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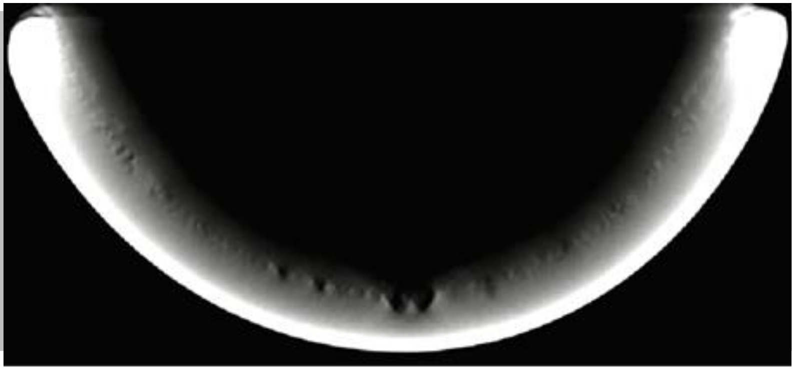

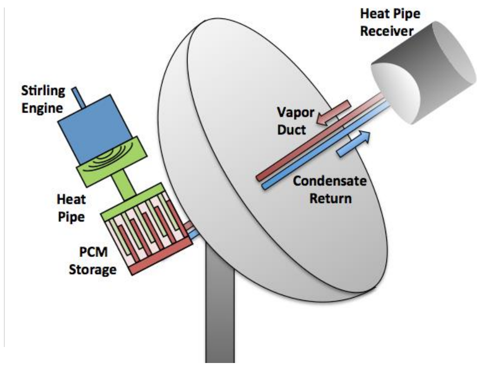

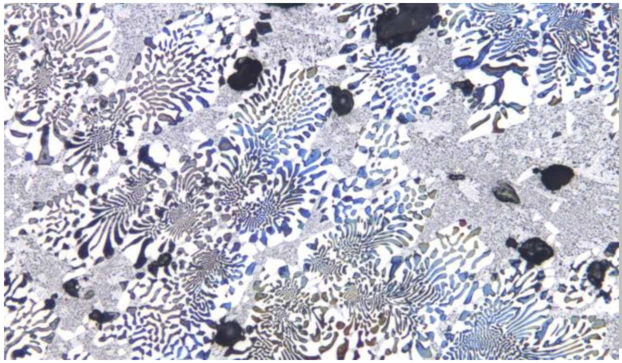

Materials compatibility in Dish-Stirling Solar Generators using Cu-Si-Mg eutectic for latent heat storage

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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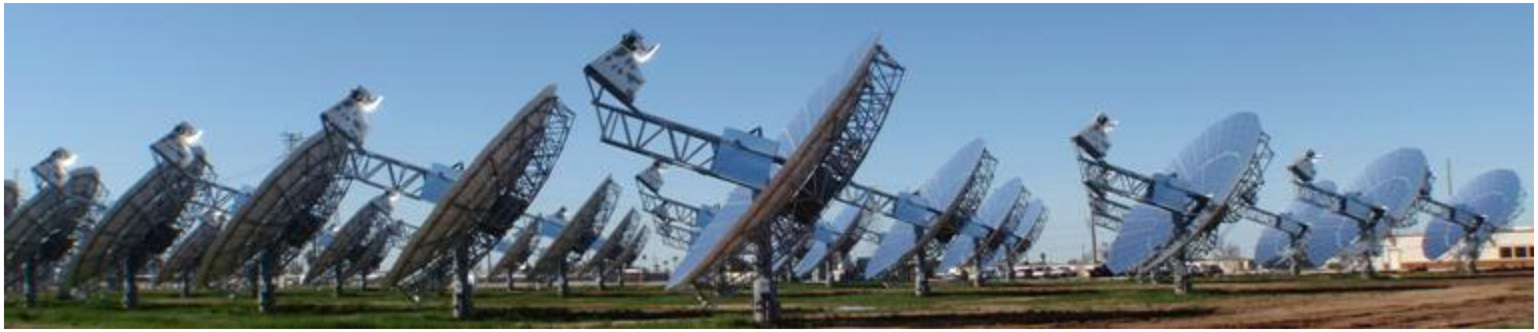
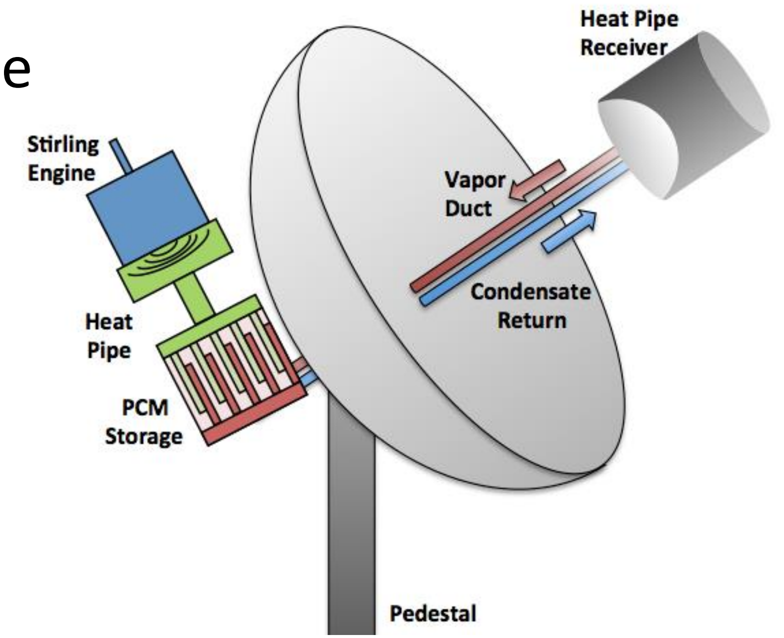
Dish Stirling Technology

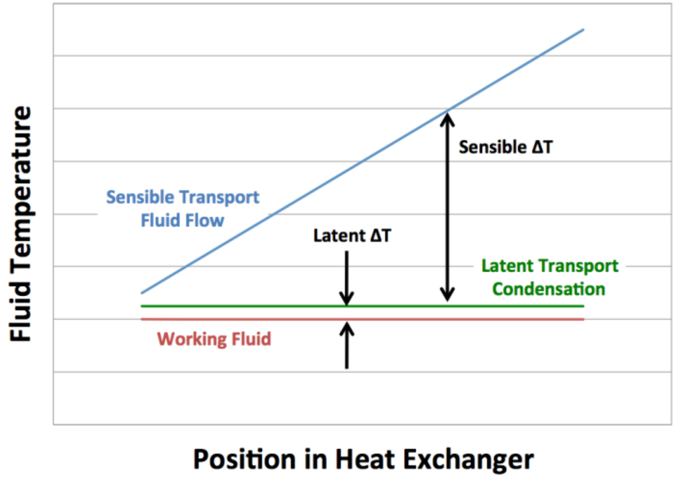
- High performance systems
  - Over 31% sunlight to grid efficiency
  - Over 26% annual efficiency
  - High temperature
  - High concentration
- Typically 3-30kWe
  - Potentially off-grid
  - Large power parks proposed for low cost
- Best technology to meet SunShot goal
  - $0.06/kWh attainable
    - Deployment
    - Supply chain development
    - Design for manufacture
- <u>Needs storage</u>
  - Match demand curves
  - Utilities/PUC's need to "value" evening generation
  - Differentiation from PV



Dish Storage Concept

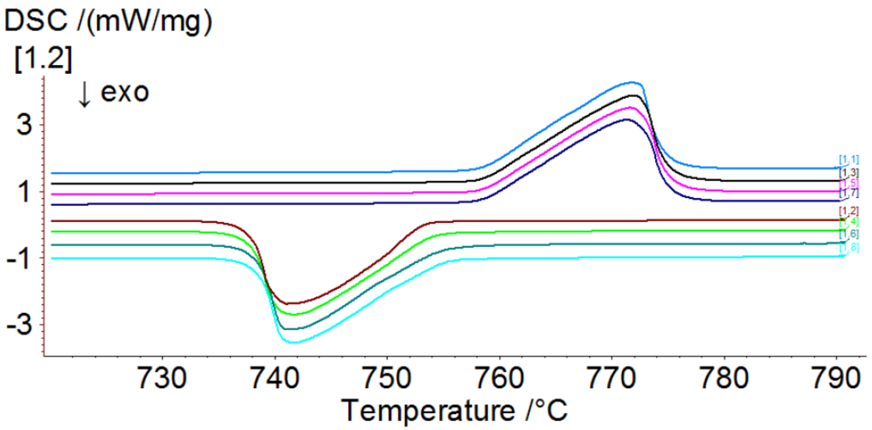
- Phase Change Material (PCM) storage
  - Heat pipe transport to storage and to engine
  - Latent transport and storage ideal for Stirling input
  - Condensate return via pump
- Rear dish mount
  - Rebalances system
  - Allows heavy storage
  - Closes pedestal gap
- Isothermal input to engine
  - Sensible heat input results in large exergy loss
  - Latent input matches engine needs

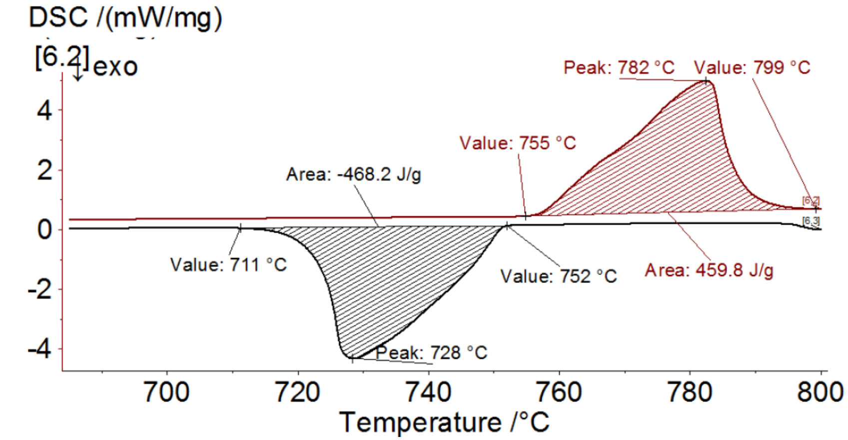


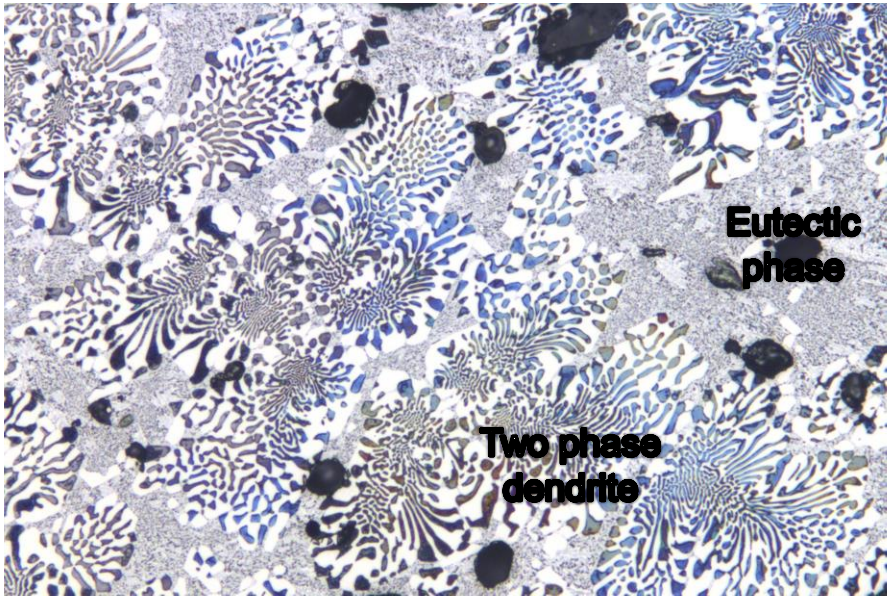


Storage Material

- Cu-25.3Si-21.1Mg alloy:
  - Heat of melting 462J/g
  - Onset of melting at 755C
  - Fully melted at 800C
  - Repeatable thermal cycling
  - Complex microstructure







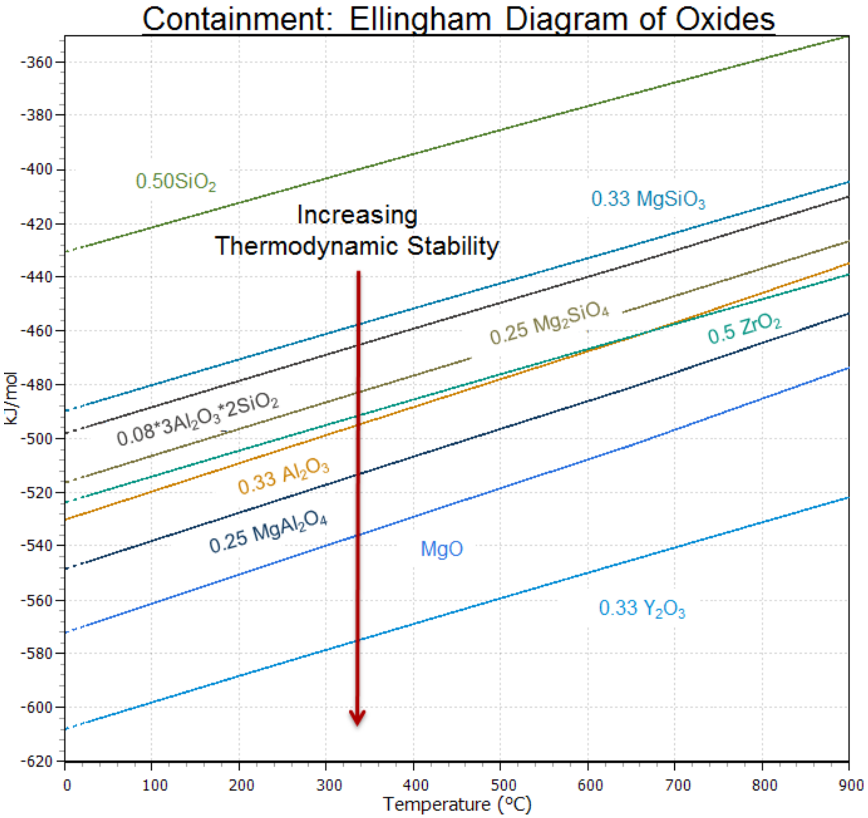
Optical Microscopy of alloy

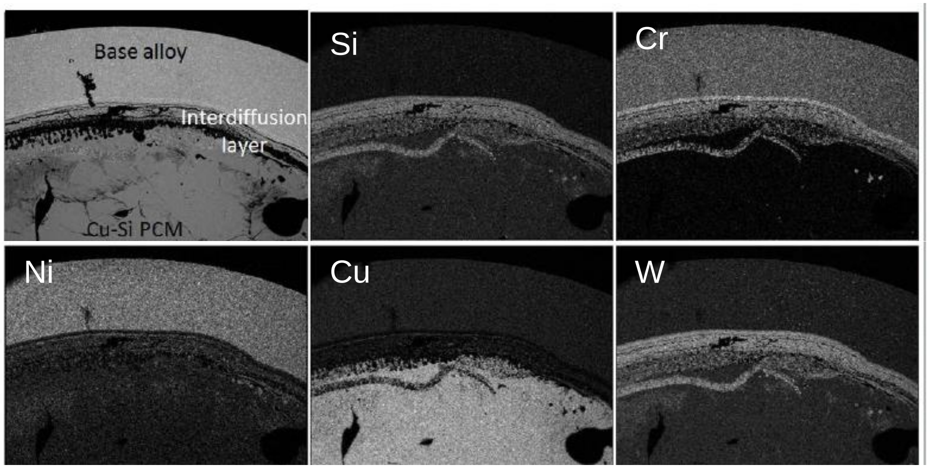

As-cast ingot

Containment Materials

Screening Tests

- Alloying is rapid
- Nickel dissolved into solution
- 30% wall thickness lost in 6.5 days





Need to choose materials based on lowest energy of formation to prevent material degradation.

Tests using best available thermodynamically compatible materials were pursued.

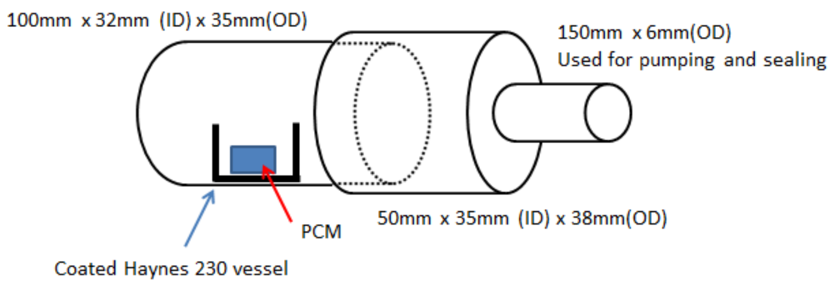
Methods and Test Matrix

Test 1 evaluated most promising thermodynamic materials

Test 2 assessed kinetics margin for best performers

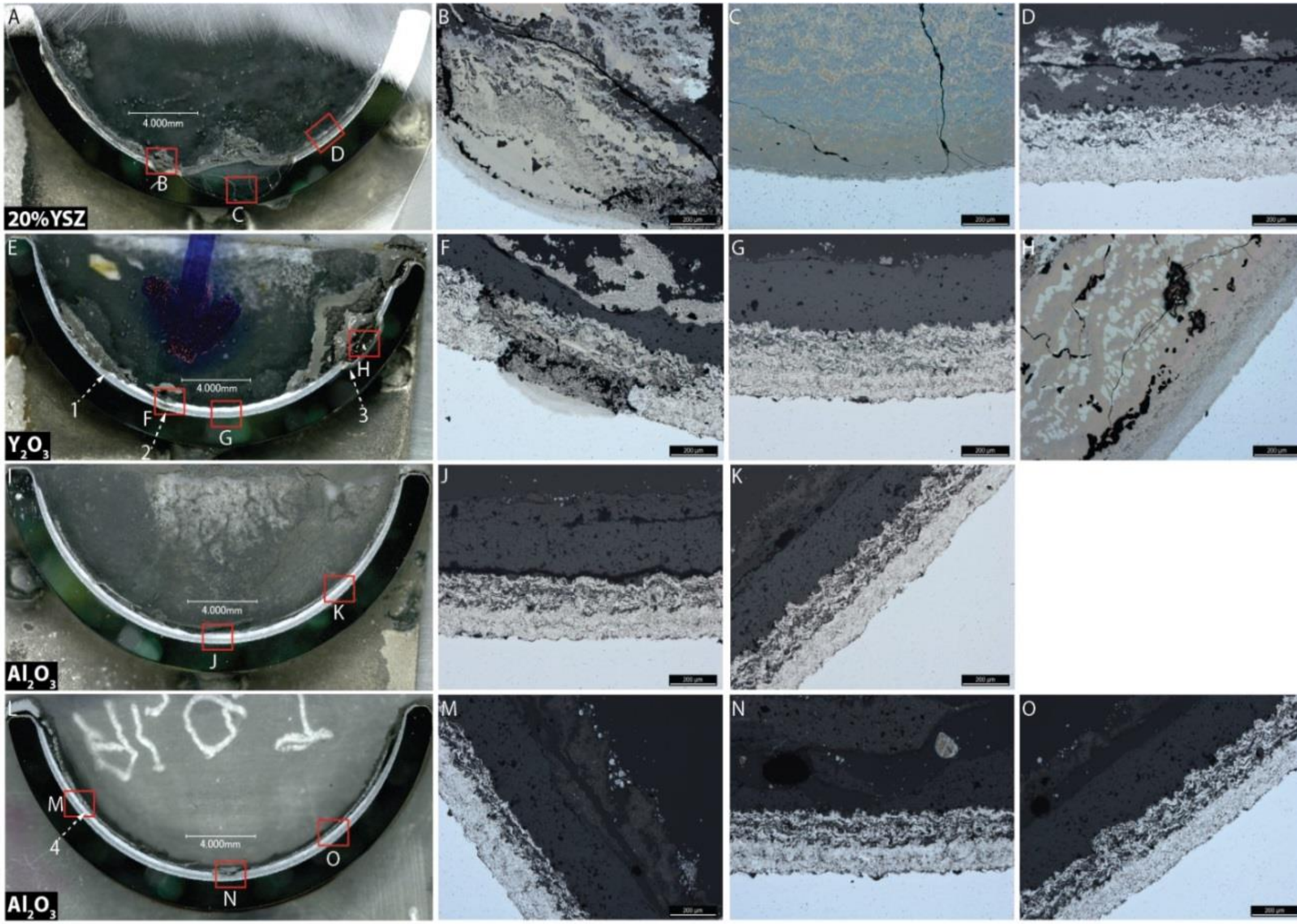
Test 3 Modified longer term exposure with edge seal

Test	Temperature [C]	Materials
1	820	20% YSZ, Y_2O_3, Al_2O_3
2	950	Al_2O_3, $MgAl_2O_4$
3	820	Al_2O_3, $MgAl_2O_4$



1. Samples are loaded with PCM
2. Pumped under a hard vacuum (10^{-7} Torr)
3. Backfilled to 200 Torr with Argon
4. Thermal exposure
5. Opened in glovebox
6. Encapsulated within resin to prevent sample hydration and exfoliation

820°C, 500 hour results



20% YSZ analysis:

Large Failures in 20% YSZ coating

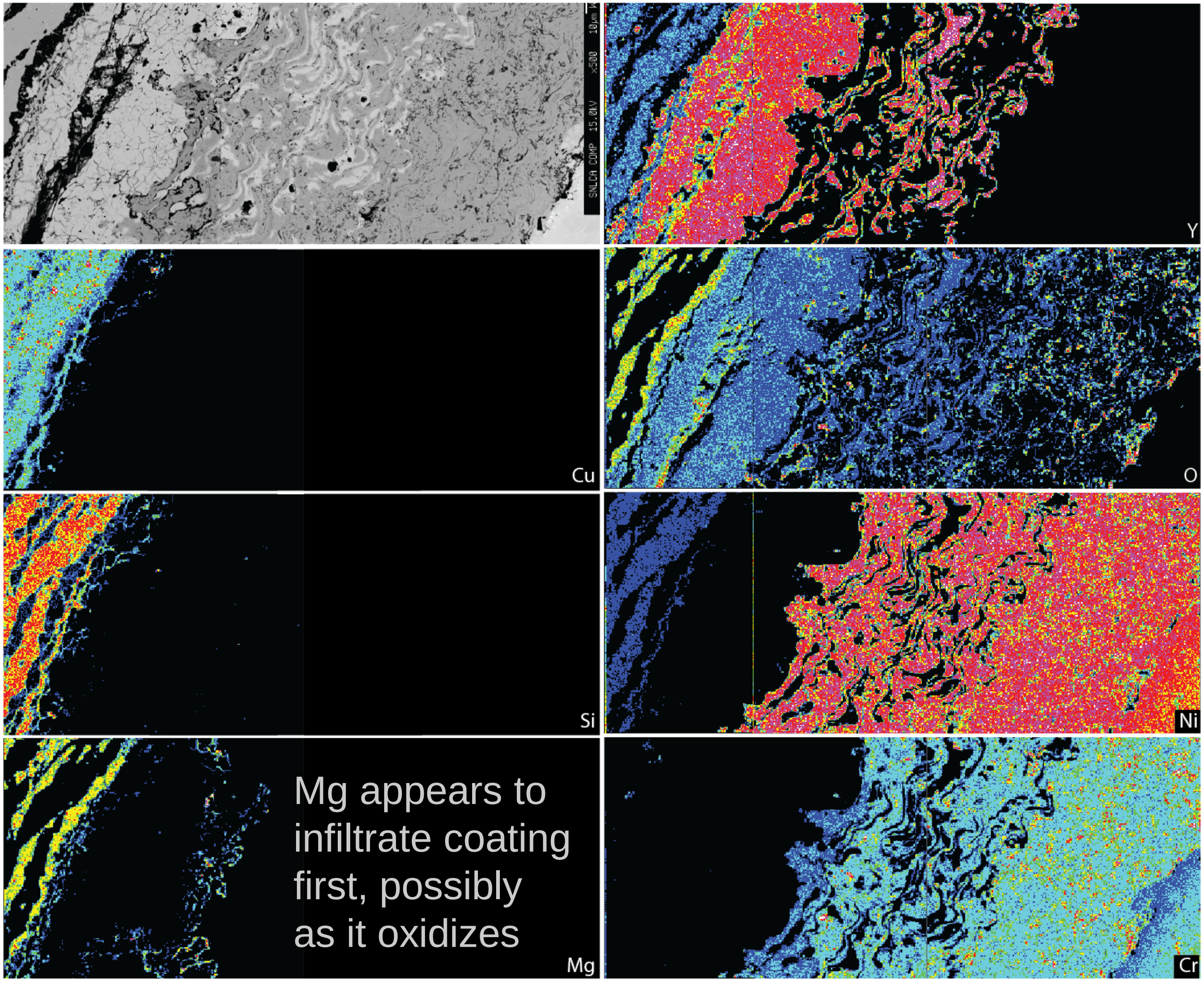
Y_2O_3 analysis:

Varying failure sizes were over the Y_2O_3

Al_2O_3 analysis:

No failures in Al_2O_3 after investigating several locations

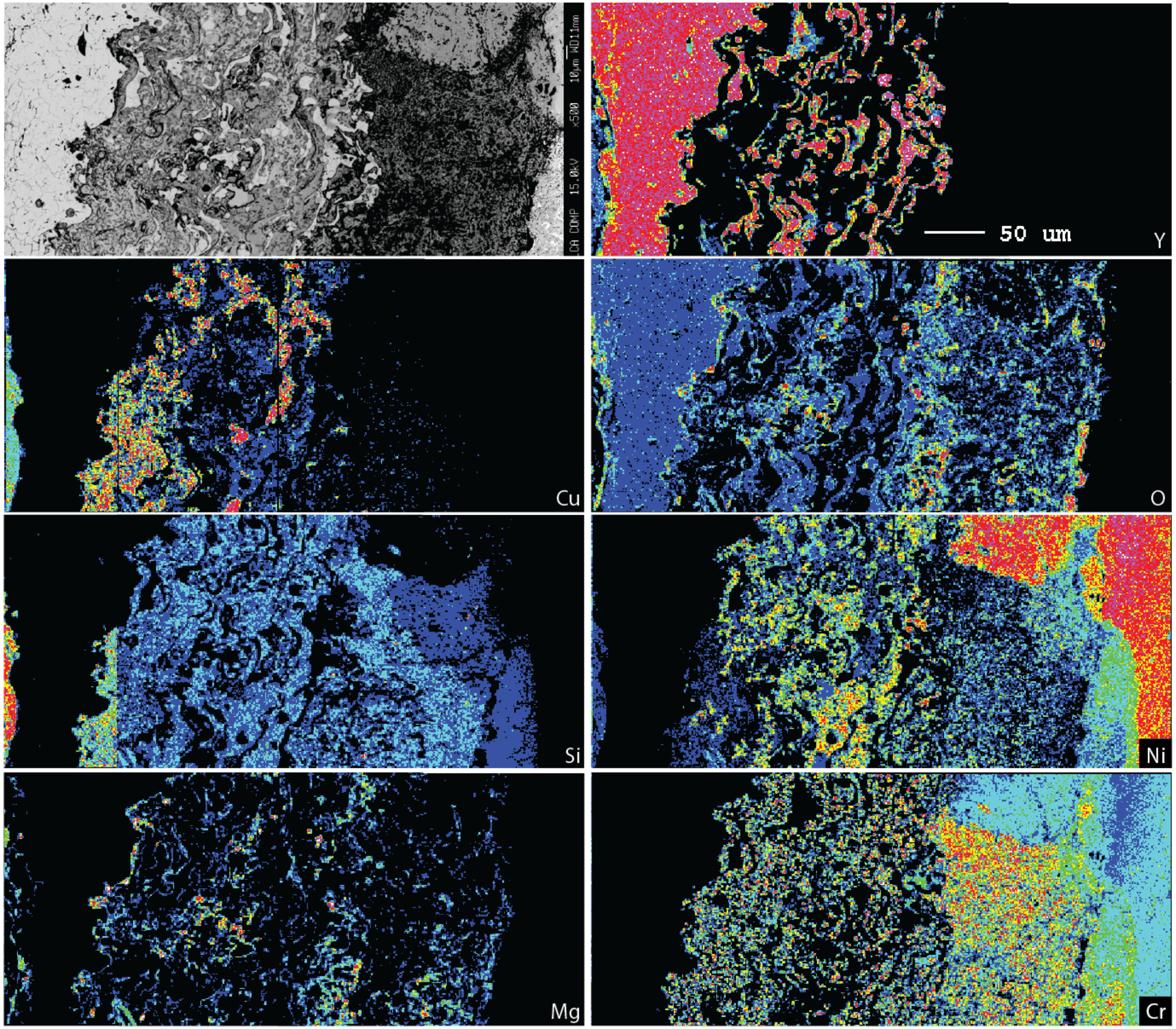
Y_2O_3 Area 1: Beginning of interaction



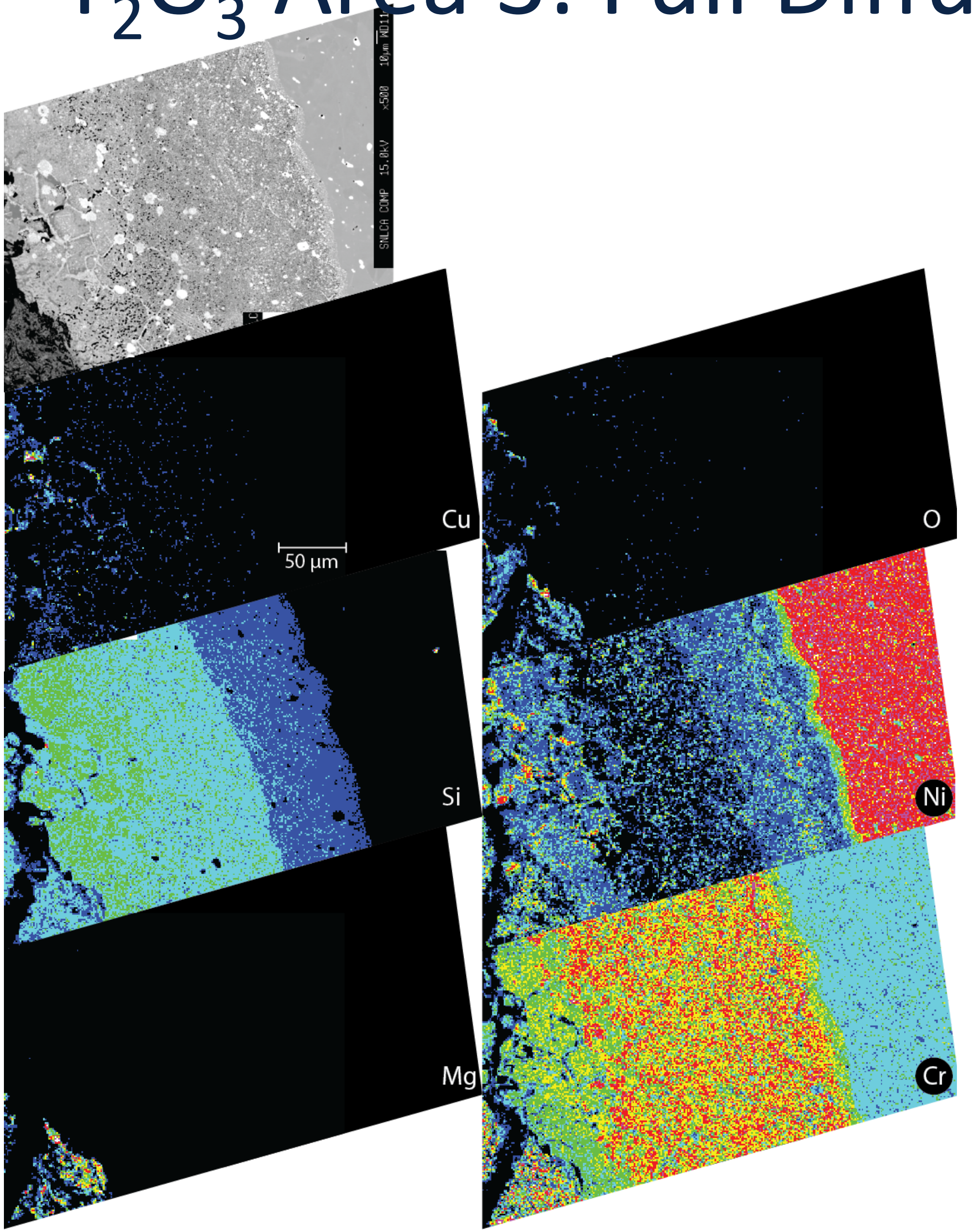
Coating structure = 80Ni/20Cr + graded 80Ni/20Cr & Y2O3 + Y2O3

Y_2O_3 Area 2: Early Diffusion Layer

In areas of further attack, Si more invasive than Mg



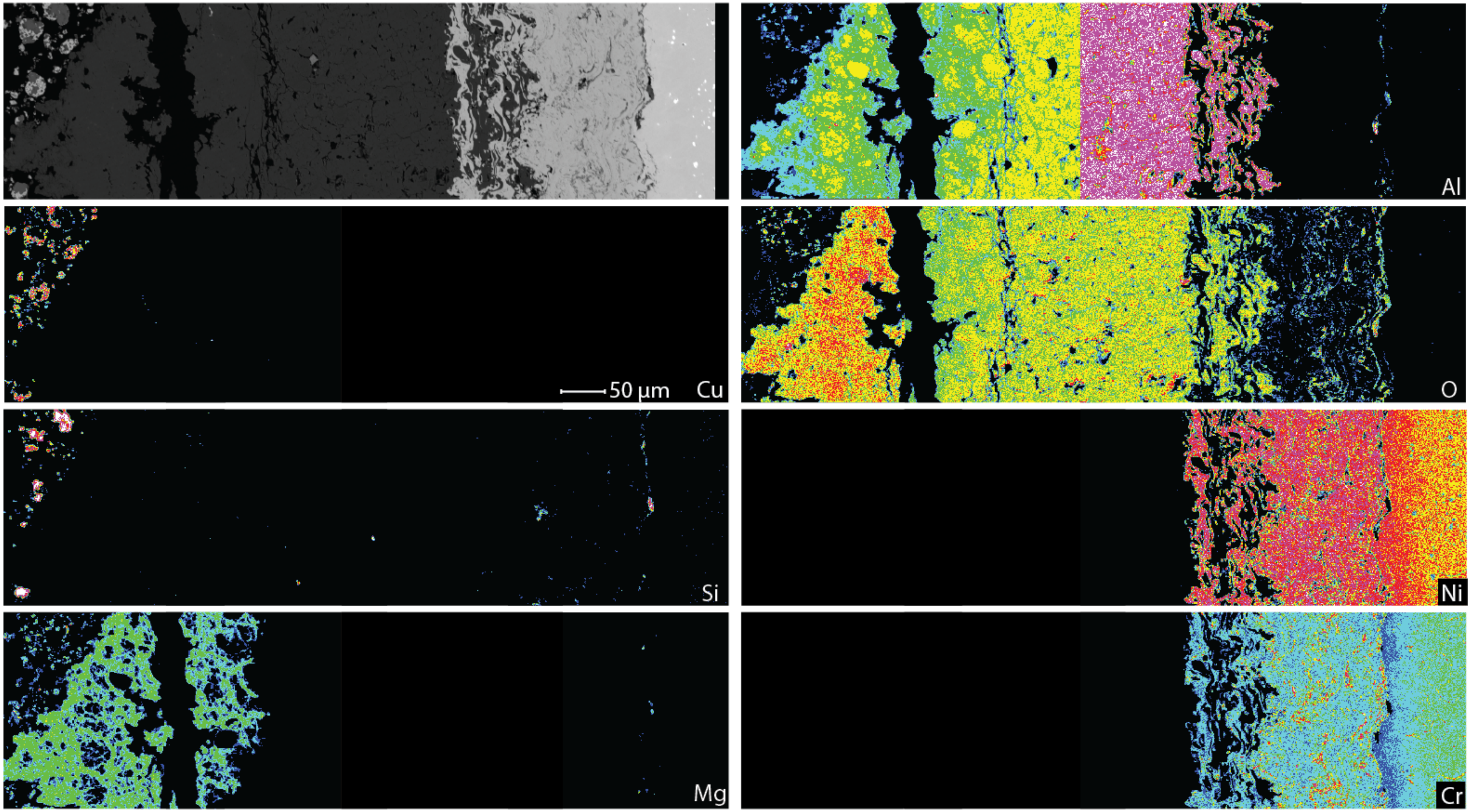
Y_2O_3 Area 3: Full Diffusion Layer



Tentative Conclusion:
Mg infiltrates Y_2O_3 as it oxidizes and leaves easy pathway for Si infiltration

- Y2O3 + 3Mg → 3MgO + 2Y will result in equilibrium amount of MgO since low driving force in either direction
- Conversion of Y2O3 to MgO results in open porosity for Si easily infiltrate and attack Haynes 230

Surface Film on Al_2O_3 Coating



Mg reacts with Al_2O_3 to form compound oxide, most likely $MgAl_2O_4$
$MgAl_2O_4$ likely behaves as a kinetic barrier that slows elemental diffusion

Finding Local Failures Reliably

- Yttria yielded failures, but none for Alumina:
  - Unexpected: yttria has a higher thermodynamic stability
  - Surface view did not indicate any failure
  - Cross section did find a few failures
    - Failure identification is critical!
    - How to find internal defects?
      - Need mapping of where to section
  - Nondestructive Methods:
    - There are many that could be pursued
    - We chose micro computed tomography (µCT)

Micro Computed Tomography

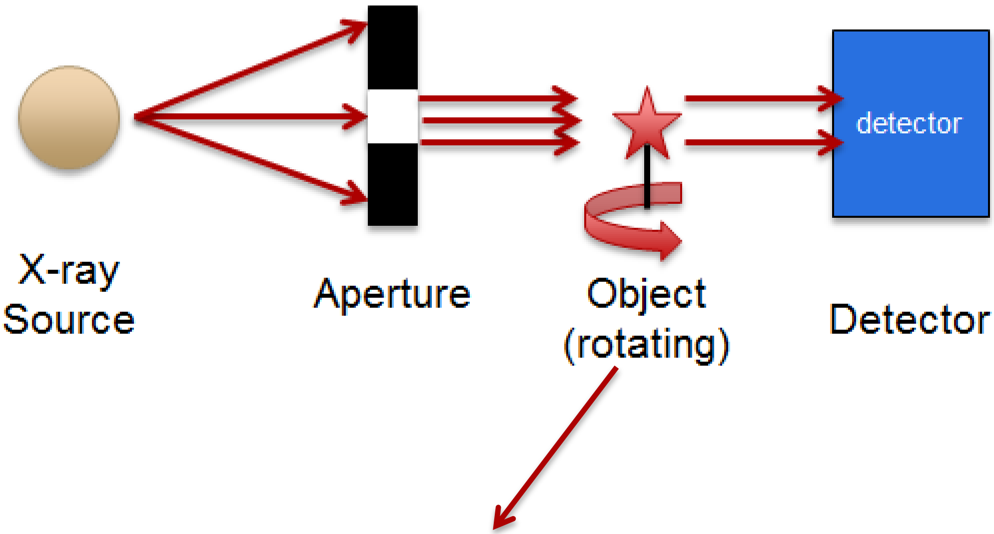
Radiography is used heavily especially in biological applications

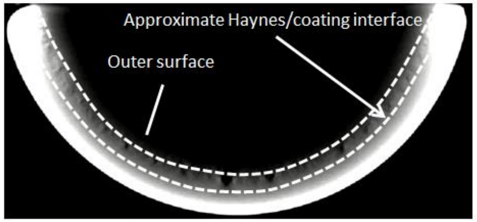
Works well for composite materials with different densities

An entire sample can be evaluated for any signs/symptoms of failure

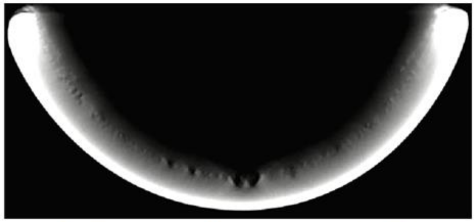
Defects, if found, are noted for location

Traditional microscopy is then performed

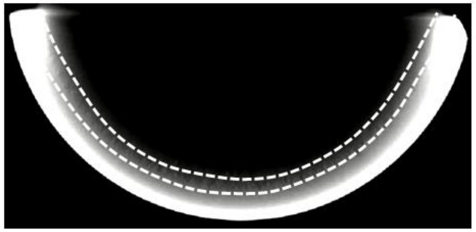




Al_2O_3 – typical CT image

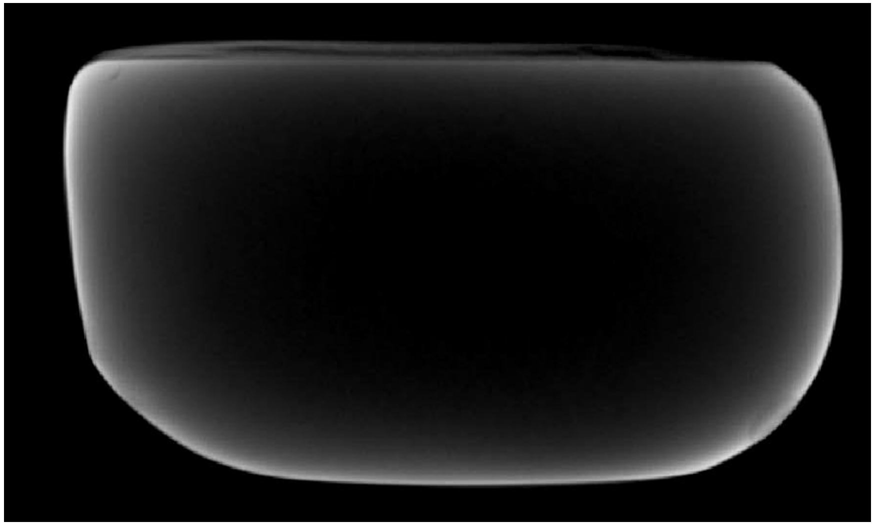


Al_2O_3 – image of cross section location

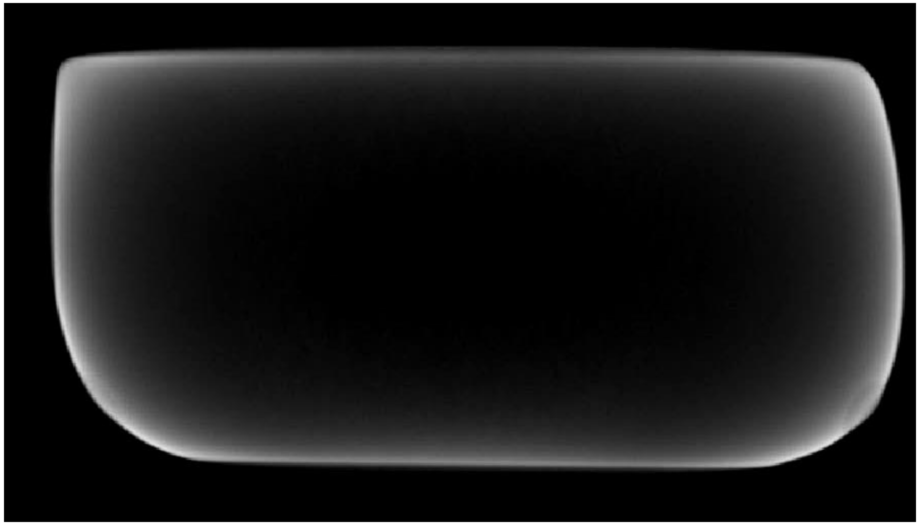


$MgAl_2O_4$ – typical CT image

3D Scans after 500 hours



Alumina Scan



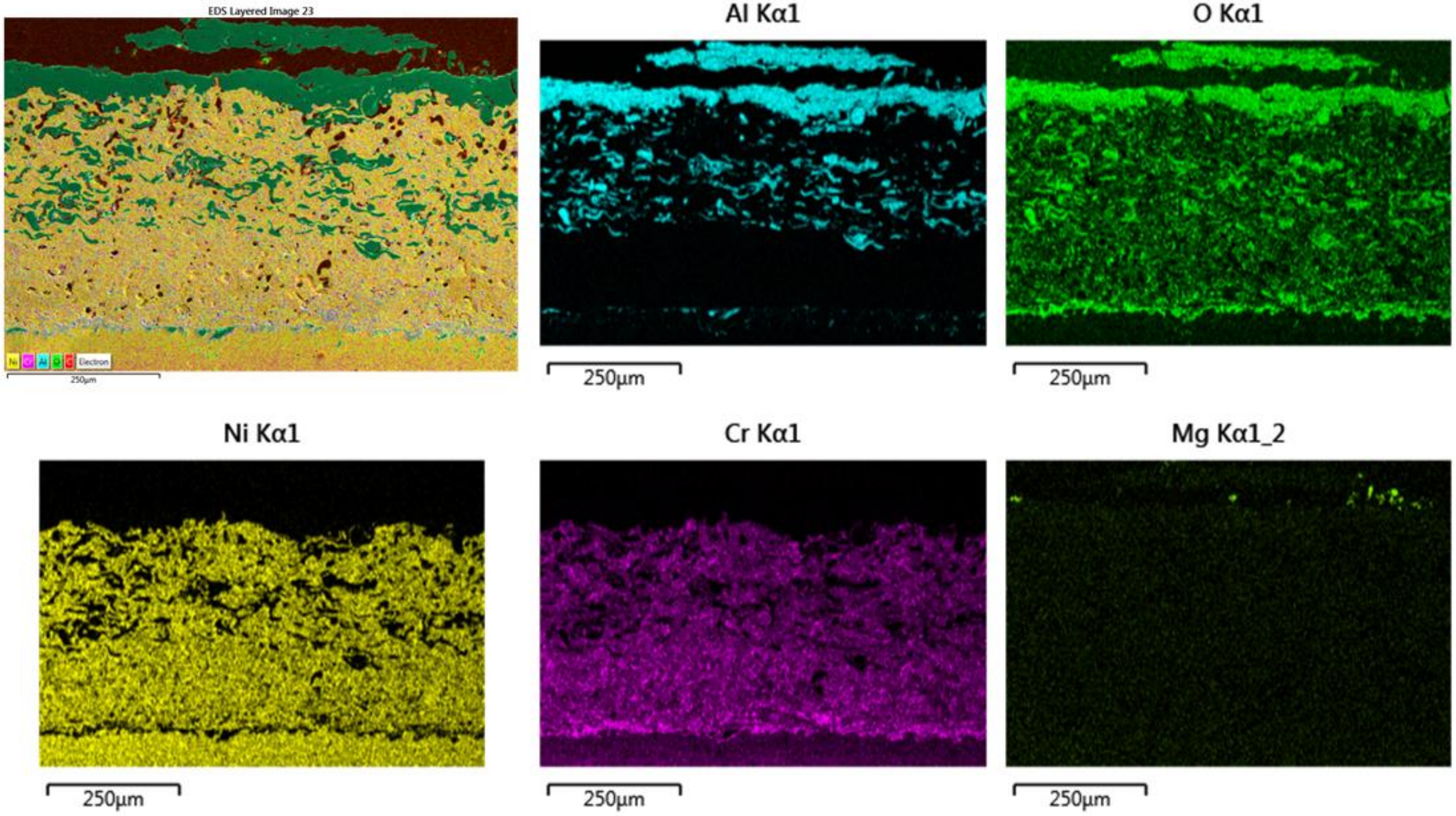
Spinel Scan

Al_2O_3 – image of cross section location

No obvious defects were observed on spinel samples

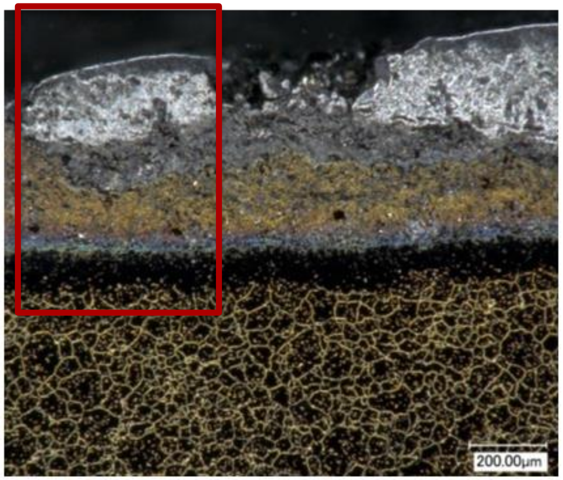
Some areas of interest were observed on the alumina

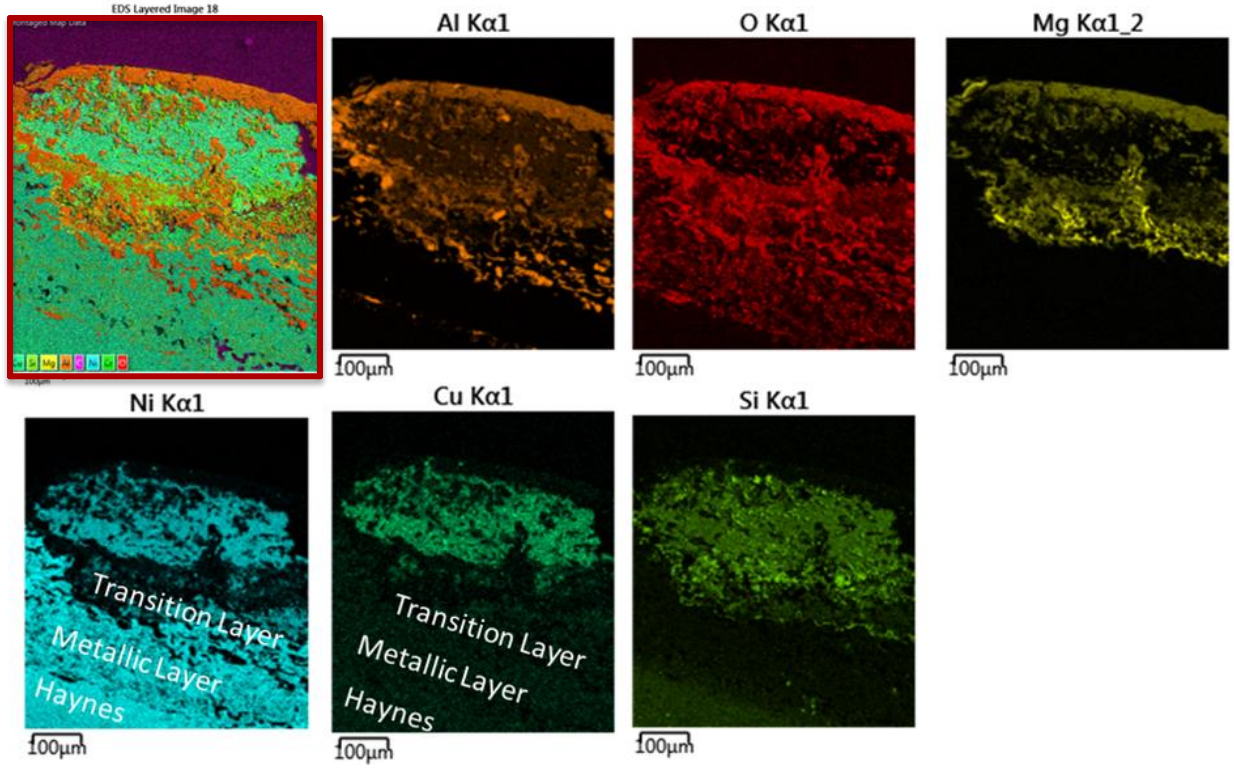
Alumina microscopy



- Pure alumina outer layer were found to be relatively thin
- Low Mg content indicates no PCM contact, therefore thin initial coating
- Transition layer of Ni/Cr was found to have oxygen present (likely chrome oxide)

Localized Attack Observed





Local attack:

- PCM penetration of the alumina resulted in interaction with the transition layer:
  - Mg reaction with alumina – likely forming spinel
  - Cu/Si reaction with Ni (as observed in previous studies)
- Unclear if attack resulted from an initially thin region or acute chemical attack

Conclusions

- Yttria is most thermodynamically stable, but failed due to mechanical stresses induced by equilibrium concentrations of MgO formed in the coating
- Alumina had no through-failures 500 hours at 820C
  - Apparent Mg reaction of the surface Al_2O_3 cause some concern
  - Thickness control may be an issue
- Micro Computed Topography worked well to scan for failures over large areas
- Increasing PCM temperature to 950C appeared to increase the kinetics of reaction
  - Localized failure of the alumina was observed
  - Mg appeared to react forming $MgAl_2O_4$
  - Cu and Si reacted with Ni forming an intermetallic

Questions

Micro CT