fragments, respectively.
- Requirements for ground- or ship-based observations and for airborne observation are very similar as far as cameras and grating choices are concerned.
  For a ship-based observation, motorized tracking devices should be considered.
  (Commercial imaging solutions in high spatial resolution for ship-based are commercially available [10]).

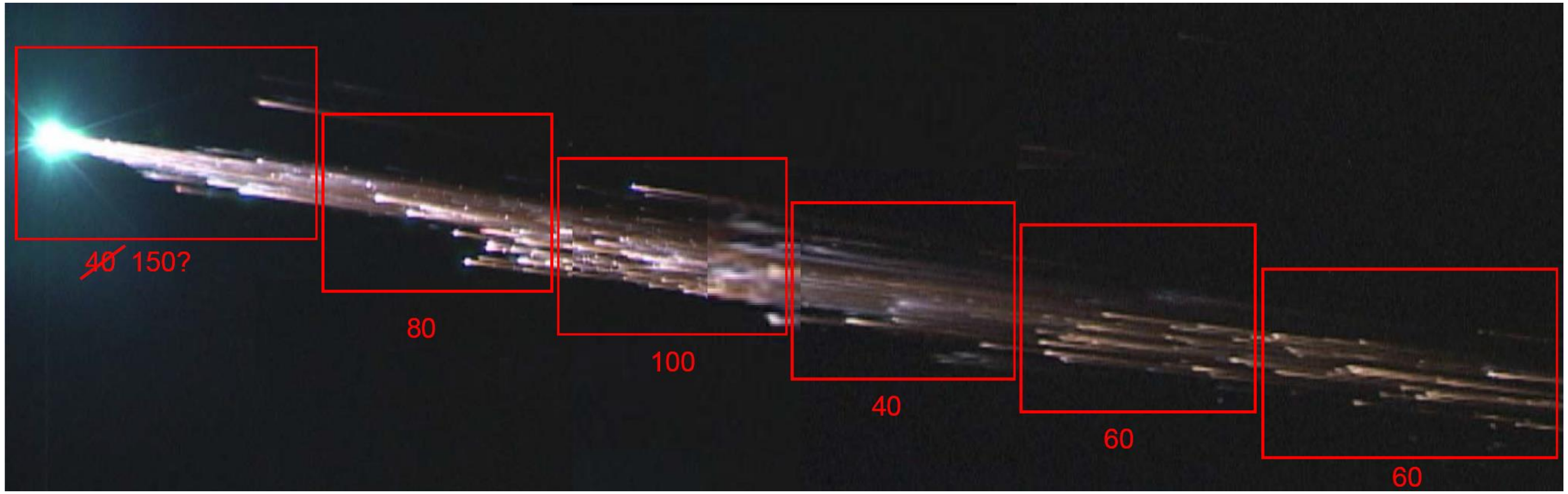




[10] MARS Scientific: http://marsscientific.com/gyrostabilized-ship-based-ktm.php, last visited May 2023.

Requirements for Pure Imaging Data

- Main purpose: describe the spatial distribution of fragments and individual trajectories.
- Challenges:
  - Cover the entire fragmentation cloud while maintaining ability to resolve individual fragments
  - Typically significantly brightness changes with time and altitude
- Conventional HD colour videos proven highly useful to describe the general timeline of fragmentation
- Typically very effective to describe the process to the public but also for scientific analysis.



ATV HDTV video still image at 60km altitude with identification of the number of fragments [11].

[11] Bavandi, A., “Number of Fragments from E-HDTV recording,” ESA workshop on “Jules Verne Multi-instrument aircraft campaign intermediate science results”, 9-12th March 2009.

Requirements for Pure Imaging Data

Resolution and sensitivity:

- the higher the number of pixels, the better the video quality
- For scientific analyses, a higher digital depth (e.g., 16 bit) desirable
  → higher signal-to-noise ratio and a better dynamic range.
- Intensified cameras would increase the sensitivity but usually offer smaller numbers of pixels
- Image sequences with different acquisition parameters for alternating frames → one picture with reduced sensitivity (capture bright events without over-exposure), followed high sensitivity → enhance weak signals.

Frame Rate:

- Capsule re-entries → frame rate not overly important (down to several Hz)
  Break-up scenarios → high speed events (explosive ATV events) on time scales of milliseconds.
  → requires specialist equipment (e.g., TERAS camera system used on ATV by ESA).
- Baseline configuration: regular frame rates (30Hz) might be acceptable.

FOV:

- Maximum FOV containing fragments bright enough to be detected and tracked FOV of 20°, (tracking camera for the FROG experiment [12], 50km altitude, 200km distance), smaller at higher altitudes.
- Colour HD video → larger FOV of 40-50° is recommended (e.g., for wake effects)
- Imaging systems for fragment number, size, and trajectories → higher spatial resolution → minimized FOV. Still able to track the re-entering objects→ large FOV → 20° good compromise.

[12] Winter, M., Laux, C.O., "Multiband Imaging Photometry of the Jules Verne Re-entry with FROG," ATV Re-entry Observation Campaign Workshop Manchester, UK, CEAS Congress October 28-29, 2009CEAS 2009

Recommended minimum and extended list of imaging systems

Minimum recommended number of imaging instruments:

1. Conventional HD (or even 4k or 8k) colour video with broad field of view (typically 40-50°)
2. Scientific, monochromatic camera system with reduced FOV (e.g., 20°) and high dynamic range (16 bit)

Additional systems in order of usefulness:

1. Narrow FOV (e.g., 5°) 16 bit monochromatic camera
2. High-frame rate camera (e.g., 5000 fps) with long term storage capacity.
3. High sensitivity camera (e.g., intensified scientific camera – ICCD) to observe the very early phase of the re-entry. If the entry trajectory still shows large margins at the time of observation, a large FOV might be useful.
4. As an alternative to the high sensitivity camera, an infrared camera might be considered to give early phase information.

Requirements for Imaging Data with Spectral Resolution

Frame Rate:

- Probably low, since not integrating over spectral range → lower intensity, unless intensified cameras.

FOV:

- Very similar requirements as the pure imaging systems (20°)
  focusing on the leading edge of the fragmentation cloud might be most useful
- Not necessary to constantly monitor spectral markers for individual segments → assign to individual fragments at some point in time, then monitore along the trajectory in the imaging data.

Configurations:

- Conf. I: Monitor the 0th order (pure imaging without spectral resolution) and higher orders (typically 1^{st} or 2^{nd} order) on the same camera.
  - simplifies the assignment of spectra to the generating fragment
  - complicates the analysis of the data since objects at different positions in space may be seen as a superposition to spectrally resolved emission from other fragments
- Conf. II: Only monitor the diffraction order of choice and optimize to the wavelength range of consideration.
  - requires a separate imaging camera on the same scale as the spectrally resolved images to assign spectra to individual fragments
  - requires a careful alignment of the different cameras.

Recommended minimum and extended list of imaging systems with spectral resolution

Minimum recommended number of imaging instruments:

1. Overview spectra from 300 nm to 900 nm with 0^{th} and 1^{st} order diffraction on the same CCD chip. The wavelength resolution should be as high as possible but is considered rather uncritical.
2. Overview spectra with an instrument in Conf. II (separate imaging and spectrally resolving cameras), again from 400 nm to 900 nm.
3. Increased spectral resolution system focusing on the UV and low-VIS wavelength range (300 nm-450 nm) in Conf. II, well suited for detecting air plasma emission (N_2, N_2^+, CN) for plasma temperature information and multiple atom emission lines. This system might be combined with instrument 2. by using the same imaging camera

Additional systems in order of usefulness:

1. Higher spectral resolution system to better resolve atom lines close to each other in the UV but still being able to detect air plasma emission (N_2, N_2^+, CN) for plasma temperature information; basically, split up the system 2 into two systems with the wavelength ranges 300 nm to 370 nm and 360 nm to 440 nm.
2. Higher spectral resolution system focusing on AlO and C_2 emission between 400nm and 550nm.

Alternatively using commercial solutions instead of building these systems in house :

Mobile Aerospace Reconnaissance Systems, Inc. (MARS), has provided the entire suite of observation instruments from the US side for the observation of Hayabusa 2 [6]. Assuming these instruments still exist at MARS, they might be reconfigured to the needs for upcoming observations of destructive re-entries as projected by ESA.

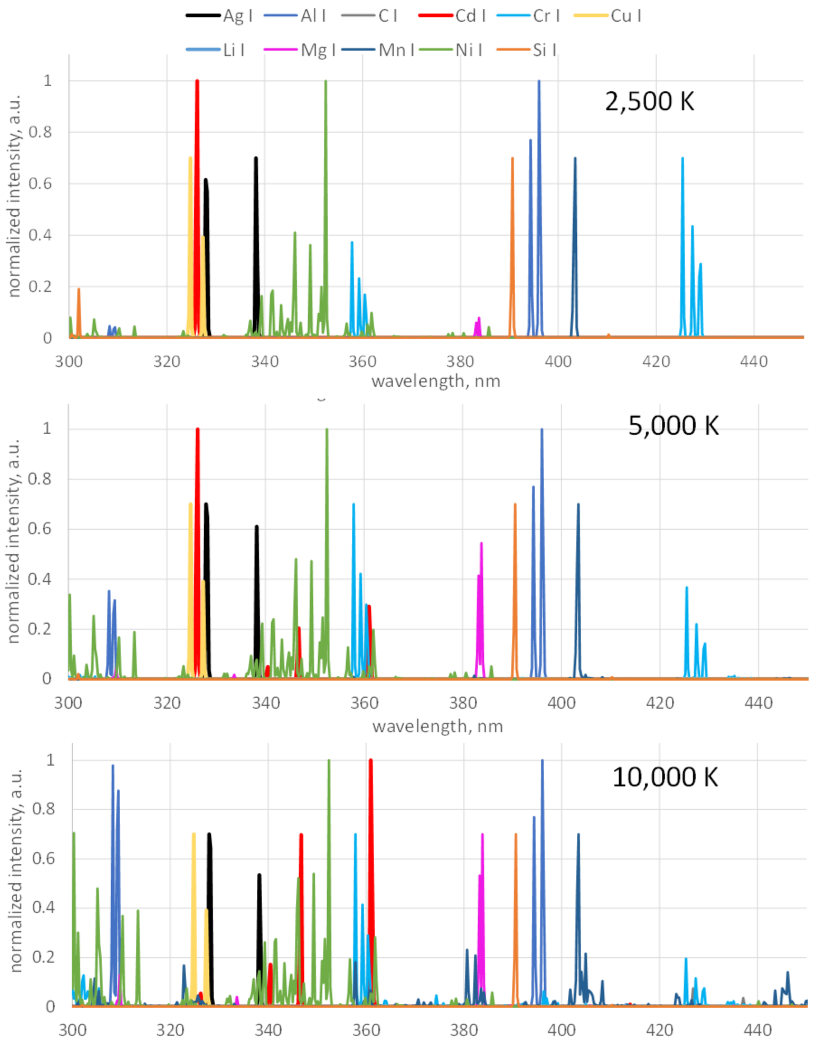
[6] Carey F. Scott Jr. et al., "SCIFLI Airborne Observation of the Hayabusa2 Sample Return Capsule Re-Entry," AIAA Aviation 2022 Forum, June 27-July 1, 2022, Chicago, IL & Virtua.

Observation Strategies for Concrete Re-entry Missions - Observation of the CLUSTER re-entries

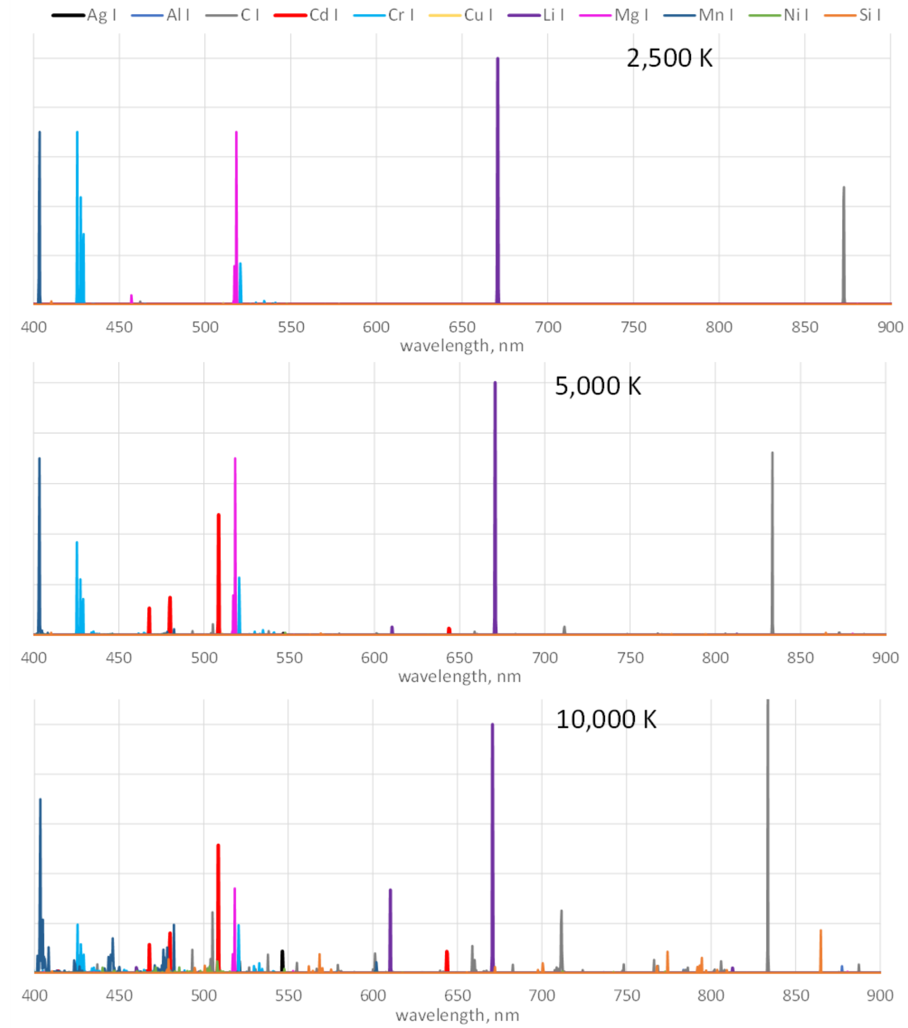
Table 1. Emitters seen in Component Tests

Tested component	emitters: all, wake (W), boundary layer (BL)
printed circuit boards (PCBs) **Internal Printed Circuit Board #1**	CH, CN, NH, C2, Na, K, H, Pb, Cu, Zn, Mg, Ag, Ba, Li, Si **W:** CN (380-390 nm), Cu I (around 325 nm, 510-525 nm, and 570-580 nm), Li (671 nm), Pb I (360-370 nm, 405 nm) **BL [446-562 nm]:** H I (486 nm), Cu I (511 nm, 516 nm, 522nm), C2 (513 nm and 517 nm)
Side Cover Printed Circuit Board #2	**W:** CN (380-390 nm), Cu I (around 325 nm, 510-525 nm, and 570-580 nm), Li I (671 nm), and Pb I (360-370 nm, 405 nm) **BL [446-562 nm]**: Zn I (481 nm, 472 nm, 468 nm), Cu I (511 nm, 516 nm, 522 nm), Mg I (517 nm)
Cluster BRB DSub Connector	CH, CN, AlO, Cr, Al, Na, Pb, Cd, H, Ca, Zn, Ag **W:** CN (380-390 nm), Ag I (328 nm, 338 nm), Zn I (306 nm, 325-335 nm, 471 nm, 481 nm) **BL [418-534 nm]:** Cr I (425-430 nm, 421 nm), H I (486 nm), Cu I (511 nm)
BRB Swagelok Fluid Connector	Ni, Cr, Mn, Mo, and Li **W:** Ni (345-360 nm), Li I (671 nm), Cr I (428 nm, 520 nm) **BL [440-556 nm]:** Cr I (465 nm, 522 nm)
CFRP honeycomb, bracket and struts	CH, CN, C2, Na, H, Pb, Cu, Zn, Mg, Ag, and Ba **W:** CN (380-390 nm), H I (656 nm) **BL [418-534 nm]:** C2 (418-428 nm), Mg I (519 nm)
Aluminium Honeycomb Plate	CH, CN, C2, H, Na, Al, Mg, Cr, and Mn **W:** CN (380-390 nm), Al I (396 nm), Mg I (520 nm), H I (656 nm). **BL [418-534 nm]:** C2 (418-428 nm 522 nm), Mg I (519 nm)

Observation Strategies for Concrete Re-entry Missions - Observation of the CLUSTER re-entries



Simulated emission of selected spectral markers in the UV/low-VIS range.



Simulated emission of selected spectral markers in the UV/low-VIS range.

Observation Strategies for Concrete Re-entry Missions - Suggestions of Strategies for DRACO

Elements tested as spectral markers for remote recession measurements.

Element	Delivery Method	Detected?	Emission Strength
Silver (Ag)	pure	Yes	Strong
Aluminium (Al)	pure Al2O3	Yes Yes	strong strong
Boron (B)	VB2	No	None
Chlorine (Cl)	NaCl MgCl2	No No	none none
Chromium (Cr)	thermocouples	Yes	Medium
Hafnium (Hf)	HfO2 HfC	No No	none, none
Indium (In)	pure	Yes	Strong
Magnesium (Mg)	MgCl2	Yes	Strong
Manganese (Mn)	thermocouples	Yes	Medium
Sodium (Na)	NaCl	Yes	Strong
Nickel (Ni)	thermocouples	Yes	Strong
Silicon (Si)	pure SoiO2	NA NA	Already strong emission from sample holder.
Titanium (Ti)	pure ToC	Yes Yes	strong strong
Vanadium (V)	pure VB2	Yes Yes	strong strong
Tungsten (W)	pure	Yes	Strong

Delivery Methods:

- Simplest method in form of painted surfaces
  Sufficiently large area with a thick layer of paint
  → prolonged emission might be generated.
  Carefully designed ground tests should be conducted.
- Deposition of marker materials inside of porous materials → information on recession depth.
  Use of carbon fibre form → carbon and CN emission
  → marker emission indeed is generated by the targeted fragment.
  Alternatively, porous metals (e.g., tungsten)
  → long-lived structure containing the marker.
- Structurally weak containers containing substantial amounts of one particular spectral marker or of different combinations of selected markers, placed at strategic positions across the spacecraft
  → strong but short-lived bursts of spectral emission.
  Combinations of various spectral makers → sort of barcode characterizing one particular location.

PRODUCERS: The Way Forward

Ground Testing

Ground Testing

Status

- Establishment of extensive experimental reference database
  - Material (and coating) emission signatures during varying states of heating and demise
  - Characteristic component and structural emission markers correlated with specific decomposition events
  - Effects of object separation on shock structure and radiation markers
- Datasets for materials and components for integration with ESTIMATE database have been provided to ESA, containing:
  - Identified atomic and diatomic species
  - Quantitative history of respective emissions
  - Correlation of appearance with heating phases and destructive phenomena
  - Synchronised video and thermal data

Ground Testing

Lessons Learned: Materials

- Material emissions can identify not only materials but also their state of heating/demise.
- Alkaline metals (Na I, K I and sometimes Li I) can be considered ubiquitous indicators of onset of demise.
- Spectral footprint is more unique for metallic materials, less so for polymers.
- Certain emissions, e.g. primary alloy constituents and diatomic oxides result from extreme energy densities built up in droplets within the wake during re-entry flight.
  → Challenging to fully emulate in ground testing, but possible e.g. via (combination of)
  - Severely “Overdriven” high-enthalpy heating conditions.
  - Low-radius material samples (e.g. rods or wire mesh?).
  - Reassessment of OES measurement volumes – painful trade-offs likely.

Ground Testing

Lessons Learned: Components and Structures

- Certain separation events (e.g. CFRP-Al-bonds) can be associated with faint but qualitatively distinct radiation signatures (i.e. flashes), likely due to sudden exposure of adhesives.
- Spectral emissions from certain types of components, e.g. PCBs, share a baseline composition, but are also determined by individual characteristics (e.g. mountings).
- Question of length/mass/luminosity scales arises w.r.t. remote observations of small components such as PCBs in terms of cross-reading with experimental databases and modelling.
  → Definition of generic archetypes for component types in reference databases and models, containing dataset of common and potential individual lines.

Ground Testing

Lessons Learned: Splitter Probe

- Spatially resolved spectra enabled to draw conclusions on the shock structure with no significant difference observed between an opening angle of 6.5 and 16.7deg
- The proposed thickening of the boundary layer during the initial opening phase could not be reproduced experimentally and is considered to be rather speculative → Need of other dedicated splitter probe variants with precisely controlled separation mechanism and high speed camera footage
- No conclusive evidence could be found on:
  - increased apparent brightness during re-entry
    → limited observation of the whole shock structure volume
  - flashes in low-level break-up events indicate fragmentation or rapid material release
    → Stationary melt phase of Al sample did not expulsed emitting superheated droplets

Ground Testing

Outlook → The Way Forward

- Future material tests shall be optimised to maximise energy density in droplets and outgassing, will likely amend database to better reflect remotely observed emissions in wake flows (e.g. Ti I and TiO).
- Series of (semi-redundant) component tests could consolidate “archetype” databases for modelling and remote identification of generic component types.
- Future tests should examine a broader field-of-view and wavelength range to distinguish whether flashes in low-level break-up events indicate fragmentation or rapid material release. Simplifying the experimental setup may enhance understanding of underlying processes.

Future Work – Modelling

Future Work - Modelling

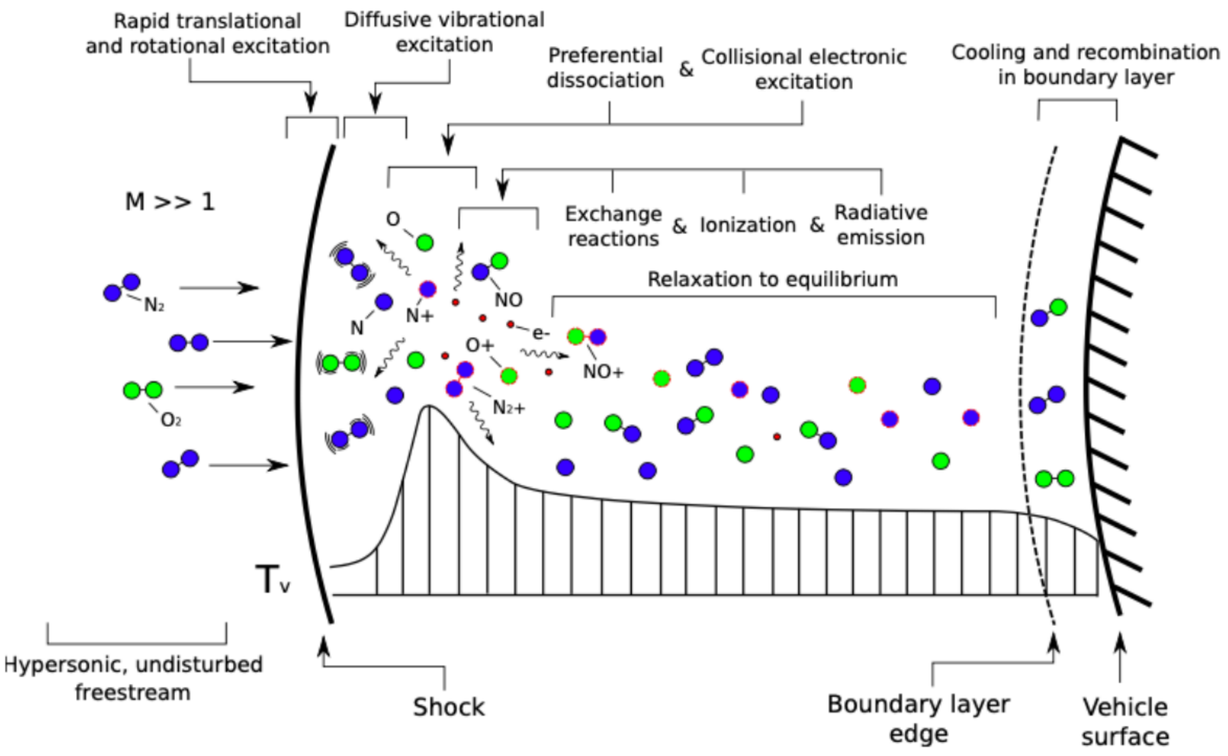
The aim for the future is have a future version of PRDUCERS that can be used

- As a design tool for the instrumentation of an observation campaign
- To allow spacecraft break-up models to be compared with observations

This is a difficult task even for high fidelity modelling which is impractical in this case

Various emission mechanisms have been included in PRODUCERS and all rely, to a greater or lesser extent, on flow-field estimation based on the trajectory based demise model.

As an example, the structure of the shock is complex but this is not modelled by the demise codes.



Future Work - Modelling

Particles

PRODUCERS includes particle modelling and this may lead to an improvement in the capabilities in conjunction with experimental work.

It is possible that the explanation of the absence of Al emissions during aluminium plate demise could relate to the heating and cooling of particles or drops of liquid metal

Given the infra-structure for particles, there is scope to look at more realistic models in light of experimental results.

Al particles have been studied extensively in the context of rocket plumes so this may be a good starting point.

Very little literature exists beyond Al but this is at least something to build on.

Future Work - Modelling

High Fidelity Modelling

High fidelity modelling is difficult for destructive entry due to the complex and rapidly changing geometries involved.

Simplified objects, e.g. spheres, that make up parts of spacecraft could be modelled to try and establish features of these items during demise.

Objects that have aerodynamically stable shapes can be modelled effectively in their stable attitude

Others that are in a fairly regular tumbling motion can also be examined though this is rather challenging. Extracting information that generates periodically emissions could be valuable for some items.

Further studies of a similar nature to the splitter probe may also reap rewards in better understanding the effects of break-up and whether this modifies or enhances emission.

Future Work - Modelling

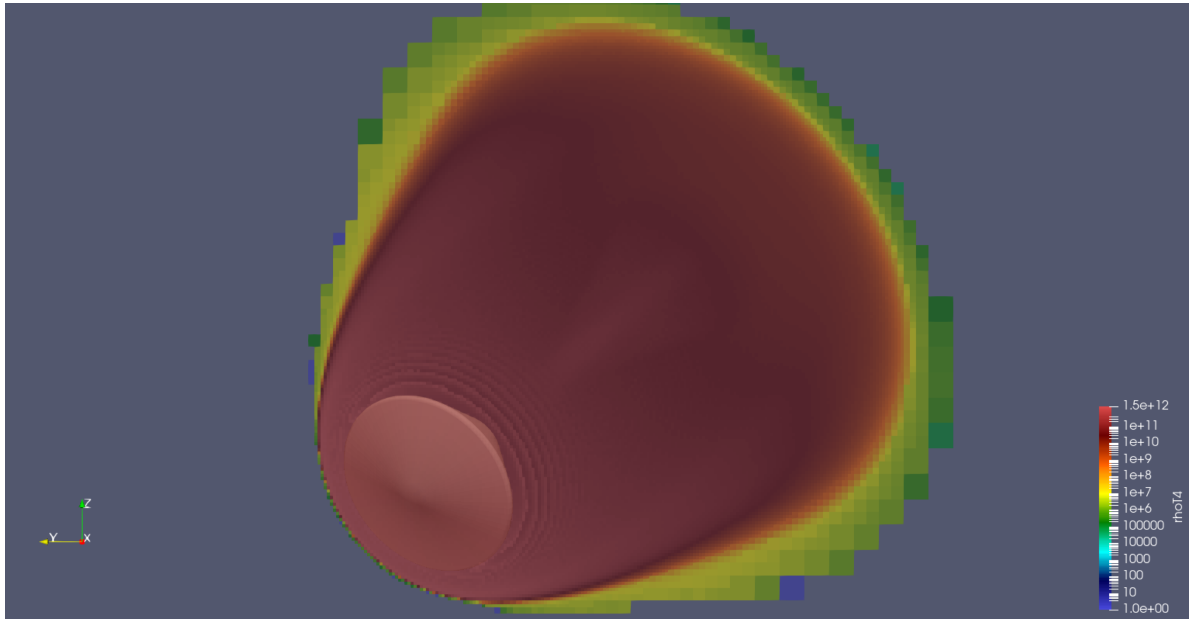
Exploitation of Existing Data

The data collected from the ATV mission and similar observing campaigns is very valuable.

This can be exploited to further study the models used in PRODUCERS and to try to identify which aspects need further work.

FGE have recently developed a capability to generate a more realistic view of what emissions should look like given a suitable model of emissions that generates are 2D image much like what would be observed. (see Schiaparelli image right)

This can be used to more easily compare the data with the results from PRODUCERS and thus help identify where the models need more work.



Future Work - Modelling

Geometrical Modelling Fidelity

The work in the verification study on the ATV simulations has led to some good comparisons with data, namely the docking adapter and the main body, but also some poor comparisons with the lithium battery.

The model battery demises earlier than the observed one based on the appearance of Lithium emissions in the data.

The model was relatively simple in that a single cell was modelled inside a largely empty shell

The effects of shielding of one component by the various others that surround it are clearly very important

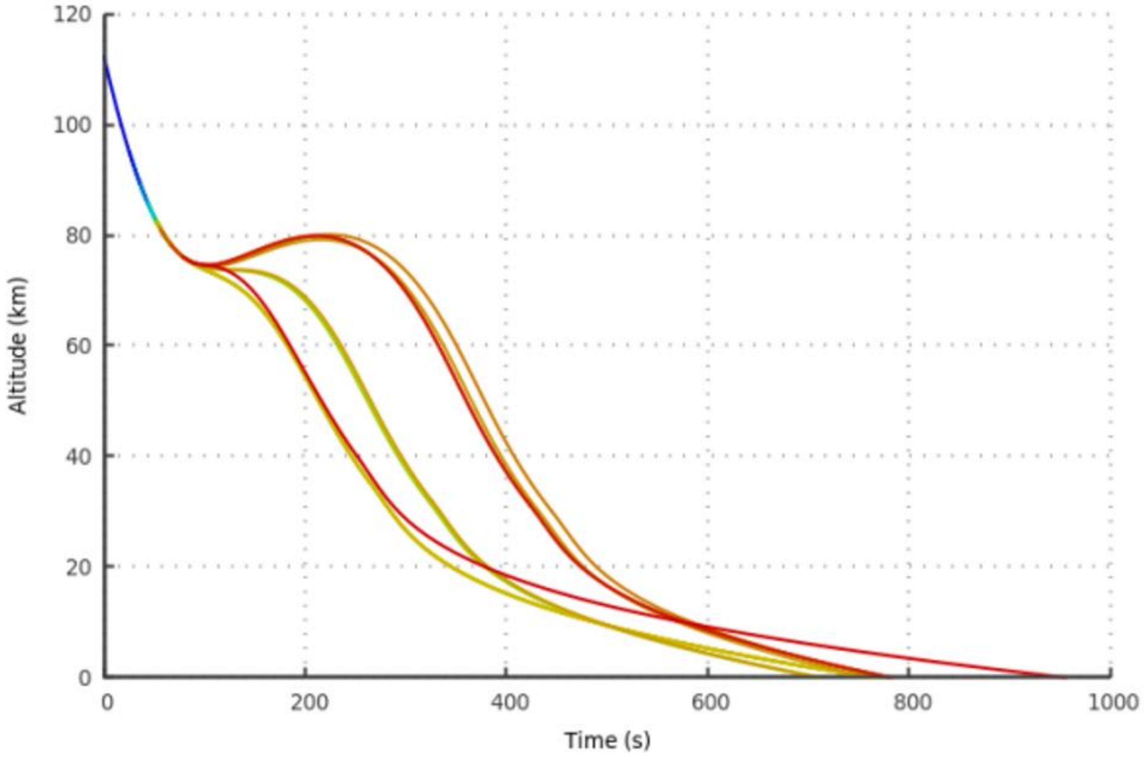
This highlights the need to get a sufficiently realistic model assembled.

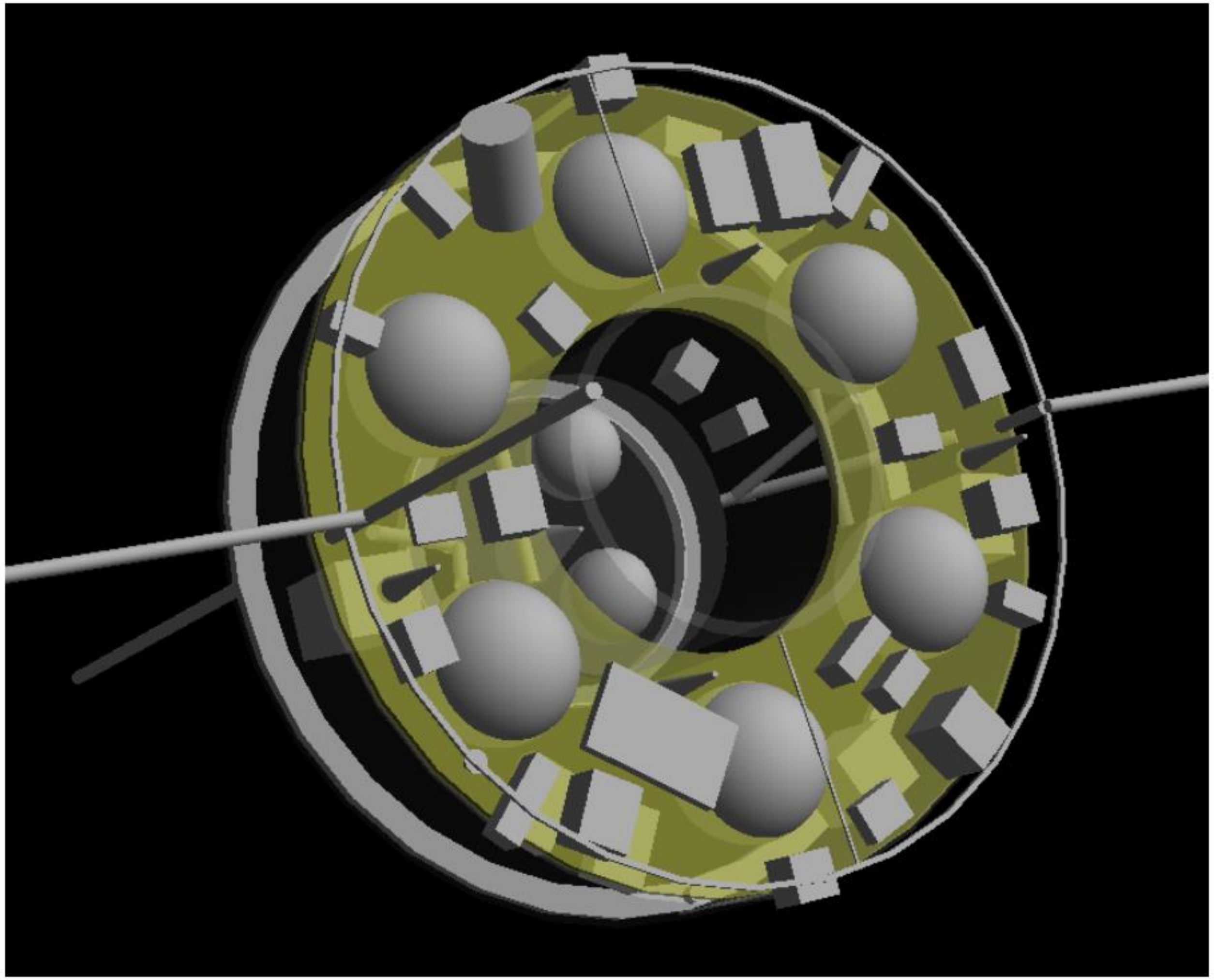
Conclusion

Cluster-II Simulation

A detailed model of the Cluster II spacecraft has been assembled by BRL

DRAMA demise prediction shows trajectories of major components and their colour coded temperatures:



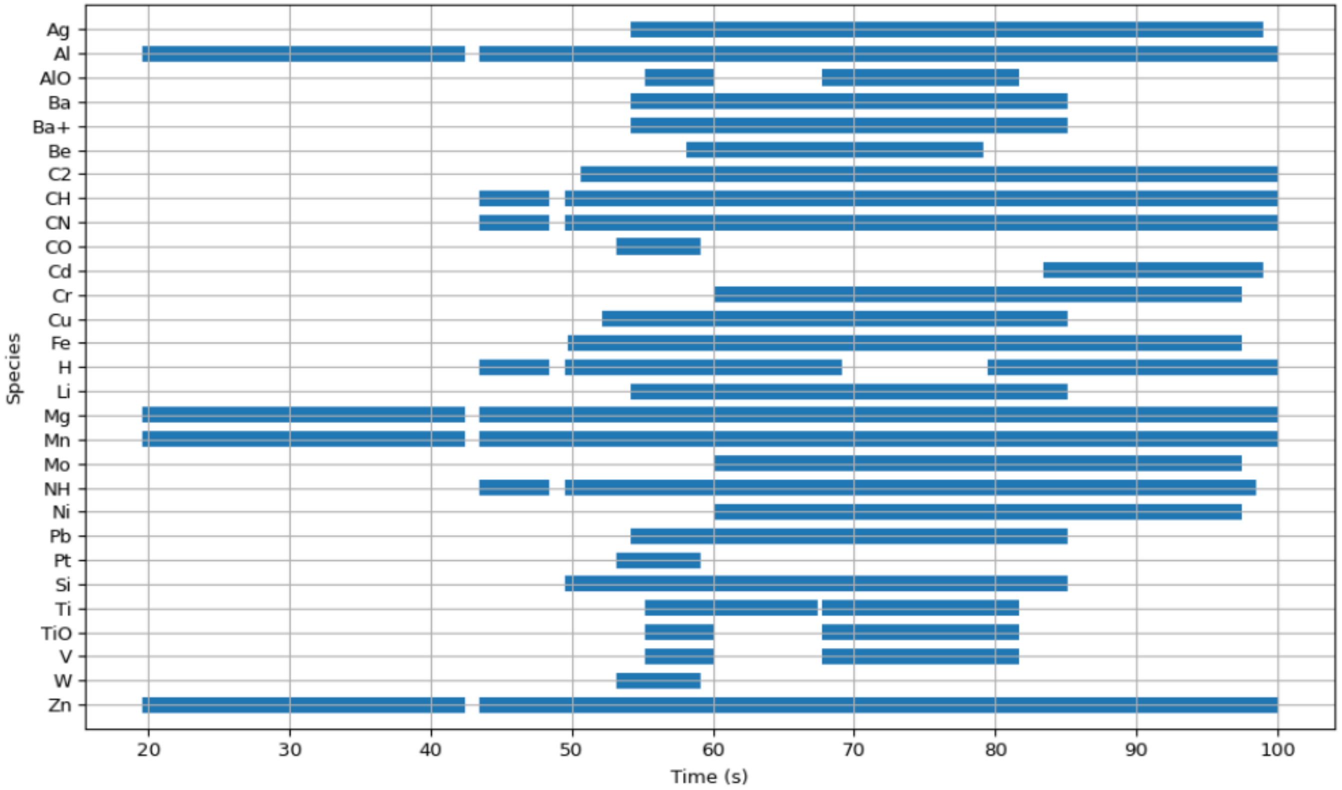


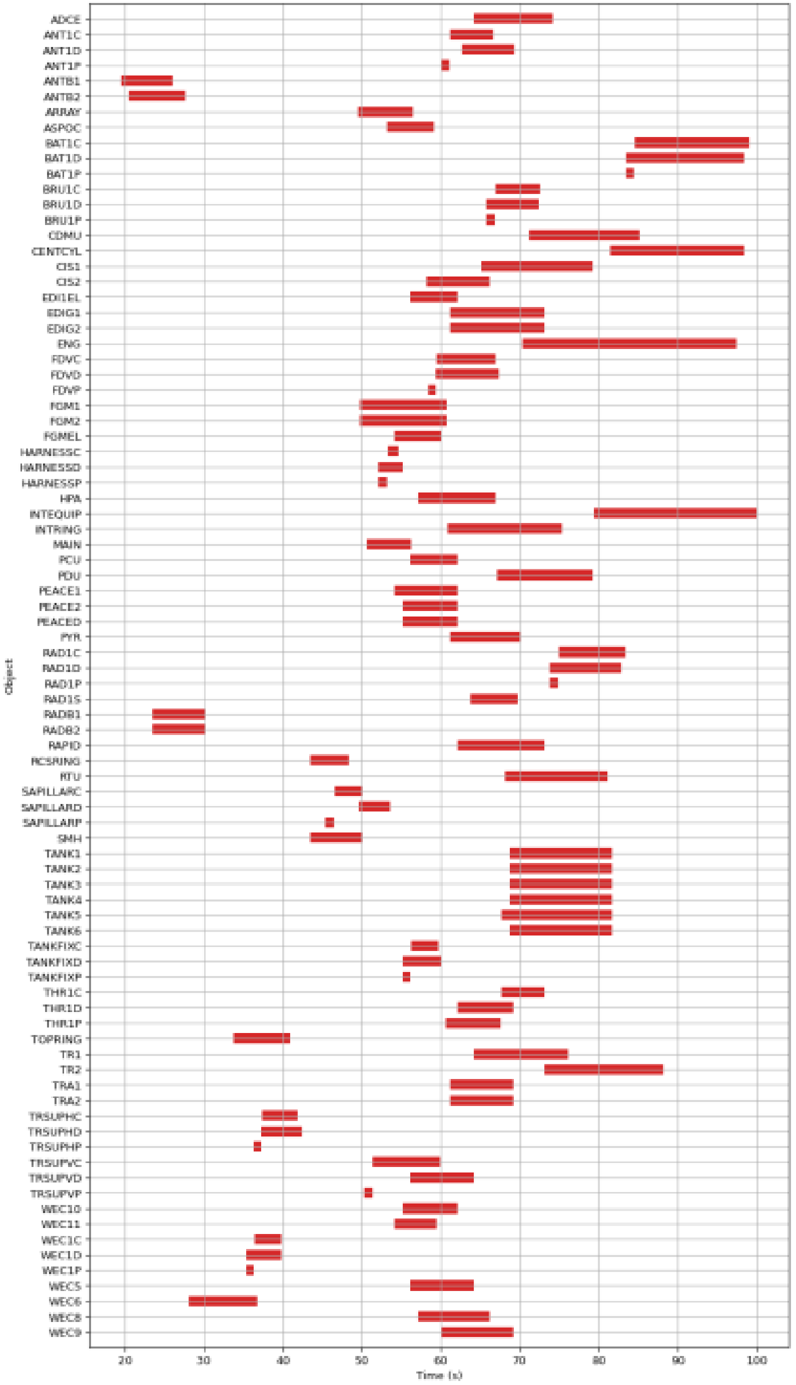
Conclusion

Cluster-II Simulation

The simulations provide a schedule of demise for each component in the model

This in turn gives a schedule of species emissions based on the physics models within PRODUCERS



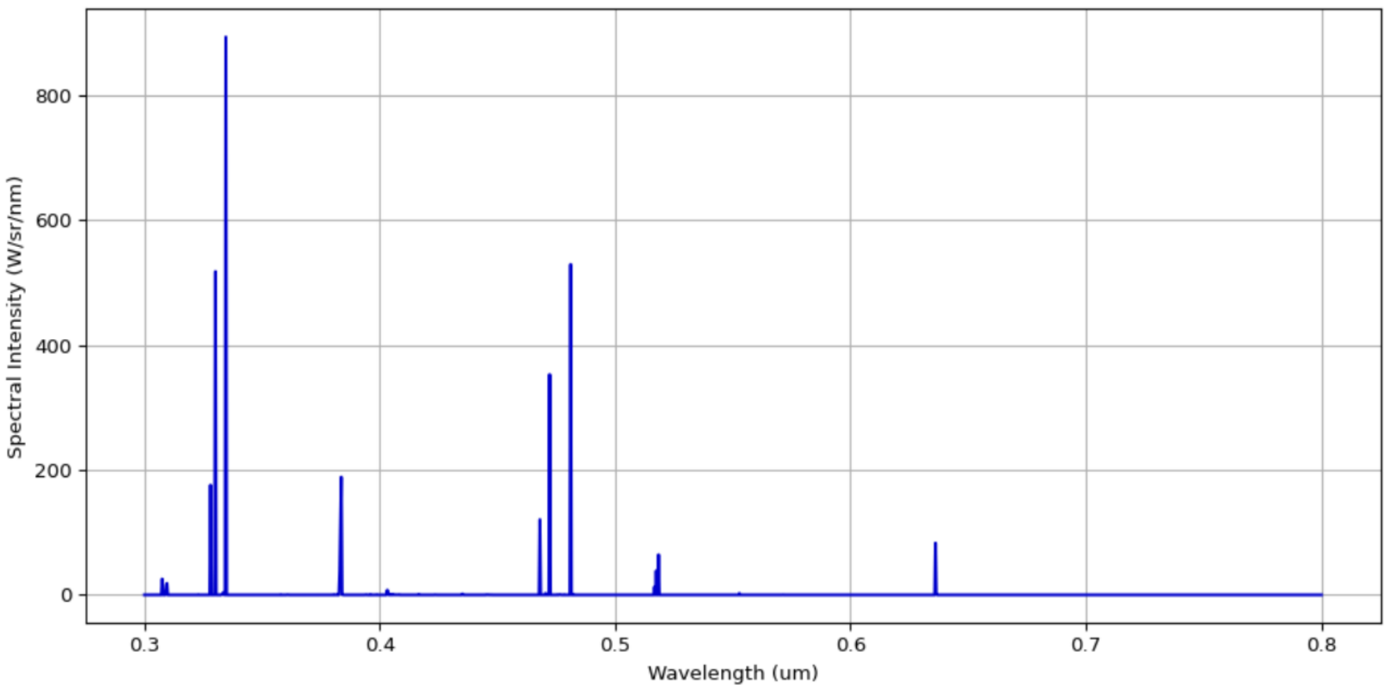


Conclusion

Cluster-II Simulation

Numerous spectra can be generated by PRODUCERS looking at single species or many and at different times during the descent

Interesting points can be explored in more detail via a re-run.



This remains a challenging problem but the PRODUCERS software has been pleasingly effective as a predictive tool and diagnostic aid.

During the project, various issues have arisen and some resolved

The others require further work which could significantly improve the software and the physical understanding via experiment and modelling and we have indicated how this could progress.

…and finally

We should build a model for a NASA toolbox…