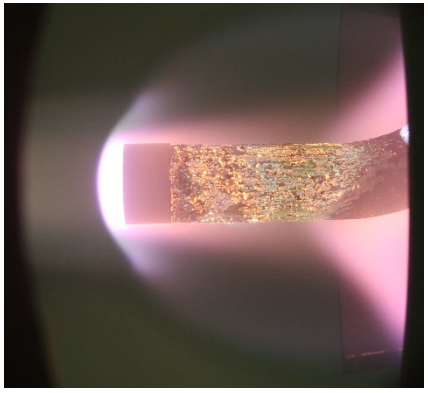
Remote Optical Recession Measurement of Orion Thermal Protection System



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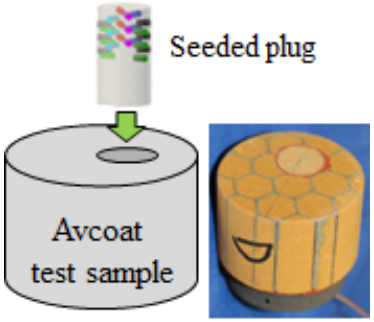

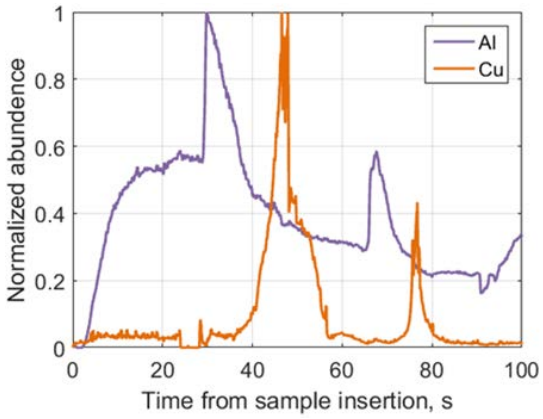

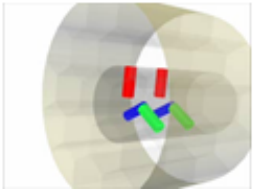

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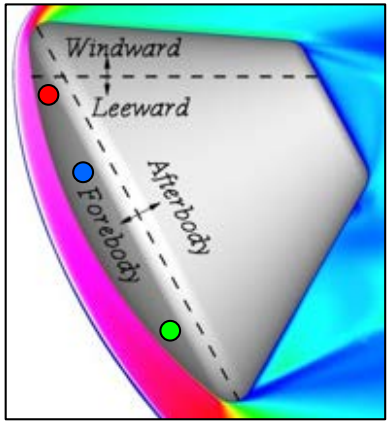
Acknowledgments: Margaret Stackpoole (NASA ARC) and Thomas Horvath (NASA LaRC)

Motivation and Measurement Concept

- **Motivation**
  - Recession models for Orion ablator heatshield material (Avcoat) have large uncertainty, necessitating large safety factors
  - Current *in situ* diagnostics are not sufficiently accurate to reduce uncertainty
    - Cannot simply improve as likely to be discontinued when Orion becomes operational
  - Need a non-invasive, time-resolved TPS recession diagnostic to support model validation and to enable lower safety factors and corresponding weight reduction



- **Measurement Concept**
  - Seed TPS close-out plugs with metals at known locations/depths
  - Metals released and vaporized during recession
  - Spectra measured by an off-board sensor
  - Detect tracer metal signatures using OKSI's **S**pectral **P**rocessing for **O**ptical **T**race **E**lement **D**etection (SPOTED) algorithm
    - Developed for rocket health monitoring
    - Detect and quantify weak metal signatures against complex background
    - Exploits predicted spectral signatures generated by customized version of **O**ptically **O**paque **P**lasma**s** (OOPS) code from Spectral Sciences, Inc.
  - ➔ Spatial-temporal map of TPS recession

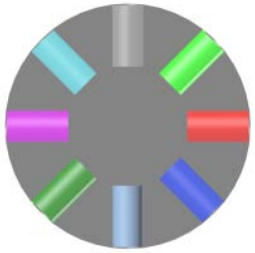
Development Path

- **Initial experiments**
  - Experiments conducted at HYMETS (NASA LaRC) in October 2015
    - **Hy**personic **M**aterials **E**nvironmental **T**est **S**ystem
    - 400kW arc-jet facility, 1.5” diameter Avcoat test articles
    - Relatively low cost, short time between tests
  - Objectives
    - Proof-of-concept
    - Verify “Do No Harm”
    - Characterize various tracer metals
    - Evaluate possible plug configurations
    - Establish relationship amongst signal characteristics, tracer metal properties, and recession depth
- **Confirmation Experiments**
  - Experiments conducted at AHF (NASA Ames) in May 2017
    - **A**erodynamic **H**eating **F**acility
    - More closely reproduces flight conditions than HYMETS does
      - Approximately the same heat flux, much higher dynamic pressure
      - 4” test articles → reduced edge effects
  - Objectives
    - Verify indicator metal behavior in different facility and under more representative conditions
    - Refine seeded plug design
    - Identify limitations on depth resolution

HYMETS Seeded Plug Configurations

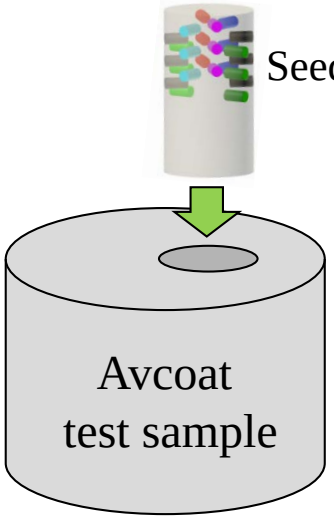
Configuration#1: Spiral Wires

Top View



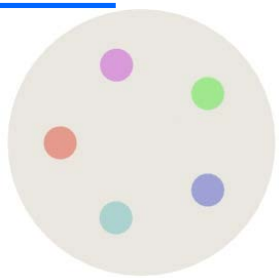
Side View

Seeded plug inserted into test sample

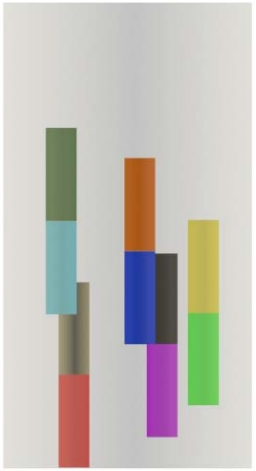


Configuration#2: Parallel Wires

Top View



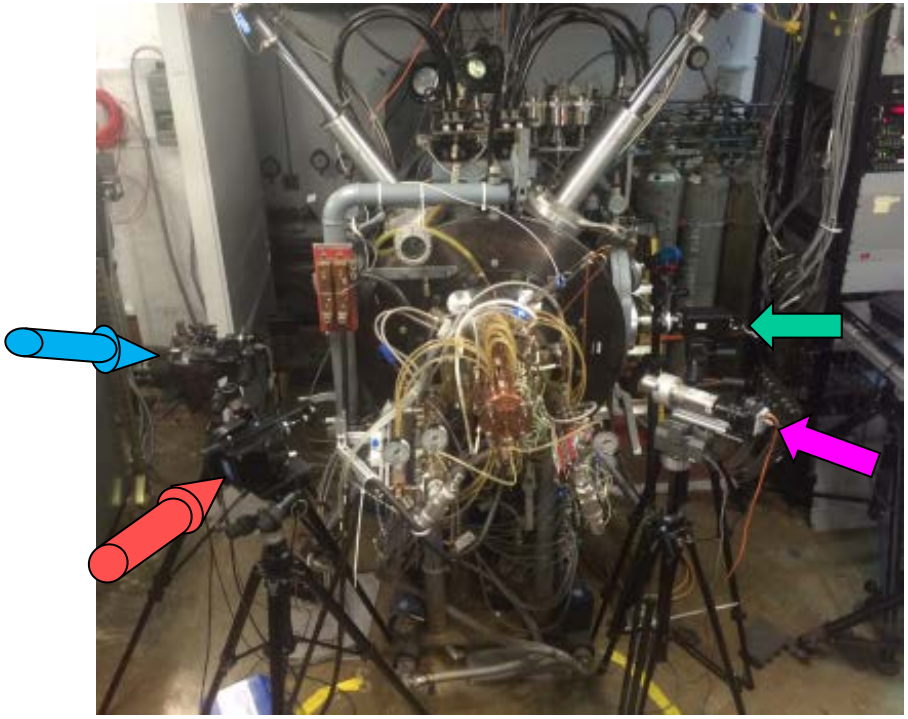
Side View



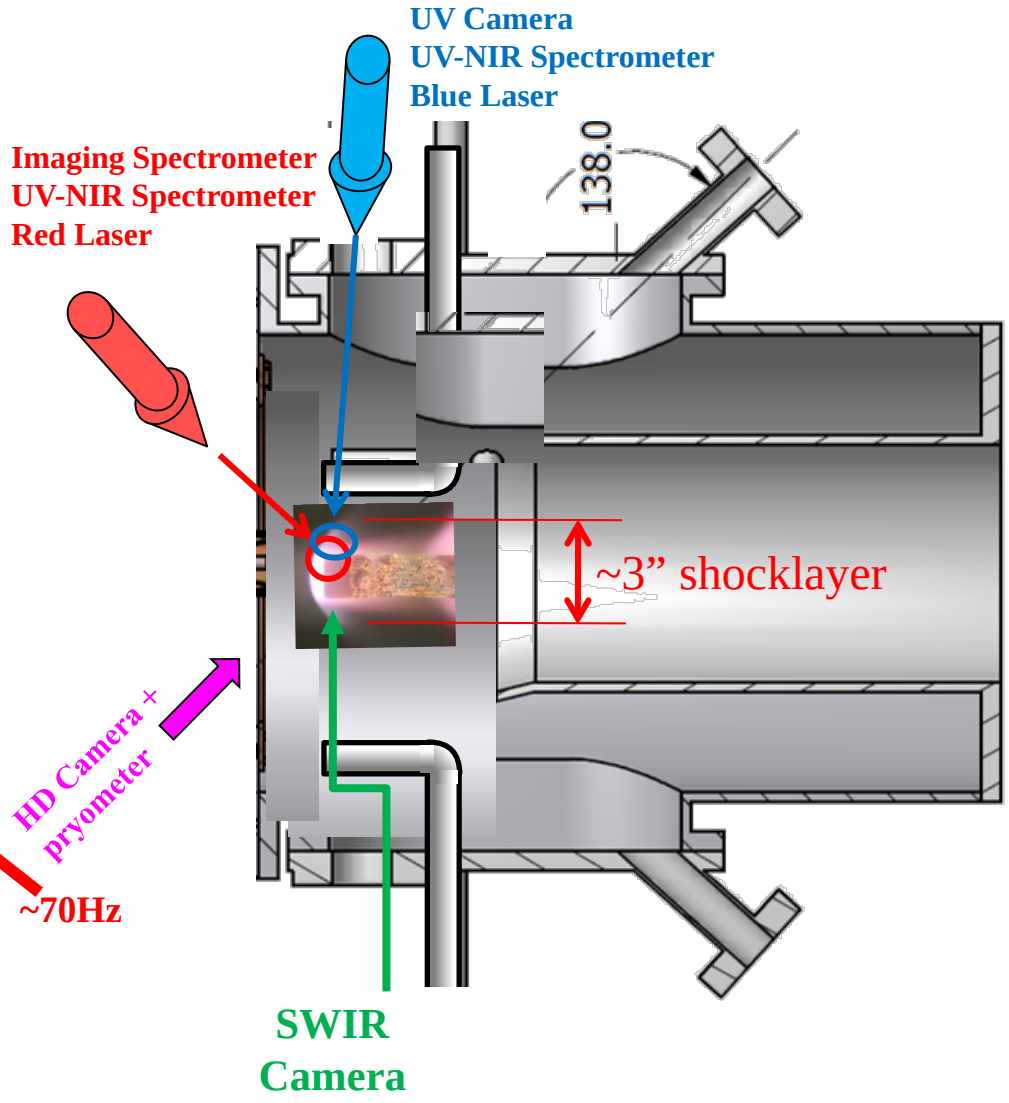
Test Matrix

Run	Sample ID	Config Type	Metals	Plug Adhesive	Comments
1	Beta	blank plug	none	RTV-560	control sample
2	Gamma	blank plug	none	non-ferous epoxy	control sample
3	W	parallel wires	Cu,Chromel-C,W,Ti,Ag,Nb	non-ferous epoxy	low to high temp metals, staggered start
4	V	parallel wires	Fe, Mo, Ta, Re, V, Hf, Zr	non-ferous epoxy	mid & high temp metals, staggered start
5	E	spiral	W, Ti, Chromel-C	non-ferous epoxy	mid & high temp metals
6	G	spiral	In, Sb, Pb, Al, Cu	non-ferous epoxy	low temp metals only
7	A	double spiral	Ti,Nb,W,Ag,Cu,Ni	RTV-560	low and high temp metals at each depth
8	B	double spiral		RTV-560	low and high temp metals at each depth
9	C	double spiral	V,Hf,Re,In,Sn,Pb	RTV-560	low and high temp metals at each depth
10	X	parallel wires	W,Ta,Re,Mo,Nb,Rh,V, Chromel-C,Cu,Fe,Zr,Ni,Ti	RTV-560	two layers: mid and high temp metals, then mid and low temp metals
11	Y	parallel wires	Ni,Hf,Mo,Ag,Cu,Fe, Nb,Ta,Re,Ti,V	RTV-560	two layers: mid and low temp metals, then mid and high temp metals
12	Z	parallel wires	Ag,Cu,V,Fe,Ti,Zr,Nb, Chromel-C,Ta,Hf,W,Mo	RTV-560	two layers: mid and low temp metals, then mid and high temp metals
13	D	spiral	Re,Ta,Mo,Nb,V,Hf,Zr	RTV-560	high temp metals only
14	U	parallel wires	In,Sn,Pb,Mg,Al	non-ferous epoxy	low temp metals, staggered start

HYMETS Setup

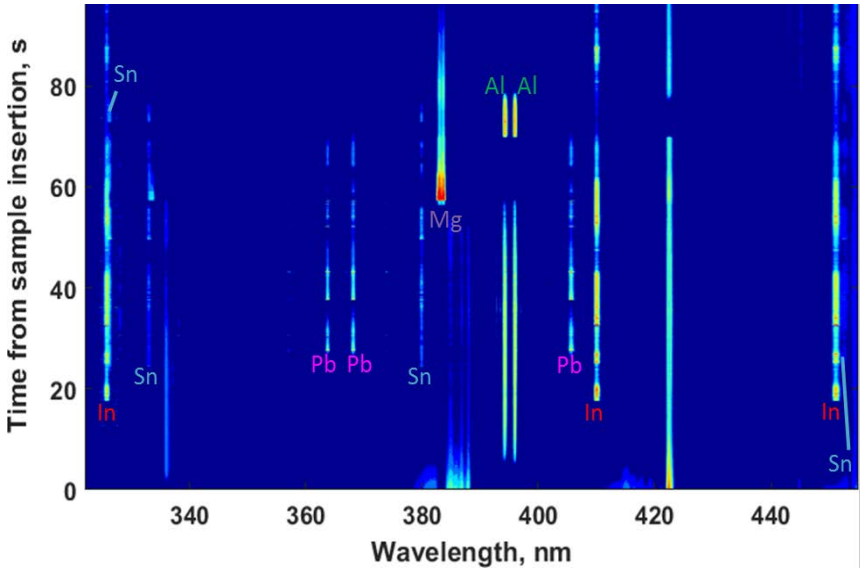


Sensor	Viewport	spectral band, nm	FWHM resolution, nm
OSS2-UV	Starboard side	320-450	0.08
OSS2-VNIR		450-1100	0.93
UV Imager		390	10
pointing laser		430	1
OSS1-UV	Starboard 45	320-450	0.13
OSS1-VNIR		450-1100	1.3
Imaging Spectrometer		380-1000	1.5
pointing laser		650	1
SWIR Imager	Port side	950-1700	N/A

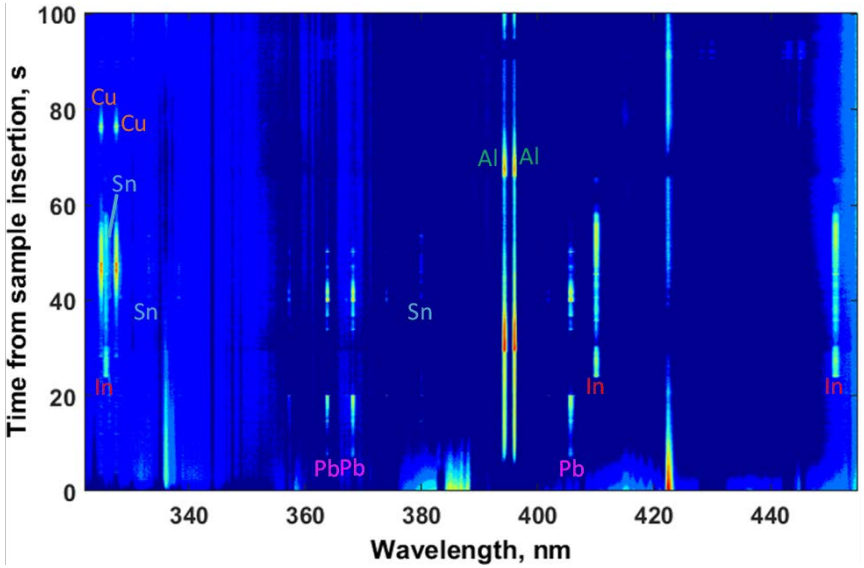


Example Spectral Data
(background removed, log radiance)

Sample U
(Parallel, Low- & Mid-temperature)

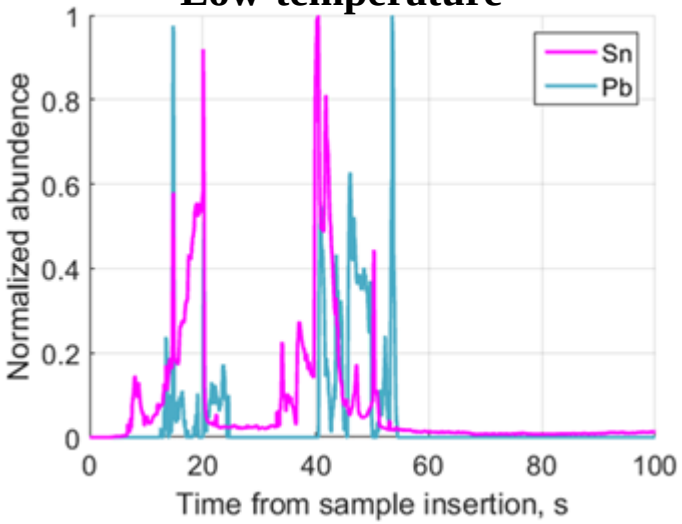


Sample G
(Spiral, Low- & Mid-temperature)

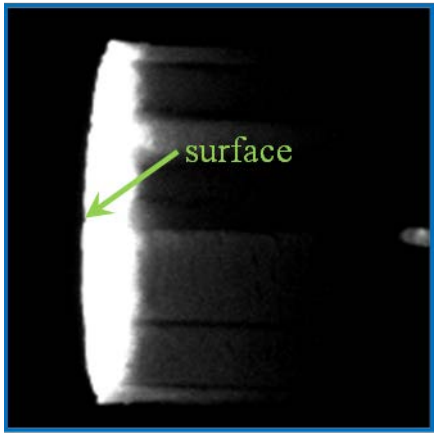


Spectral signal and recession (Sample G)

Low-temperature

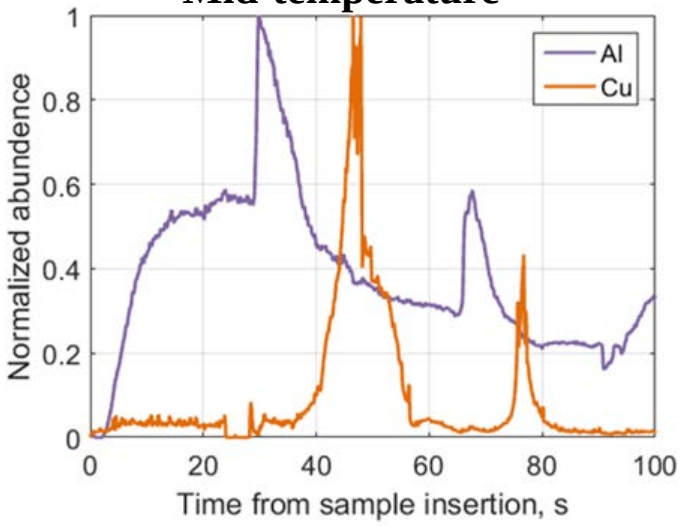


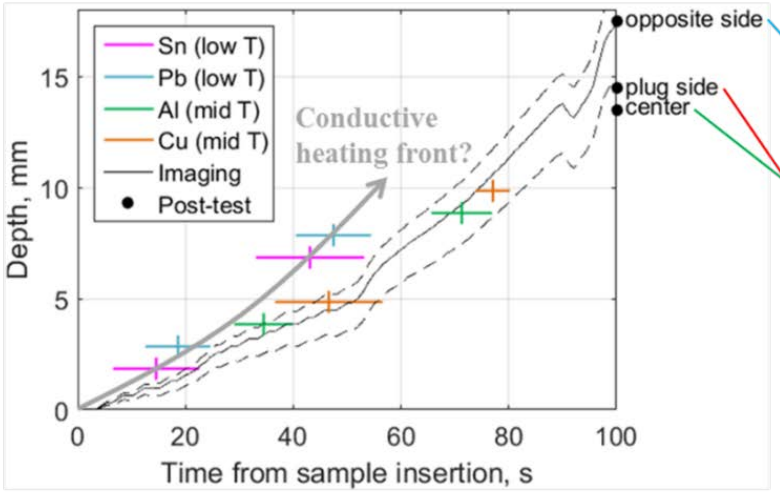
SWIR (thermal emission)

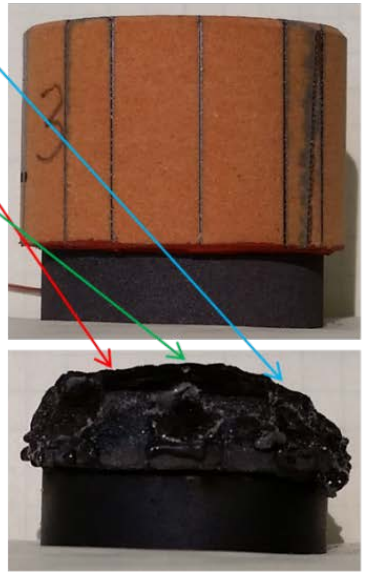


- Spiral plug yields clear ON/OFF signals
- Side view SWIR imagery used to measure recession
- Low-temperature metal signals detected before recession reaches location
- Mid-temperature metal signals consistent with recession

Mid-temperature



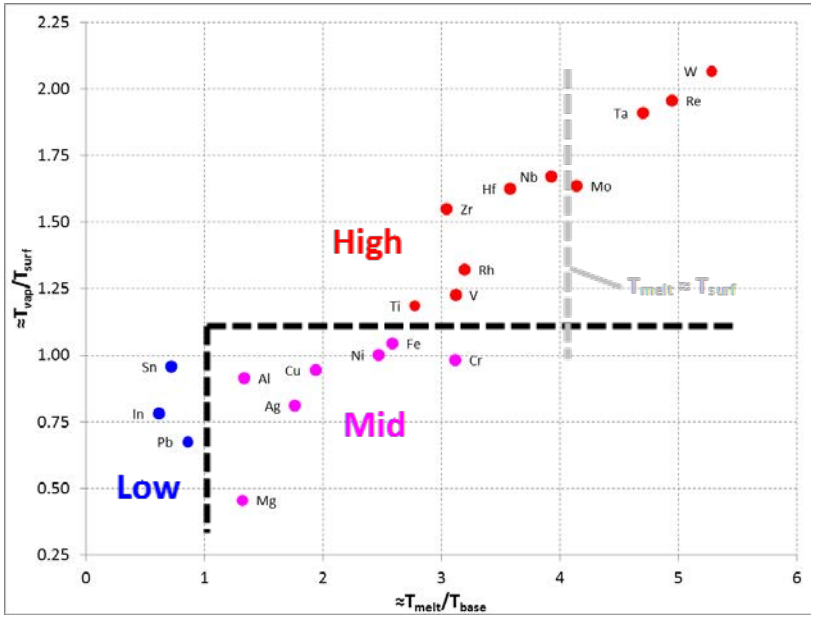


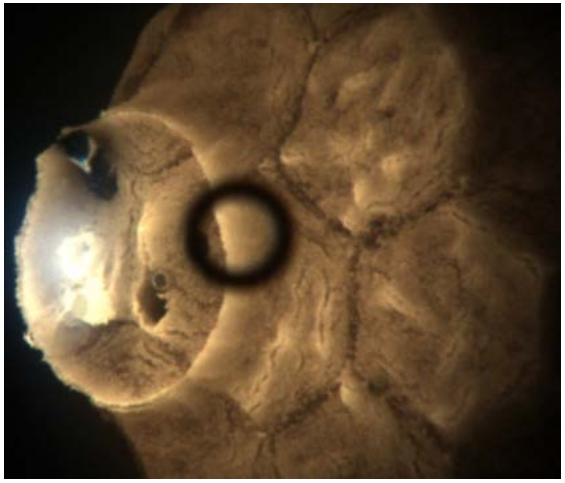


*Al is in honeycomb, Cu is in arc-jet nozzle

HYMETS Testing – Conclusions

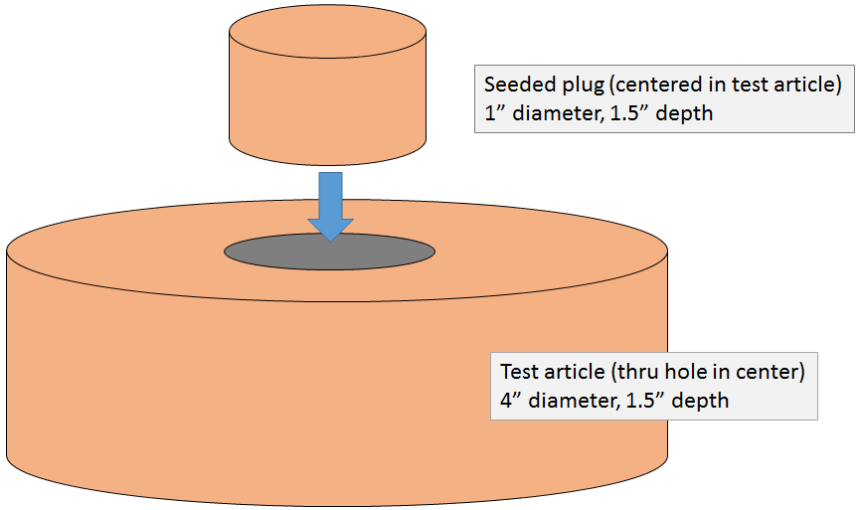
- **Clear connection between melting / vaporization phenomenology and observed signals**
  - Mid-temperature metals generate the most clear and easy to interpret signals
    - Vaporize at or below the surface temperature
    - Signal timing consistent with recession to tracer location
  - Low-temperature metals not of interest for recession indicator
    - Melt and vaporize before recession reaches tracer depth
    - May be useful to indicate heat soak or pyrolysis
  - High-temperature metals not of interest for recession indicator
    - Surface temperature below the vaporization temperature
    - Persist on surface and slowly vaporize
    - Low signal level for extended period of time
  - Phenomenology verified using RGB video
    - See paper for details
- **Spiral configuration preferred**
  - Clear start/end of signal as recession passes tracer location; signal in between more complicated
  - Multiple measurements possible per tracer metal



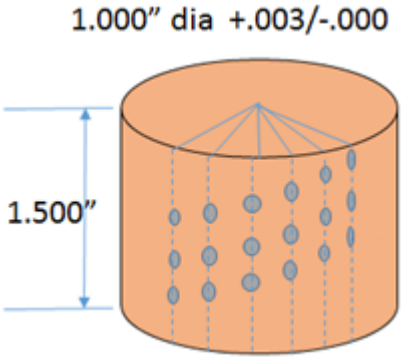


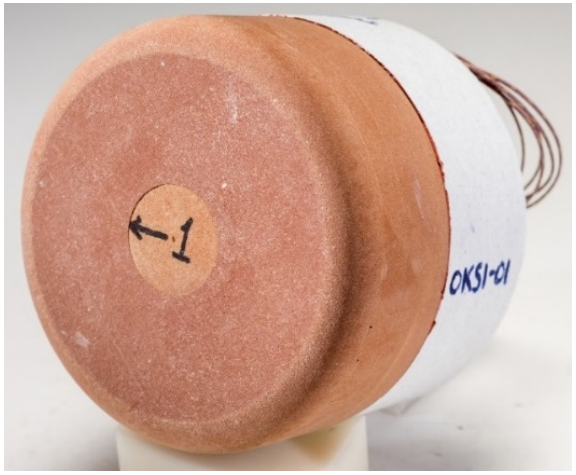
AHF test articles and setup

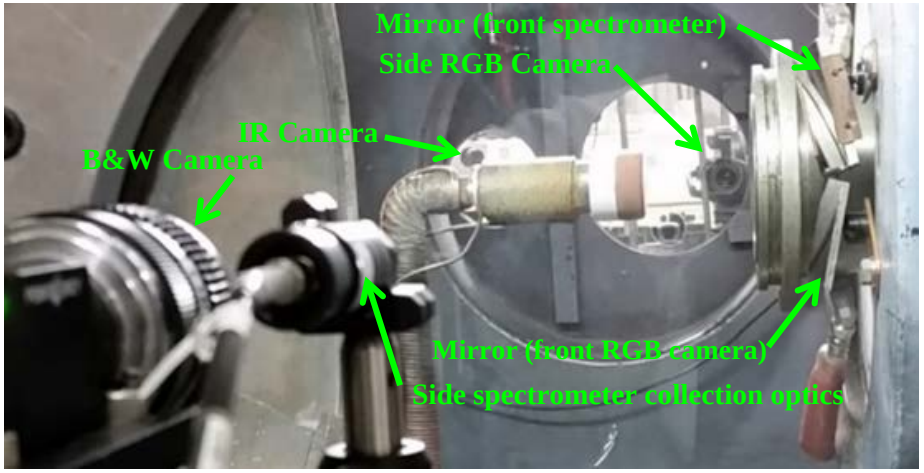
- Focus on spiral configuration
- Attempt resolution down to ½ wire diameter
- Determine if higher dynamic pressure alters performance for high-temperature metals



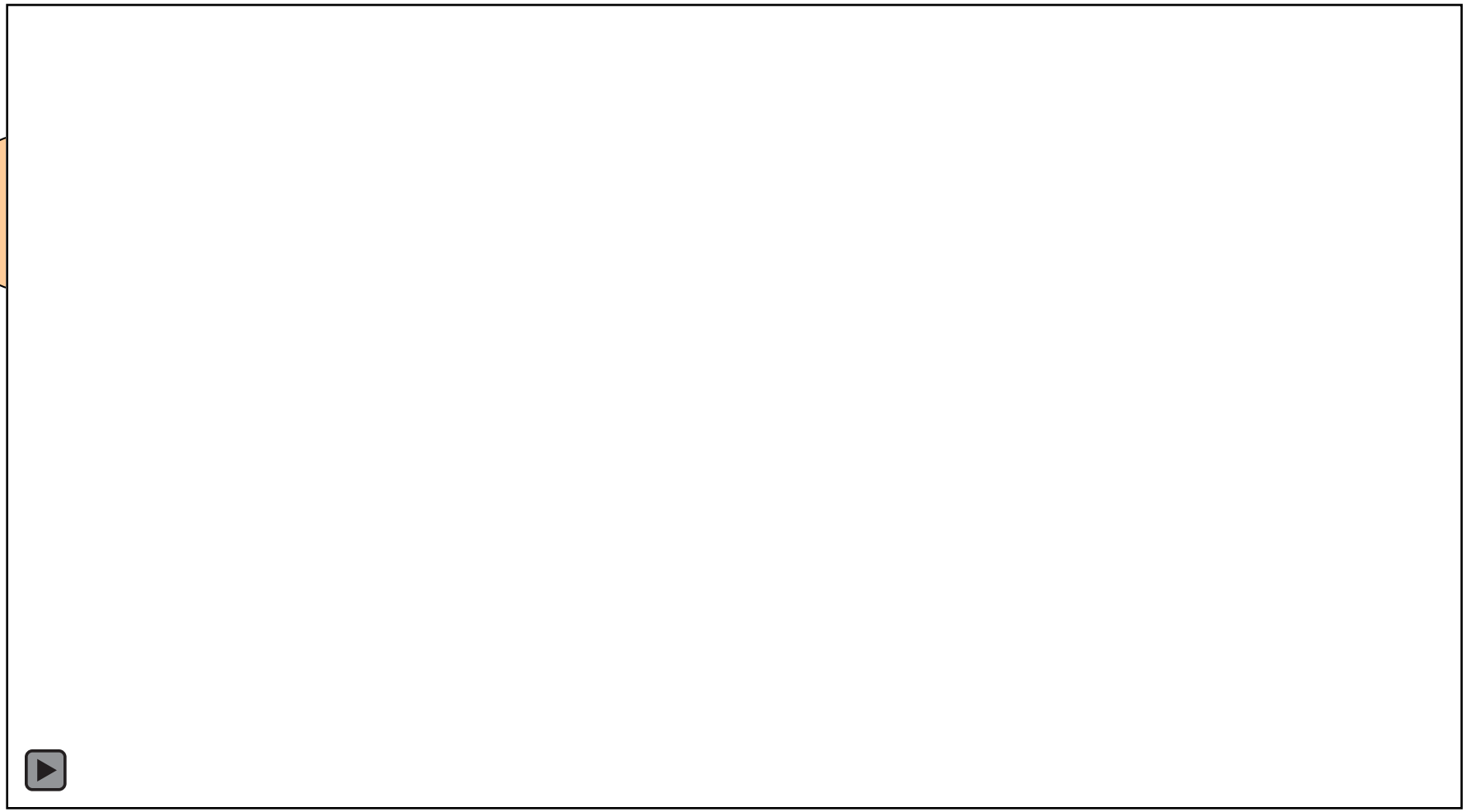
Mid-temperature metals
TA #1 & #2
Ag, Ni, Cu, Fe, Al, Chromel-C
High-temperature metals
TA #3 & #4
Nb, V, Zr, Hf, Mo, Ti







Test Article 2 – Mid-temperature metals data summary



AHF Testing – Conclusions

- **Verified that tracer metals behave consistently across facilities and conditions**
  - Phenomenology and spectral signals are consistent with interpretation developed based on HYMETS data
- **Mid-temperature metals remain the best candidates for use as tracers**
  - Focus further efforts on detailed characterizing of specific metals, including expanded set of metals, specifically in this temperature range
- **Identified local recession variation as potential limiting factor on spatial resolution and depth resolution**
  - Require input from models or experiments on typical degree of local recession variation
- **Plug configuration that produces short, distinct detection pulses**
  - Spiral
  - Thinner wires

Next steps: Plug design and validation, observation platforms

- **Additional parametric testing at HYMETS**
  - Expanded set of mid-temperature metals
  - Spiral plug detailed design (wire diameters, spacing, etc.)
  - Repeated tests to quantify accuracy and precision
- **Further modeling**
  - Expected absolute radiance of spectral features
  - Minimum detectable signal above expected background
- **Final plug design and tracer metal selections**
- **Verification testing at AHF or similar facility**
- **Targeting integration into EM-2 test flight**
- **Observation platforms and instruments**
  - SCIFLI Airborne Multispectral Imager (SAMI)
  - High-fidelity Automated Airborne Reconfigurable Tracking System (HAARTS)
  - Imaging spectrometer

Possible Platforms and Instruments

- **SCIFLI Airborne Multispectral Imager (SAMI)**
  - OKSI is building a telescope and airborne tracking system for NASA Scientifically Calibrated Inflight Imagery program
  - Designed for NASA-owned HU-25 or Gulfstream III
  - Performance capabilities
    - Better than 5 urad (1 arc sec) pointing stability
    - Reconfigurable (swap-out filters, cameras, spectrometers, optics)
    - Planned configuration: 10” aperture telescope, 2m focal length (f/8), UV-VIS spectrometer, NIR, SWIR, MWIR cameras, Field-of-Regard +/-17°

- **High-fidelity Automated Airborne Reconfigurable Tracking System (HAARTS)**
  - OKSI is the prime contractor building a telescope and stabilized tracking system for the Air Force
  - Designed for a high-altitude, long endurance UAV
  - Part of the UAV-Based Range presented in the previous talk by Thomas Horvath

- **Imaging spectrometer**
  - Spatial resolution of recession provided by using different tracer metals at different locations
    - Do not need spatially resolved spectrometer data
  - For some observations (i.e., daytime), signal to background ratio must be considered
    - Large FOV = high background
    - Small FOV = challenge for tracking
  - Solution: use an imaging spectrometer
    - OKSI has built >10 custom 4DIS (4-Dimensional Imaging Spectrometer) for various customers/applications