INL/CON-22-69130-Revision-0

Sirius Irradiation Experiments and Post-Irradiation Examinations for Nuclear Thermal Propulsion

September 2022

Jason L Schulthess, Philip G Petersen, Xiaofei Pu, Jatuporn Burns, Nathan D Jerred, Austin D Fleming, Aaron E Craft, William C Chuirazzi, Nicolas E Woolstenhulme, Robert C O'Brien

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The Sirius NTP Transient Test Series at TREAT

SIRIUS-1-CAL & SIRIUS-1

- *FY 2019 - FY 2020*
- *INL W-Re-UN Cermet Specimen*
- *Static Capsule*
- *3% H_2 in Ar.*
- *Ramp to 2600-2850 K operating Temperatures (95 K/s).*
- *Isothermal Hold*
- *7 Cycles.*

SIRIUS-2A

- *FY 2020 Q4*
- *NASA Mo-W-UN Cermet Specimen*
- *Static capsule*
- *3% H_2 in Ar.*
- *Ramp to 2250 C Peak Cold end.*

SIRIUS-2B

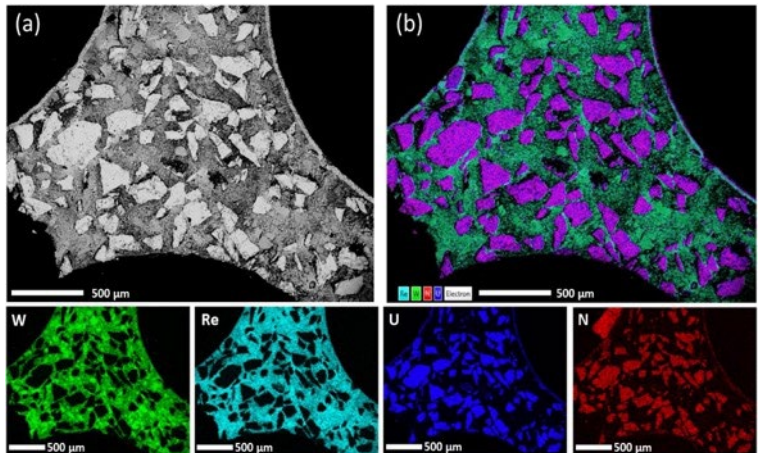
- FY 2021 (Q1/2)
- NASA Mo-W-UN Cermet Specim
- Static Capsule
- 3% H2 in Ar.
- Ramp to 3000 C

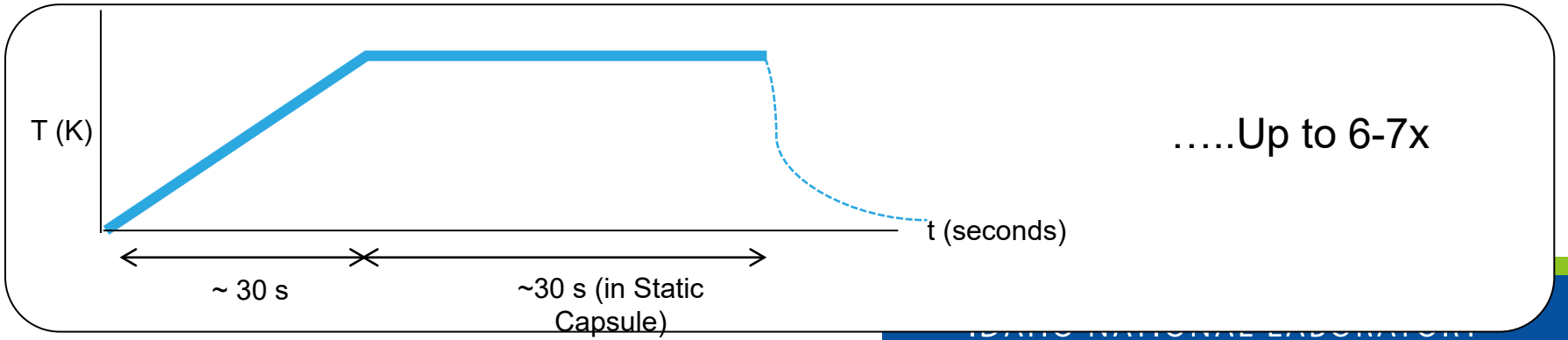
SIRIUS-3

- FY 2022 (Q1)
- 8 inch long specimen
- Static Capsule
- 3% H2 in Ar

SIRIUS 4

- FY 2023 (Q3)
- ~10” Specimen
- Flowing inert gas & H_2 loop.
- Prototypical power ramps to peak operating temperature and power density of 5 MW/L
- BIG BUSTER Required



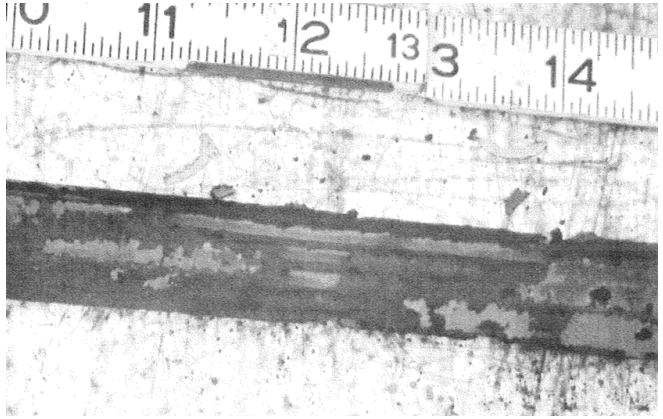


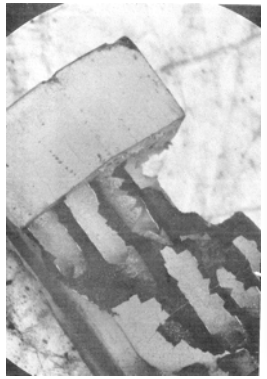
.....Up to 6-7x

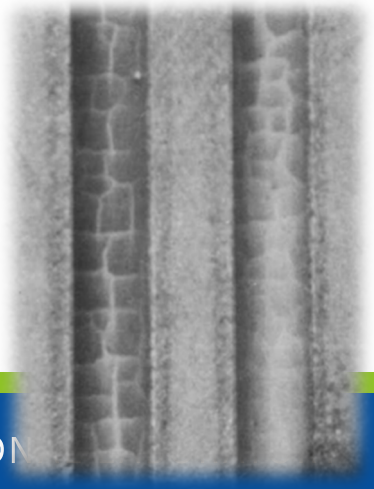
Sirius Test Series Post Irradiation Examination

Goals/Objectives:

- Develop a program library of irradiated specimens to start answering the following questions:
  - Do concept fuel specimens perform/remain integral under repeated thermal cycling?
  - What microstructural property changes are observed due to high temperature transient?
    - Incipient H_2 Interaction observations
    - Stress Crack origins and propagation behavior, if observed.
    - Phase changes (comparative microscopy to fresh fuel).
    - Porosity changes, defect creation and overall swelling.
    - Engineering property changes (requires development).
- Develop fuel qualification data for flight demonstration and eventual engine man-rating.

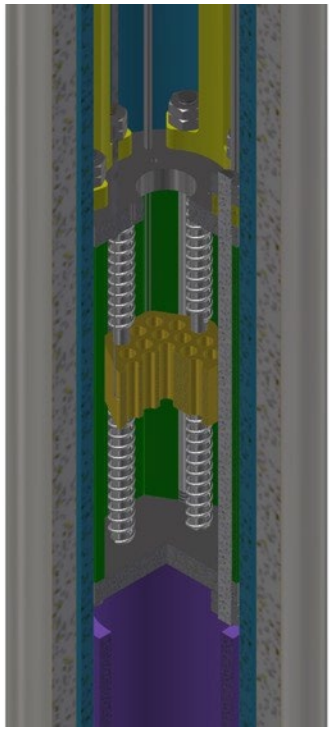


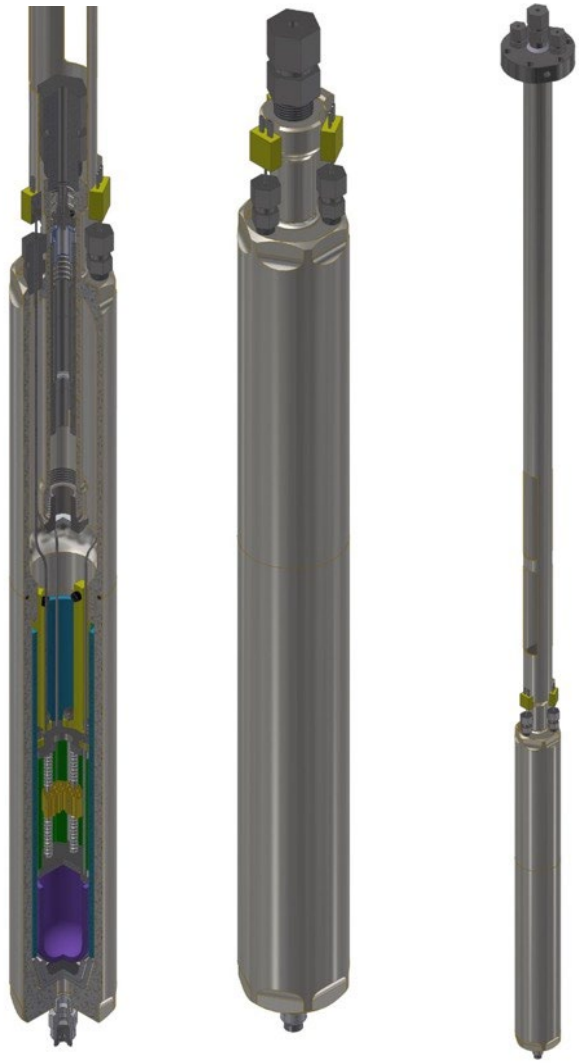




Sirius Capsule Mechanical Design

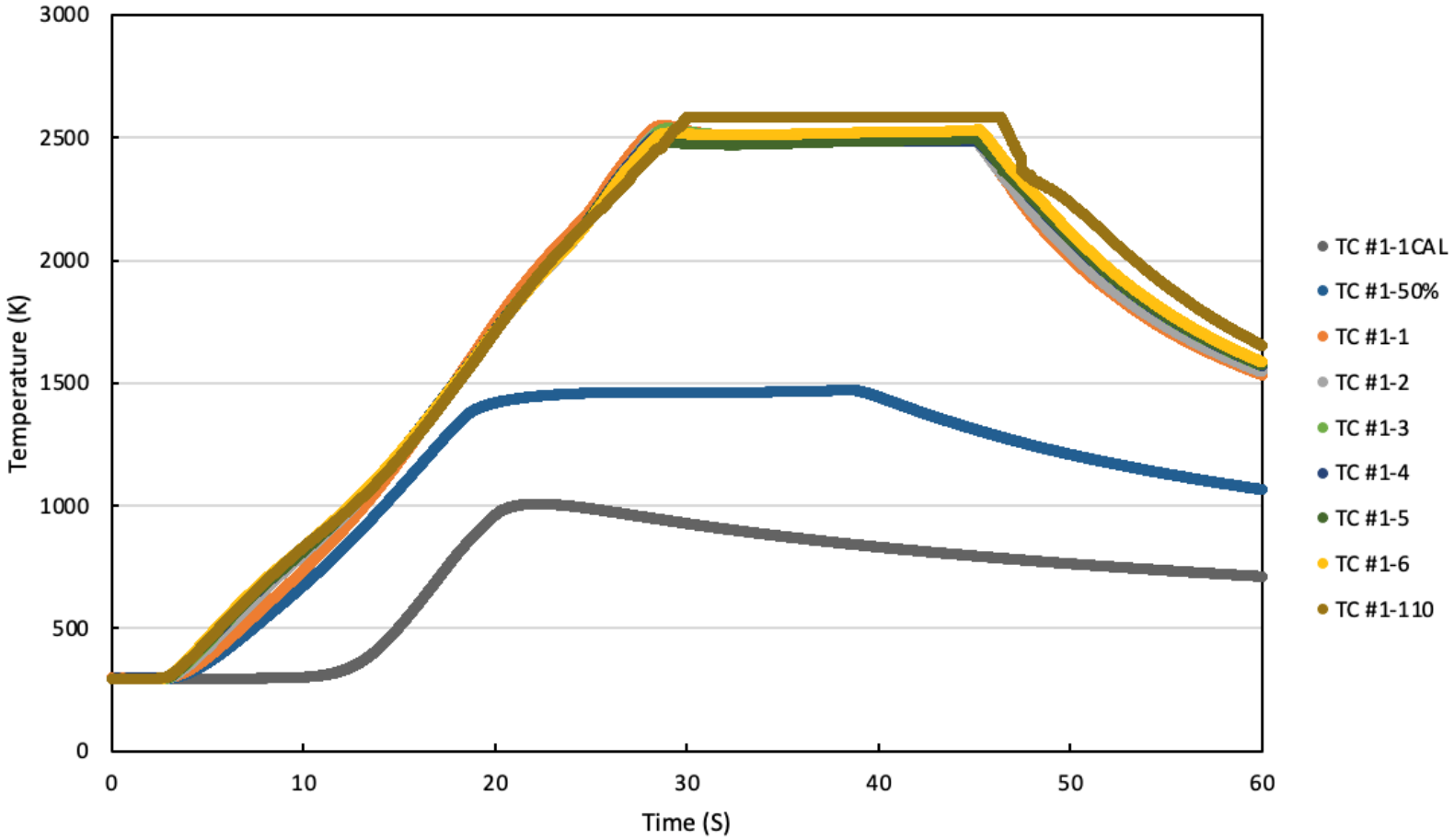
- Fits into BUSTER, single contained config, using MARCH full-slot core
- Capsule design is based on SETH, but heavily modified to enable:
  - Optical access dry well for pyrometry
  - Layout for higher temperature TC types
  - Adapted refractory specimen holder
- Fill gas will be 3% H2 with 97% Ar “safegas” blend, starting room temperature pressure of 2 atm
- Pressurization through check valve, backed up by pipe thread plug (same approach as MARCH-SERTTA)
  - Initial specimen loading and capsule closure in glovebox





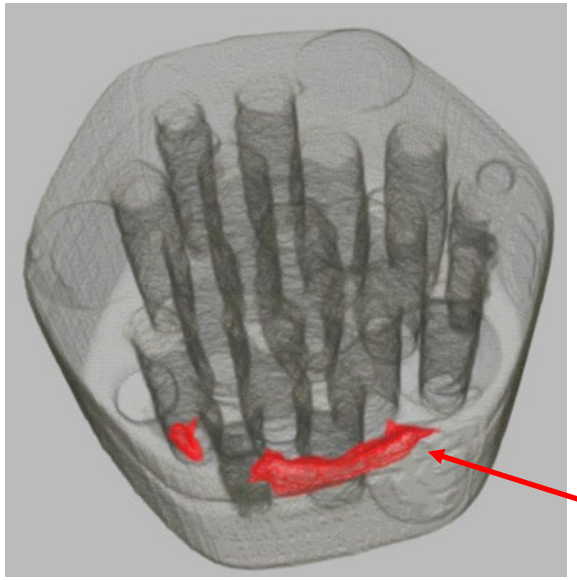
Sirius-1 In-Situ Temperature

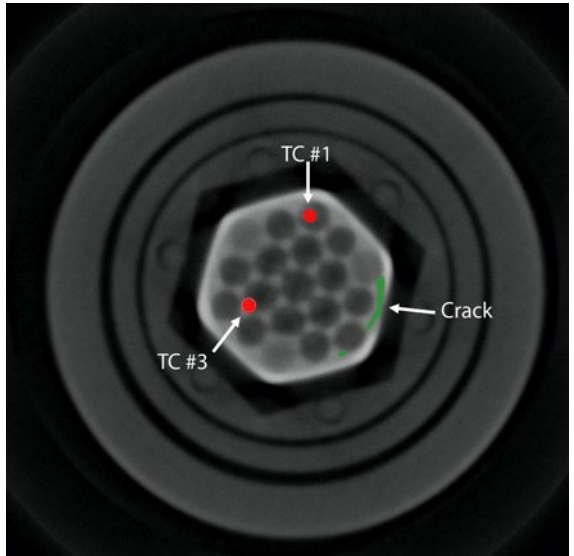
- In-situ temperature data from thermocouple attached to the fuel specimen during the transient irradiation cycles. TC #1 refers to the thermocouple attached to the fuel specimen, while -XYZ refers to the specific transient. -1CAL refers to the calibration run, -50% refers to the half power run, -1 through -6 refers to the six full power runs, while -110 refers to the overpower run which was ~10% higher than the six full power runs. Note that for the -110 run, the temperature was at, or exceeded the max temperature of the type C thermocouple at ~2583 °K

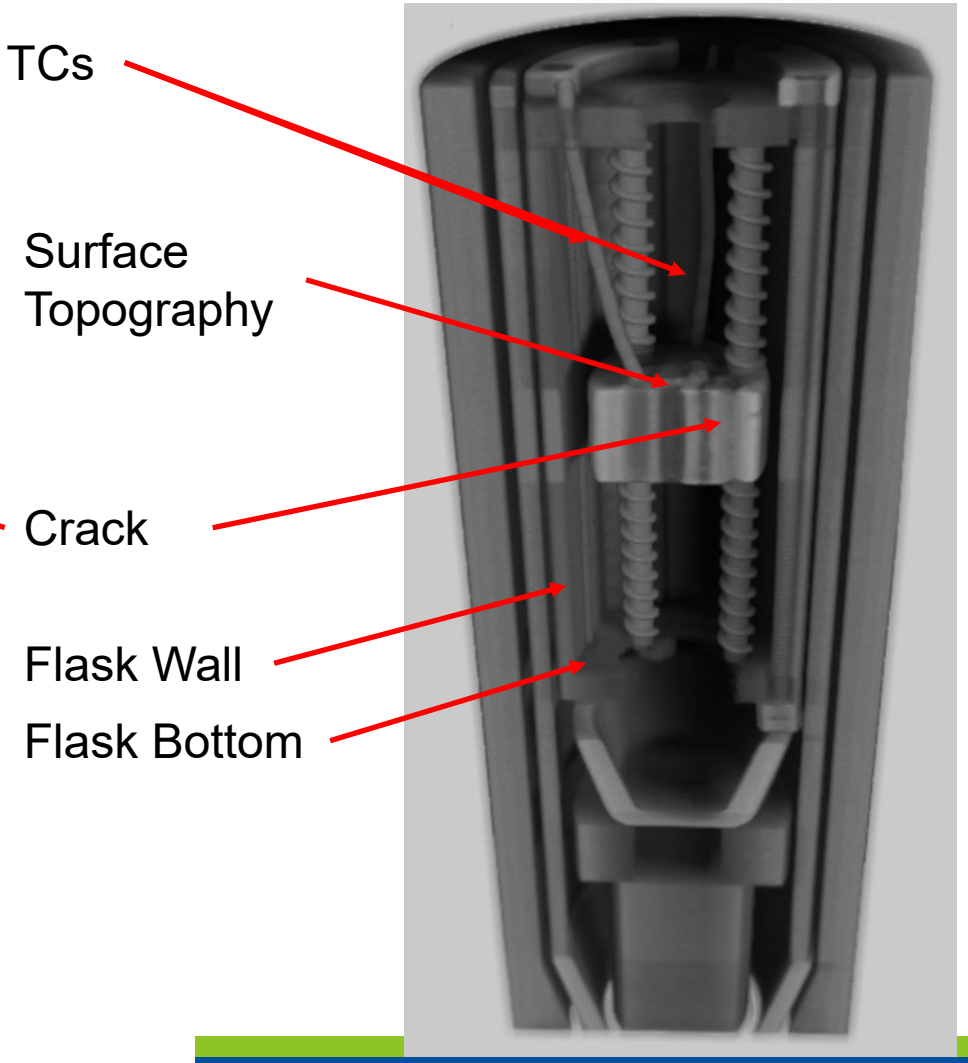


Neutron Radiography/Computed Tomography (Sirius-1)

- No radiography on CaI
- Sirius-1 Tomography reveals features not visible in 2D radiography (e.g. surface topography)
- Not visible in these selected images, but some highly attenuating material visible on flask bottom and walls. Further investigation planned during disassembly.
- Crack volume ~6.3 mm^3 (0.01% of specimen volume)

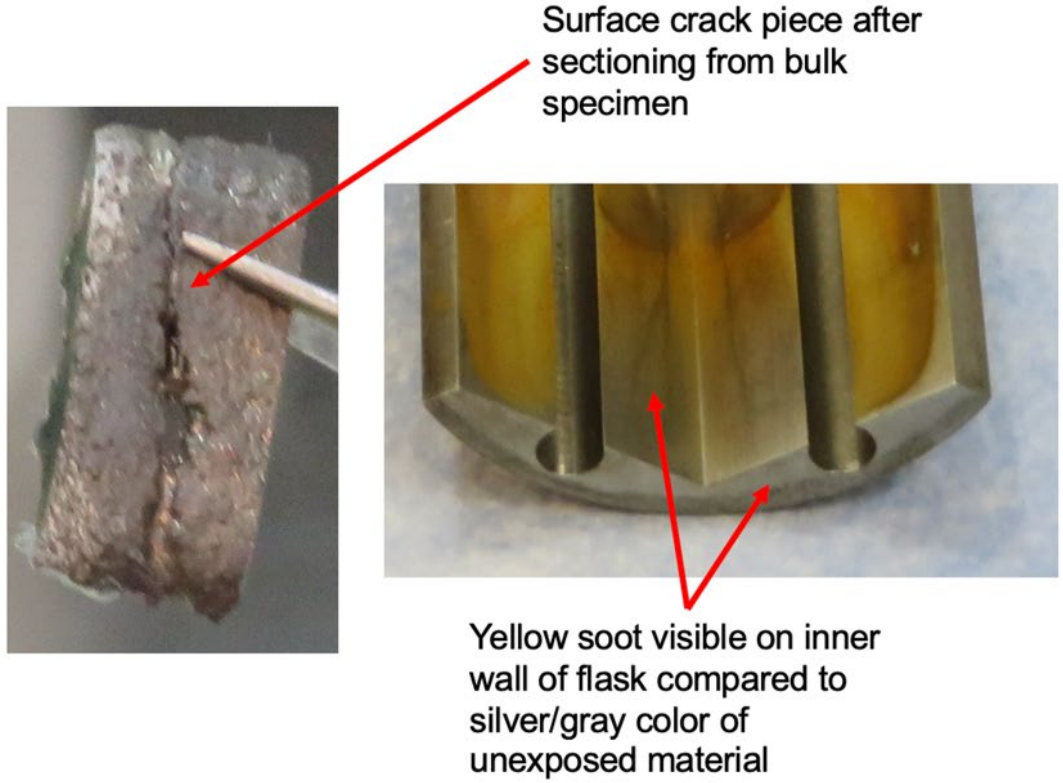


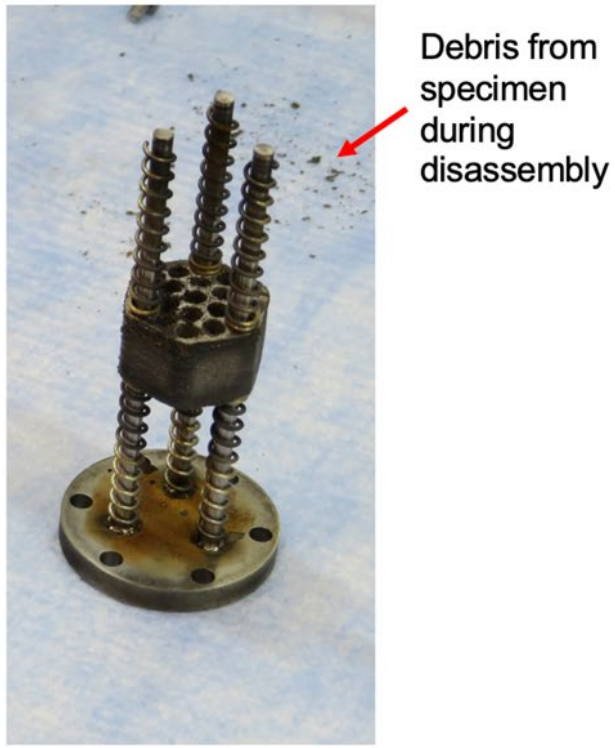




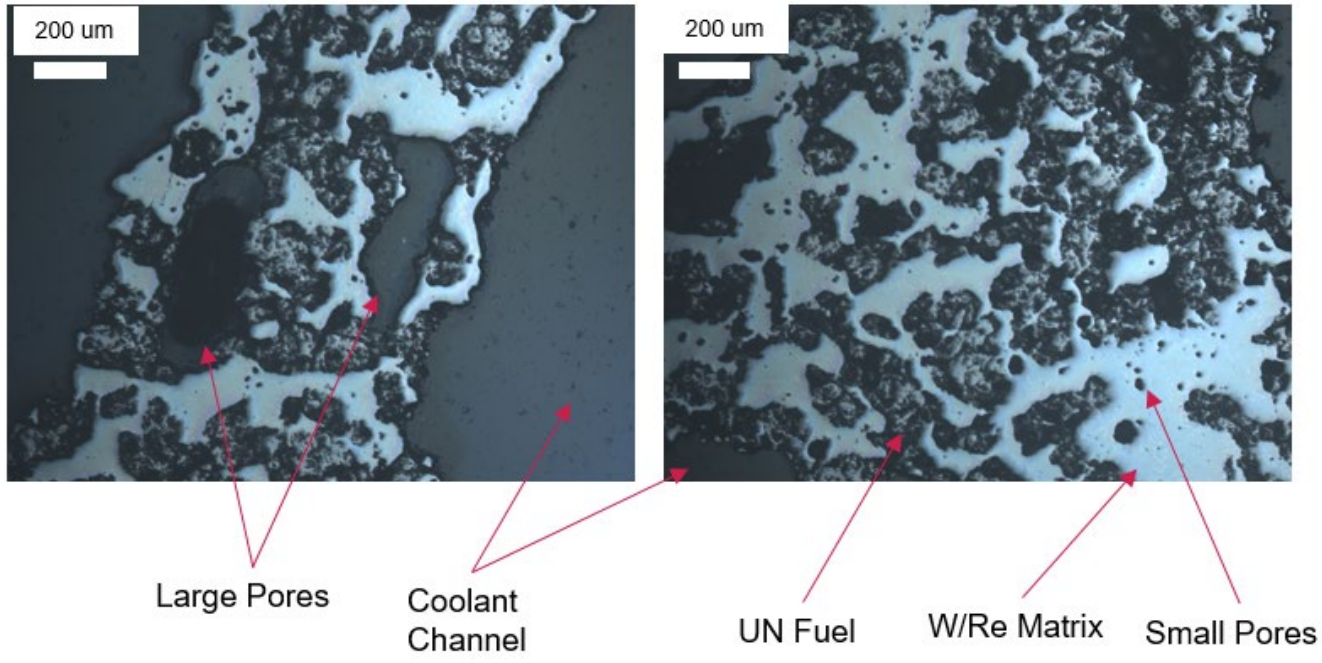
Sirius-1 Disassembly and Observations

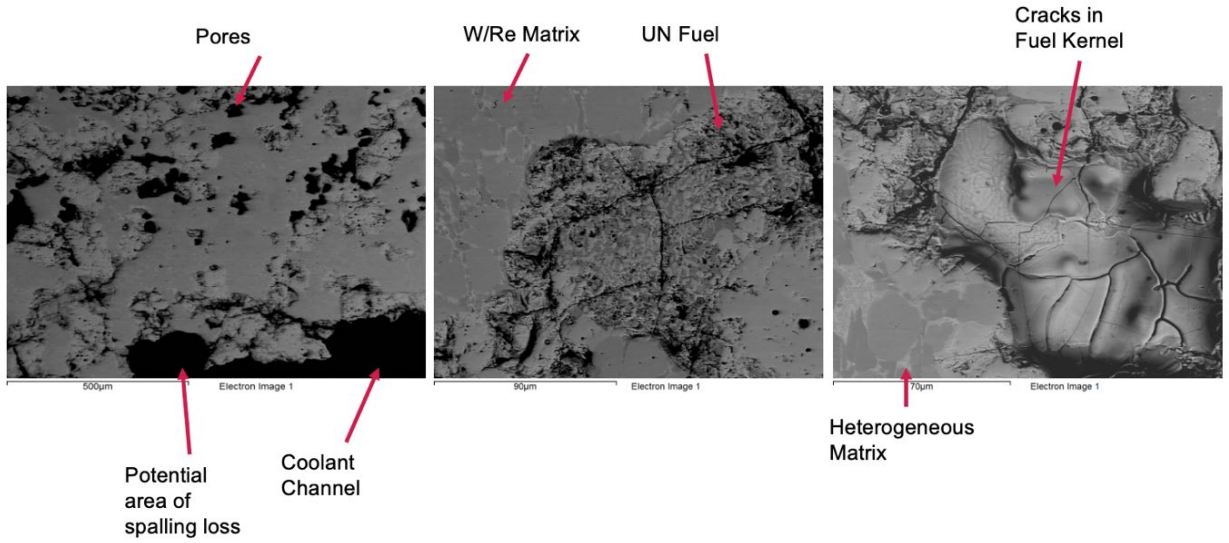
- X-ray Diffraction performed on the inner flask wall to identify the “yellow soot” confirmed to be UO2
- Cracks identified in nCT confirmed in visual inspection





Sirius-1 Microscopy

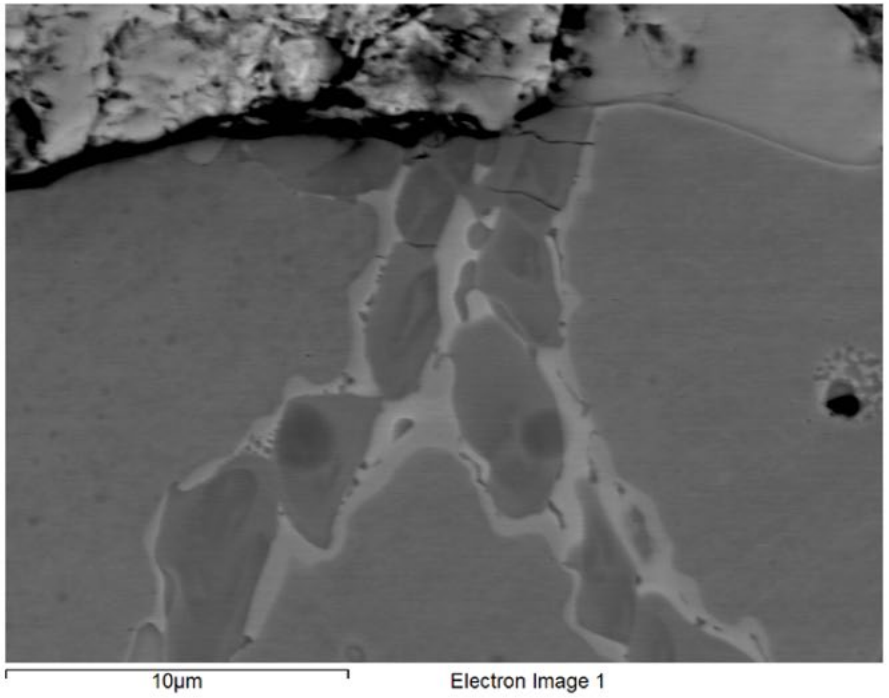


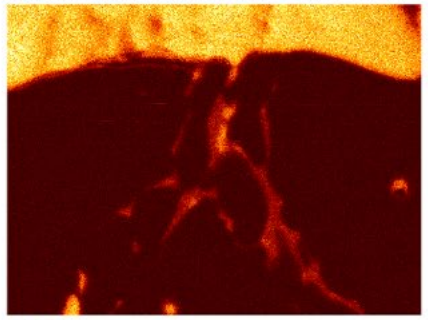


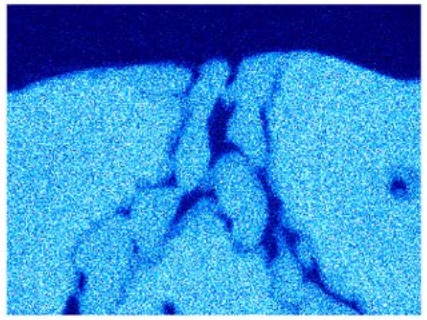
- Top: light optical microscopy showing porosity of specimen.
- Bottom: scanning electron microscopy showing heterogeneous W/Re matrix and cracks in the fuel particle.

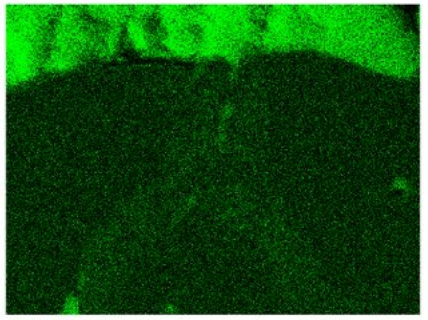
Sirius-1 SEM/EDS

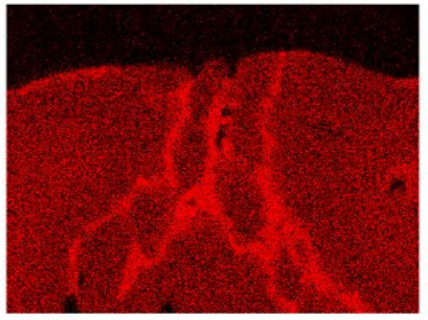
- Diffusion zones identified near interfaces between fuel particles and matrix
- Microcracking observed in the matrix, very near the fuel particle





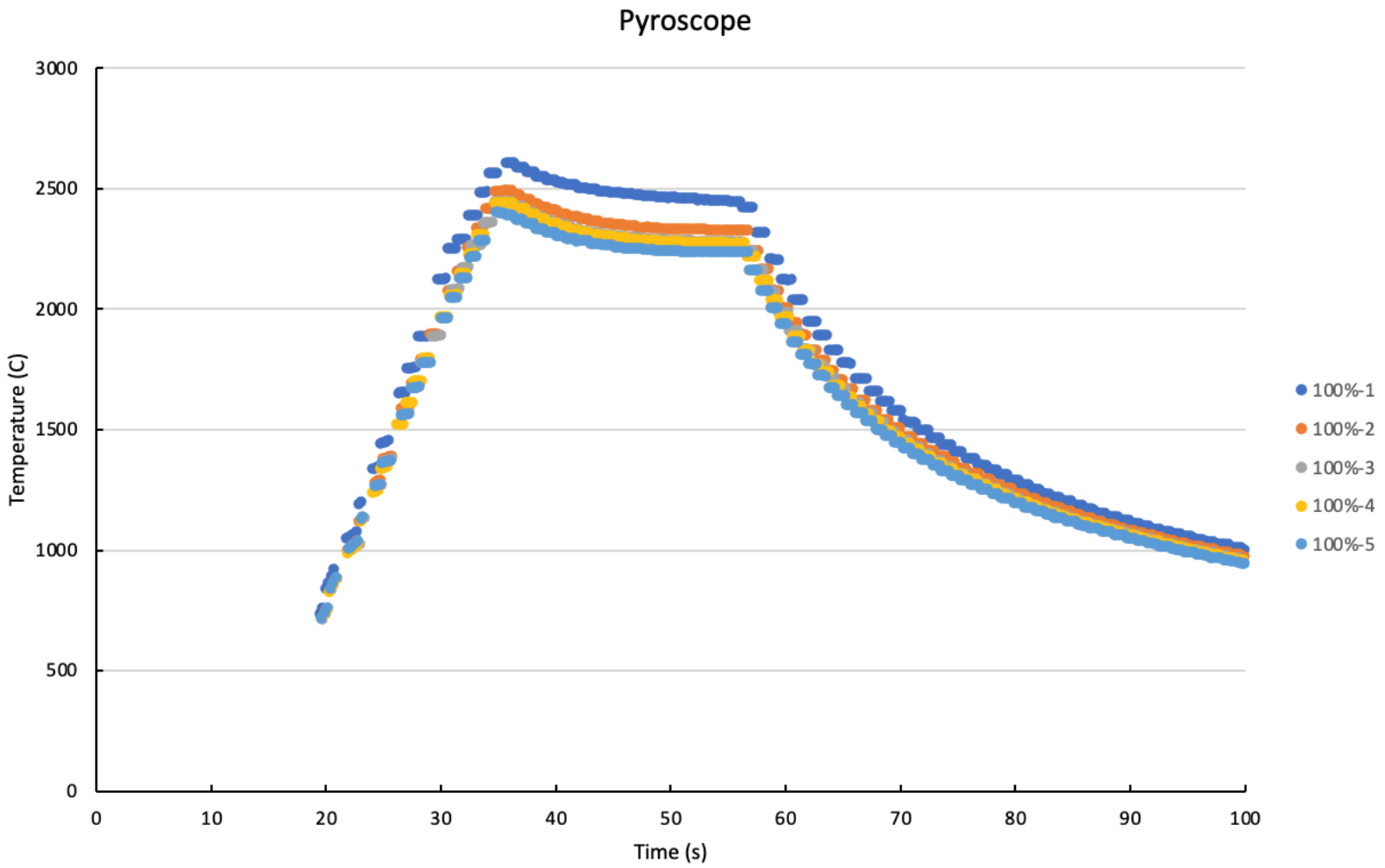






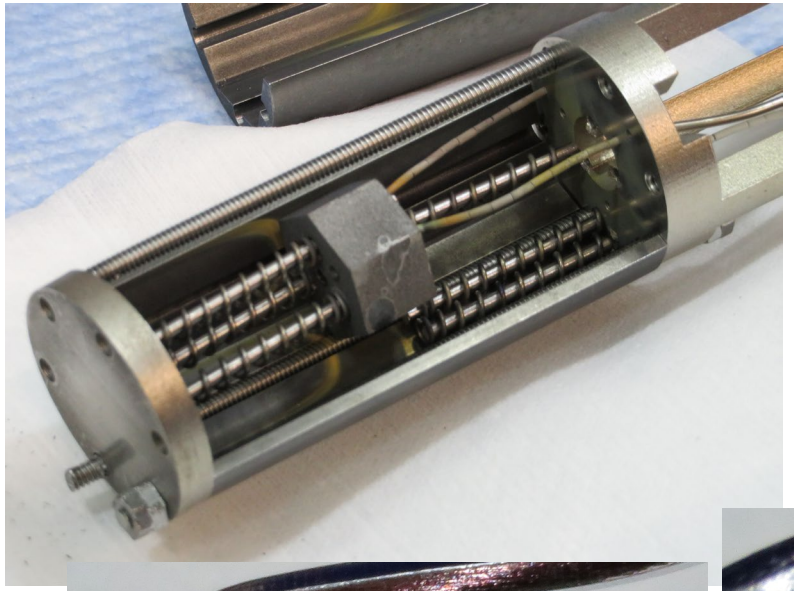
Sirius-2A In-Pile Temperature

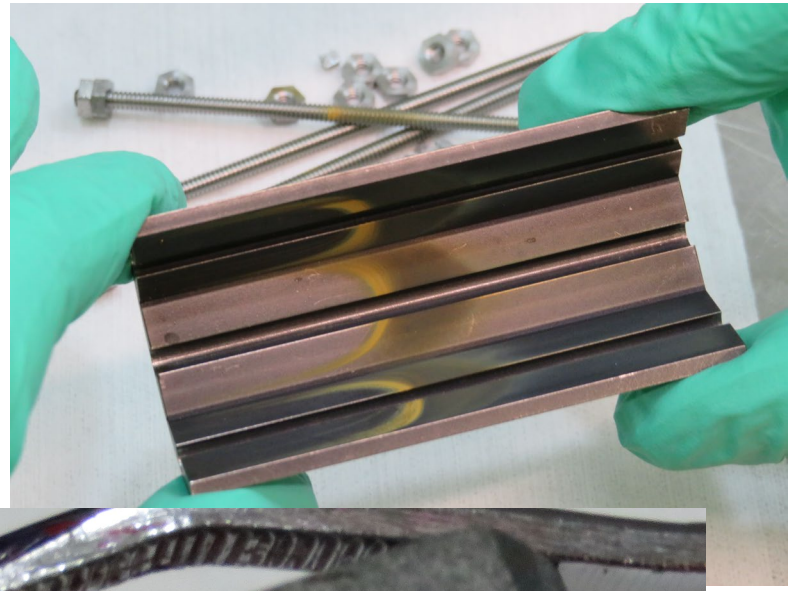
- Peak temperatures ~2600 C
- Temperature hold ~26 s

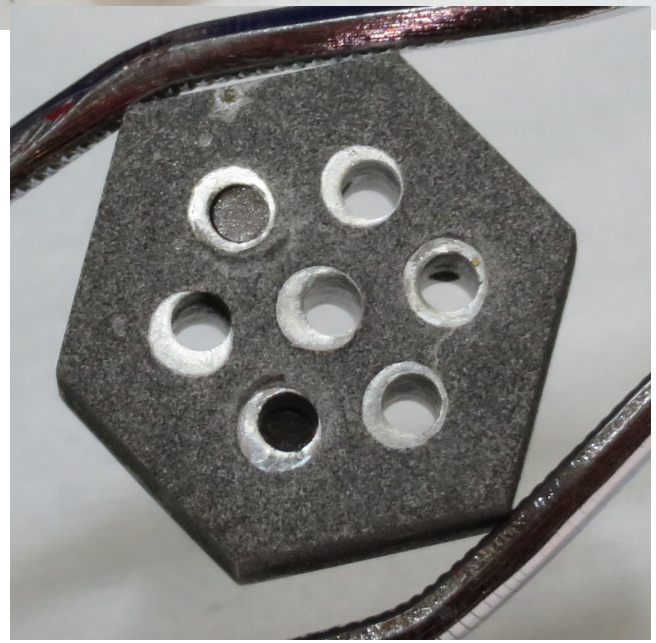


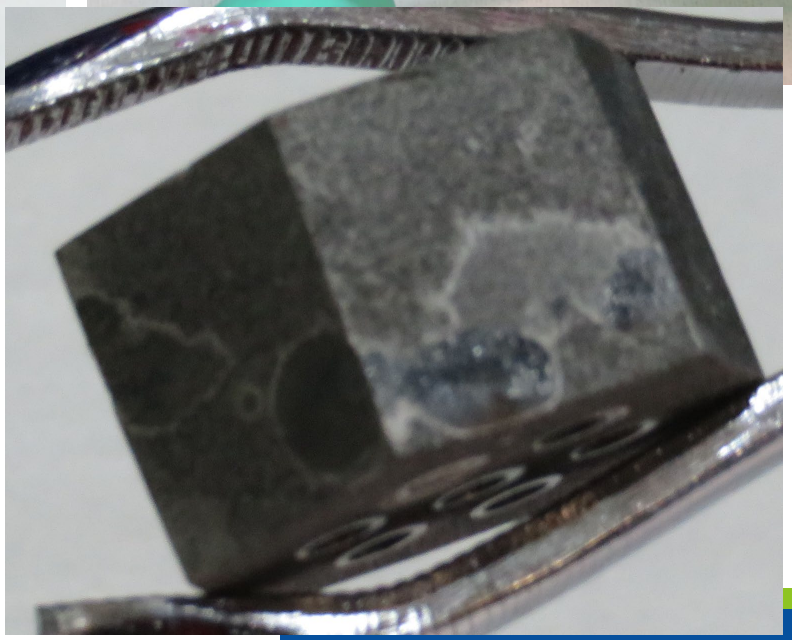
Sirius-2A Disassembly and Visual Inspection

- Specimen intact, no spalling or debris found.
- Yellow soot on inside of experiment vehicle.
- Crack in fuel specimen consistent with indications from radiography.

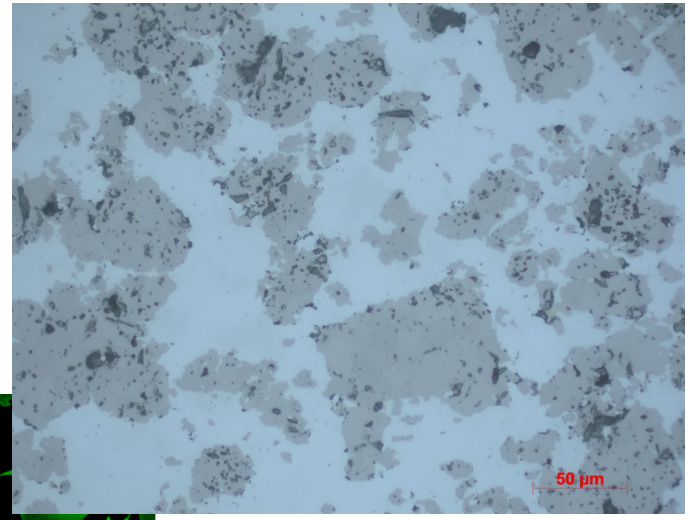




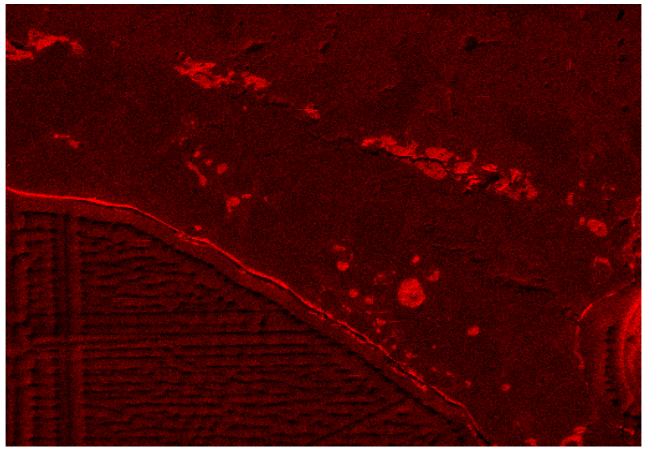


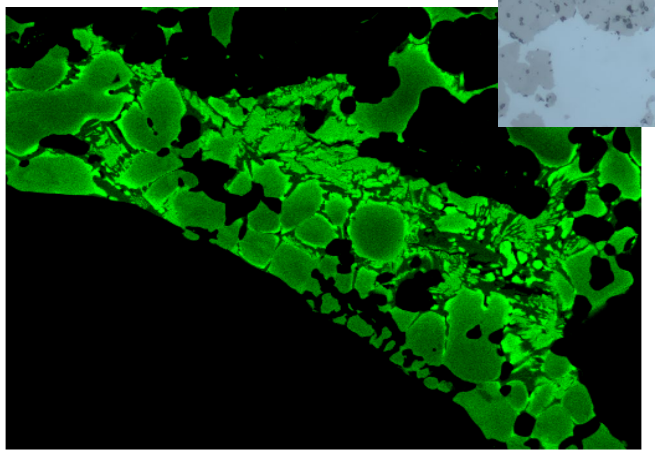


Sirius-2A Microscopy

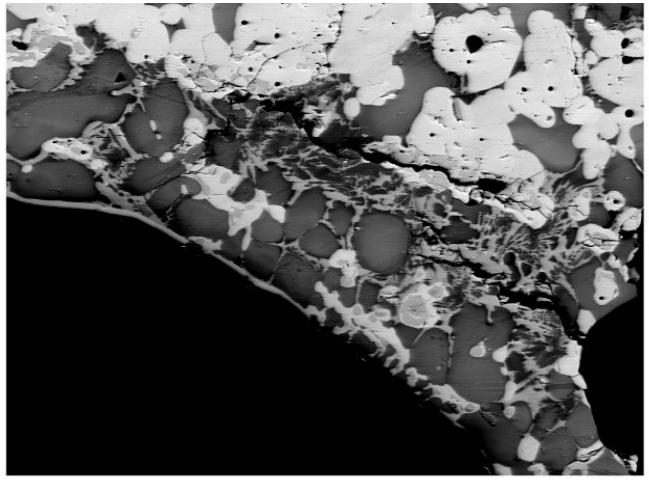


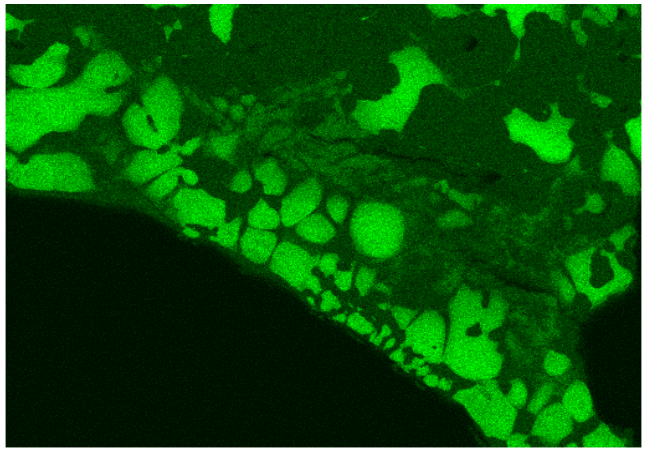
- Light red in O map: UO2
- Dark red in U map and light green in Mo map: UMo
- Yellow in U map: UN
- Light green in W map: W-rich W-Mo alloy

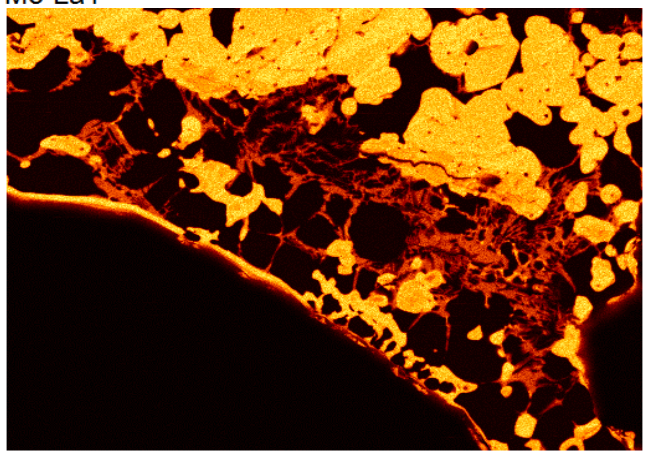

O Ka1


Mo La1

- Above: less porosity than observed in Sirius-1


Electron Image 1


W La1


U Ma1

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