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NUCLEAR and EMERGING TECHNOLOGIES for SPACE

Hot Hydrogen Testing of W-coated UN Kernels for Nuclear Thermal Propulsion

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Introduction

- **Different uranium bearing compounds and composites are being considered for nuclear thermal propulsion (NTP), e.g. UO_2, UC, UN**
- **UN is advantageous with respect to uranium concentration and neutron absorption cross section, but dissociation starts already at temperatures of 1870K, well below the required 2900K [1-4]**
- **A nitrogen vapor pressure of about 2.5bar suppresses the UN dissociation, resulting in a congruent melting point of 3100K [1]**
- **Embedding the ceramic fuel material in a metallic ("cermet") or ceramic ("cercer") matrix might suppress dissociation by preventing the initially released nitrogen from escaping, to provide the counter-pressure internally on a microscopic level.**
- **A first step is coating of the kernels with the respective metal or ceramic. Spherical UN kernels using natural uranium (UN), coated with tungsten, have been evaluated under hot hydrogen testing for temperatures from 1800°C to 2300°C (2073-2573K).**

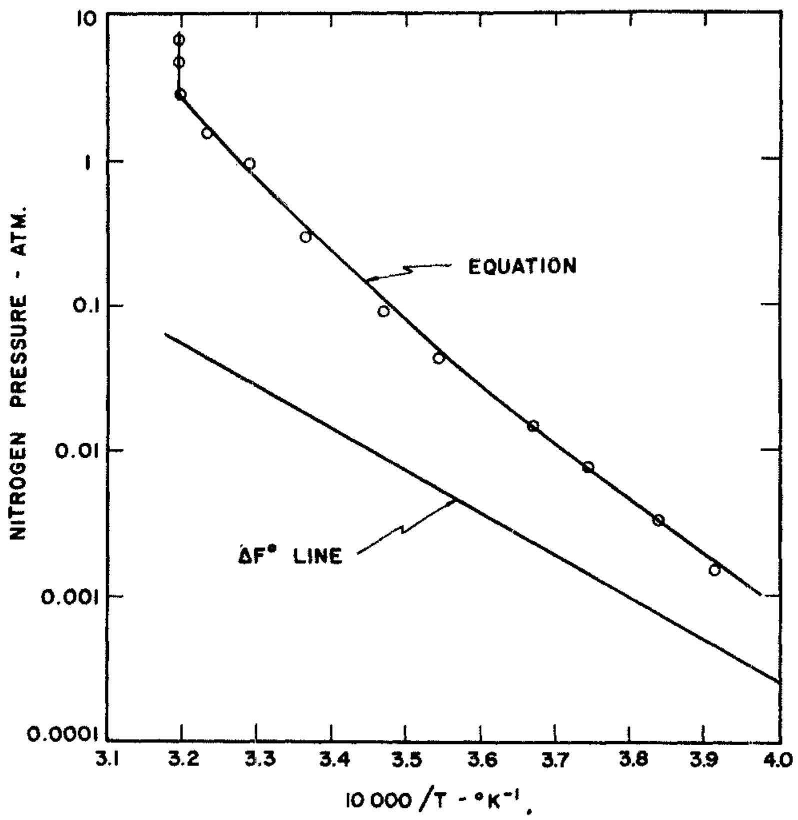

Fig. 1.—Decomposition pressure of UN, from ref. [1]

[1] W.M. Olson, R.N.R. Mulford: The decomposition pressure and melting point of uranium mononitride. J. Phys. Chem. **67** (1963), 952

[2] V. Venugopal, S. G. Kuikarni, C. S. Subbanna, D. D. Sood: Vapour pressures of uranium and uranium nitride over UN(s), *J. Nucl. Mat.*, **186** (1992), 259

[3] H. Tagawa: Phase relations and thermodynamic properties of the uranium-nitrogen system, *J. Nucl. Mat.*, **51** (1974), 78

[4] V. G. Baranov, A. V. Tenishev, R. S. Kuzmin, S. A. Pokrovskiy, V. V. Mikhalchik, V. A. Astafyev, M. L. Taubin, E. S. Solntseva: Thermal stability investigation technique for uranium nitride, *Ann. Nucl. Energy*, **87** (2016), 784

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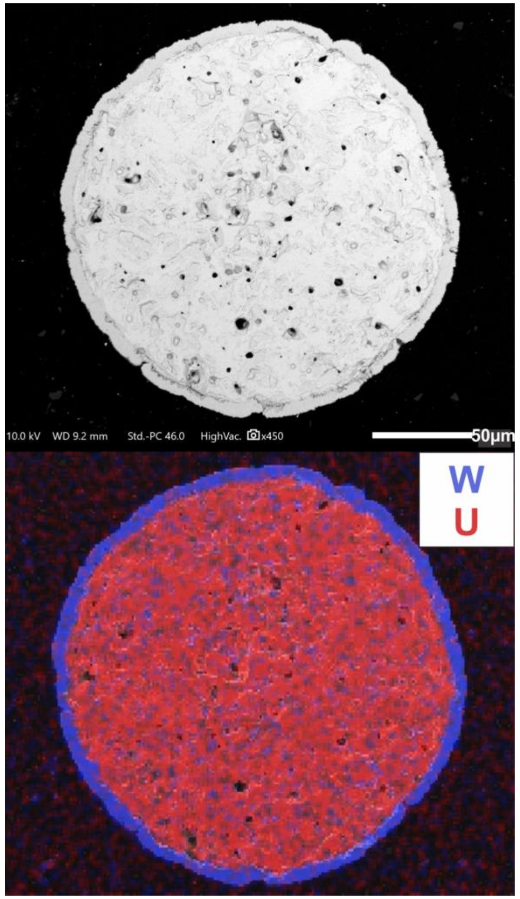
W-coated UN Kernels

- Spherical UN kernels of 220 - 280μm diameter were PVD-coated with a tungsten layer of about 5μm thickness

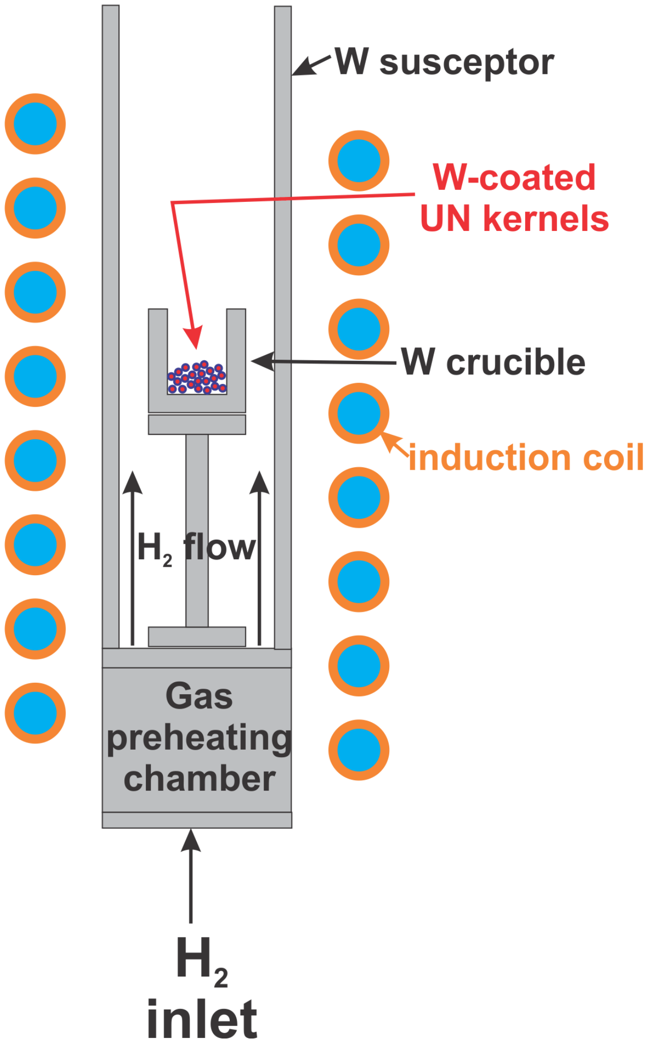
- The process was developed and the kernels were produced by BWX Technologies in Lynchburg, VA, as part of the SNP Fuel and Moderator Development Program (FMDP)

- 2.1 – 2.2 g of the kernels were used in each hot hydrogen test



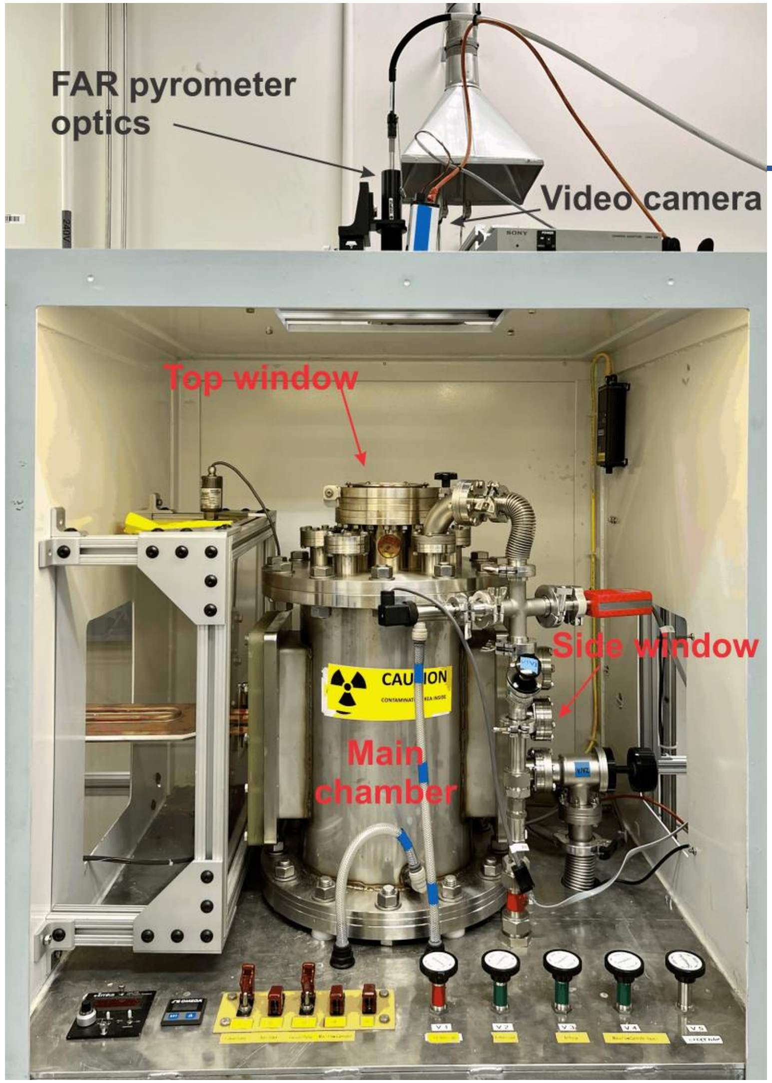
SEM image and EDS map

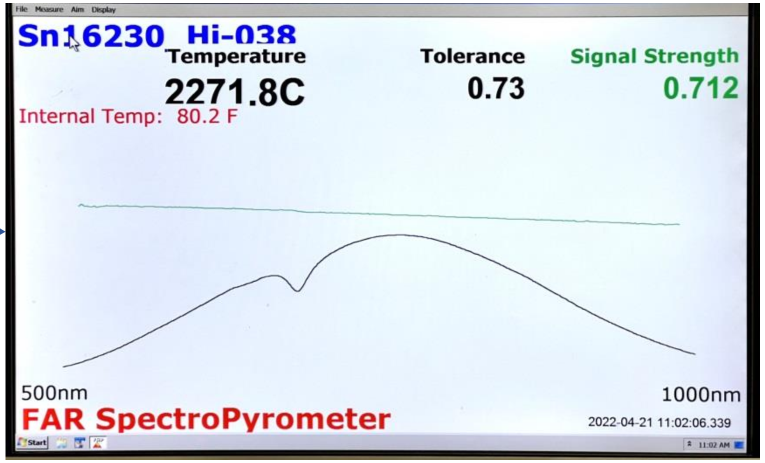
Compact Fuel Element Environmental Test (CFEET)



- Testing in flowing H_2 at ~ 6 SLPM
- Inductive heating with tungsten susceptor
- Kernels were held in a 3D-printed tungsten crucible, heat treated, carburized on the inside
- Multi-spectral pyrometry (FAR Associates) directly on the sample through the top window of the chamber

Compact Fuel Element Environmental Test (CFEET)






View through top window


View through side window

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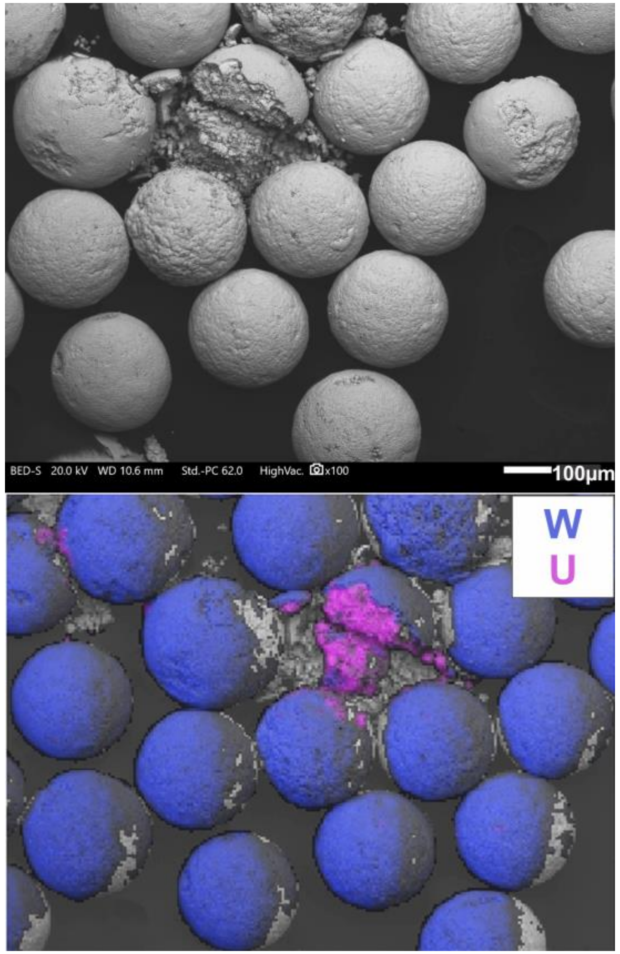
Sample Analysis

- Visual inspection after each run
- Mass loss determination by weighing before and after each run
- SEM and EDS of the samples: Jeol JSM IT200
- Phase analysis by XRD: Aeris Research Edition powder diffractometer and HighScore+ software, both Malvern Panalytical, and ICDD PDF-4+ 2020 database

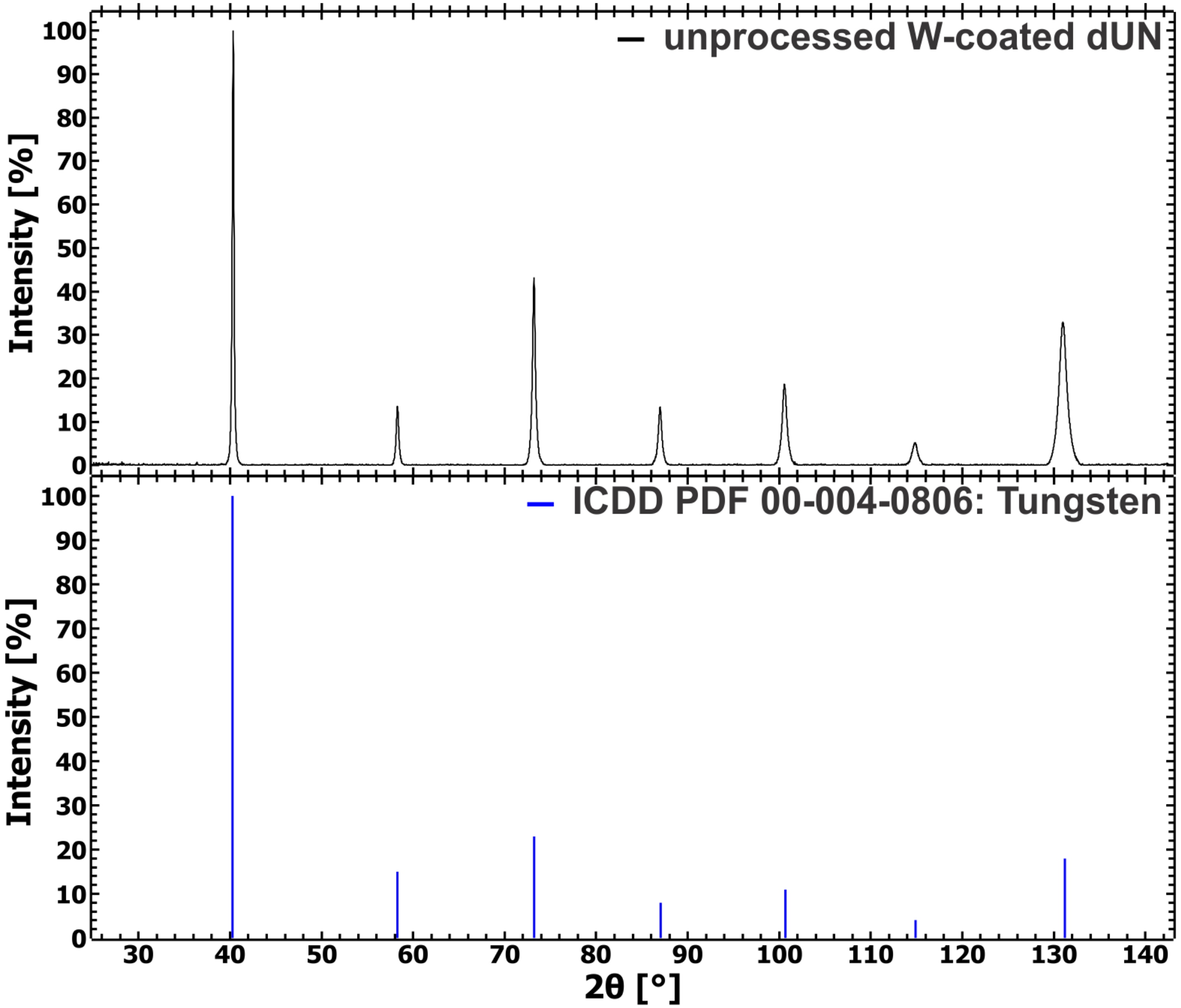
Unprocessed Kernels

- Except for a few broken kernels, only W shows up in the EDS map

- The XRD scan shows only W

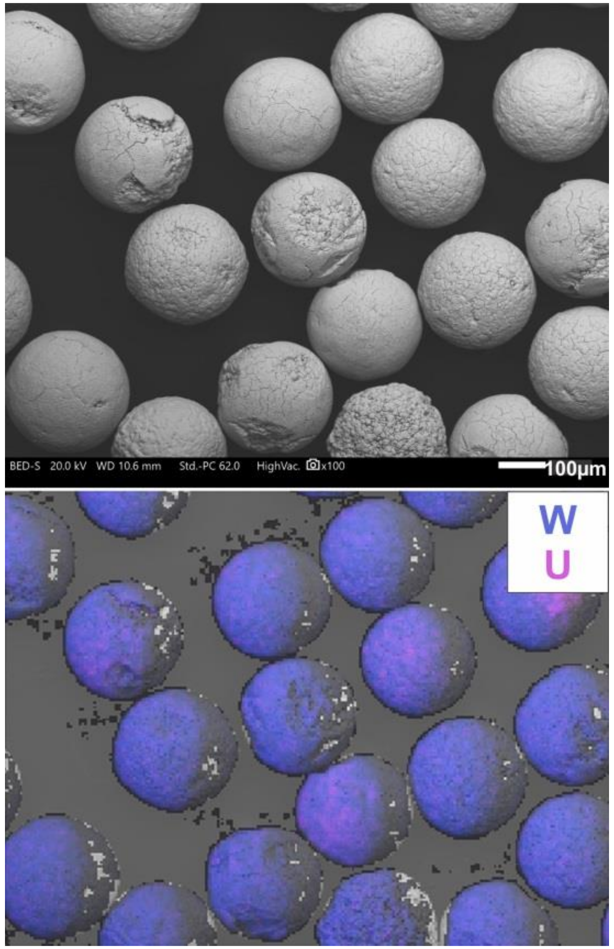


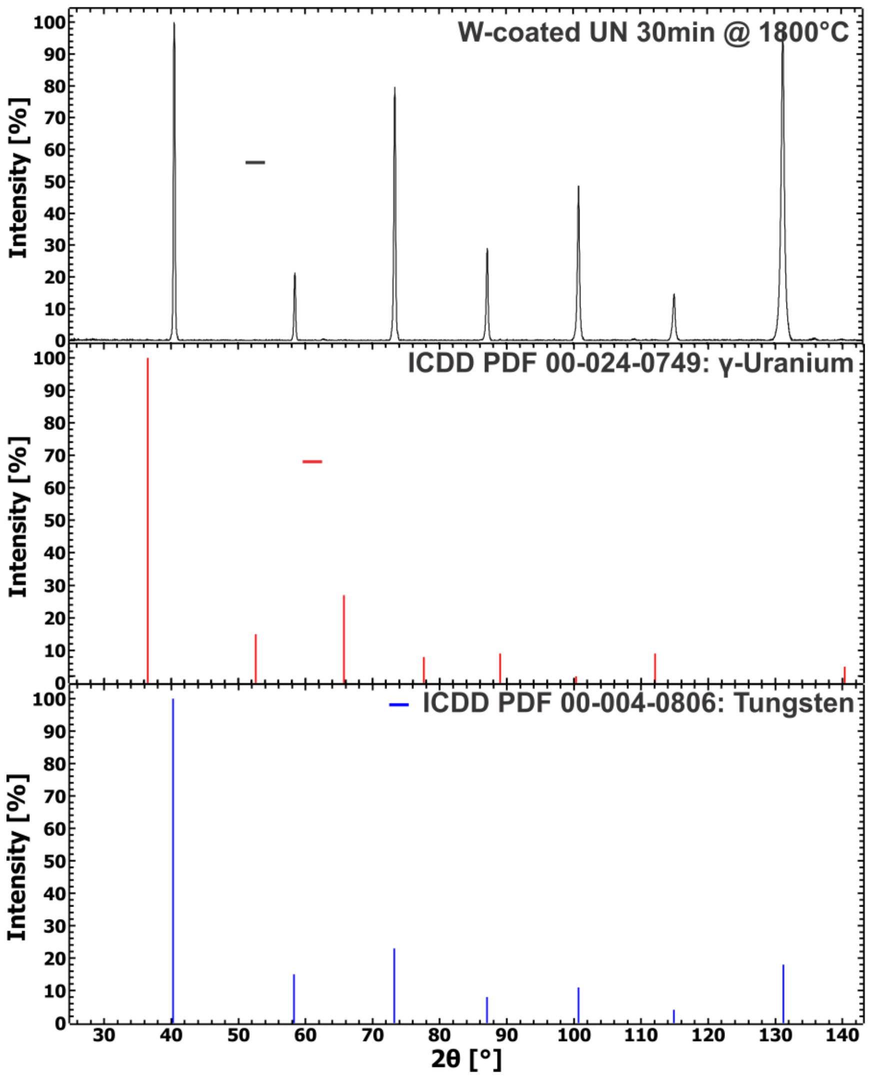
SEM image and EDS map



Processed at 1800°C for 30min

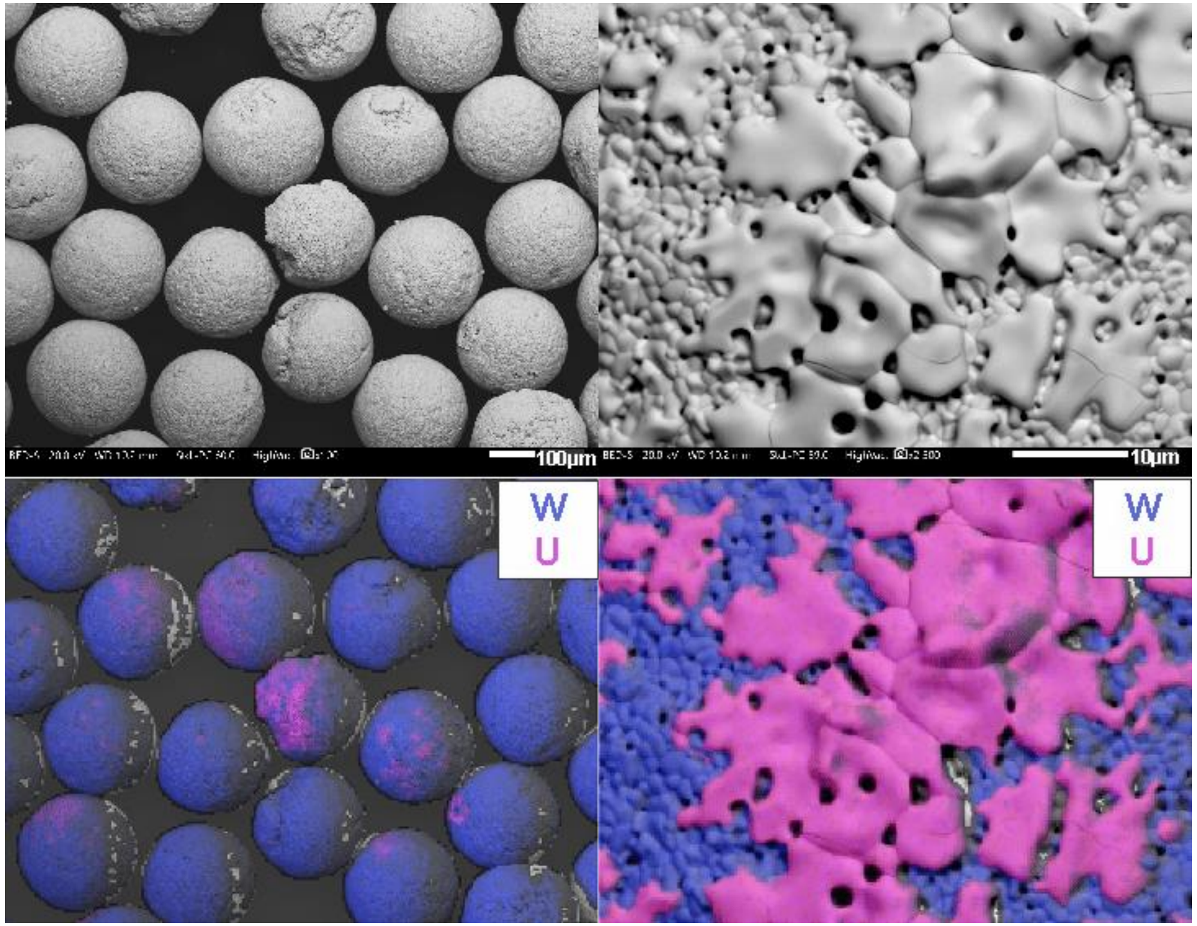
- Kernels are visually unchanged
- The EDS map shows traces of U on the kernel surface
- CFEET chamber window was slightly radioactive
- The XRD scan shows traces of UN/γ-U
- Mass loss: 0.68%



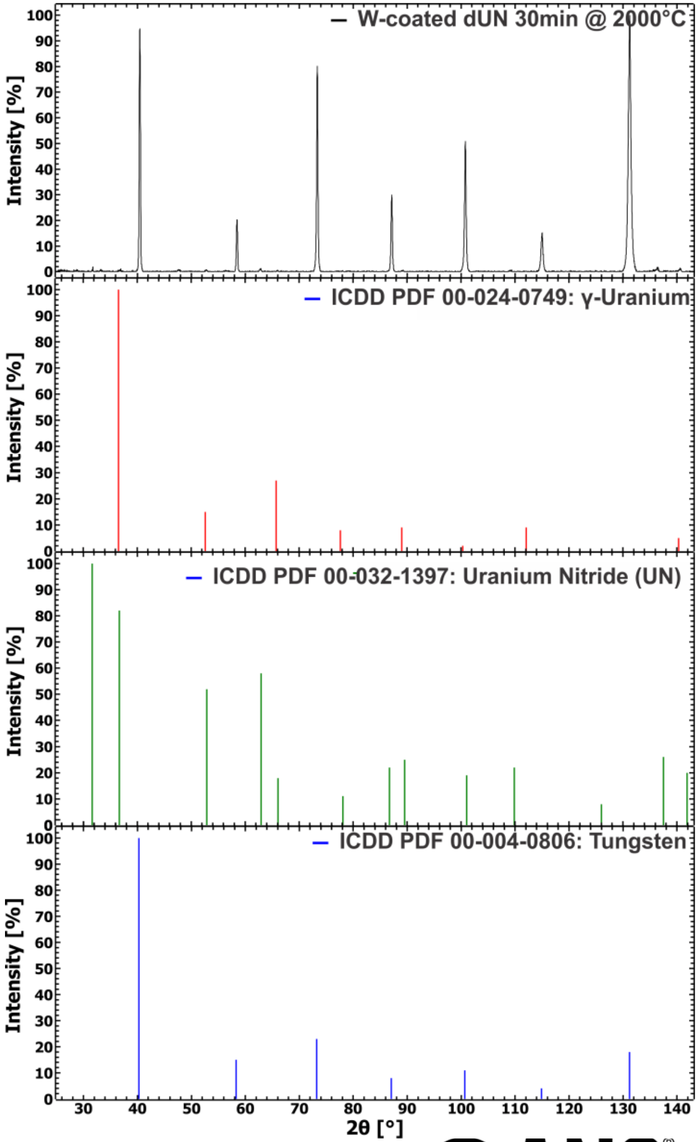


Processed at 2000°C for 30min

- **Kernels visually un-changed, some stick to the crucible wall**
- **EDS maps shows U melt on the kernel surface**
- **CFEET chamber window was slightly radioactive**
- **XRD scan shows some UN/γ-U and traces of d_H^{IV}-W nitride**
- **Mass loss: 0.70%**



SEM images and EDS maps



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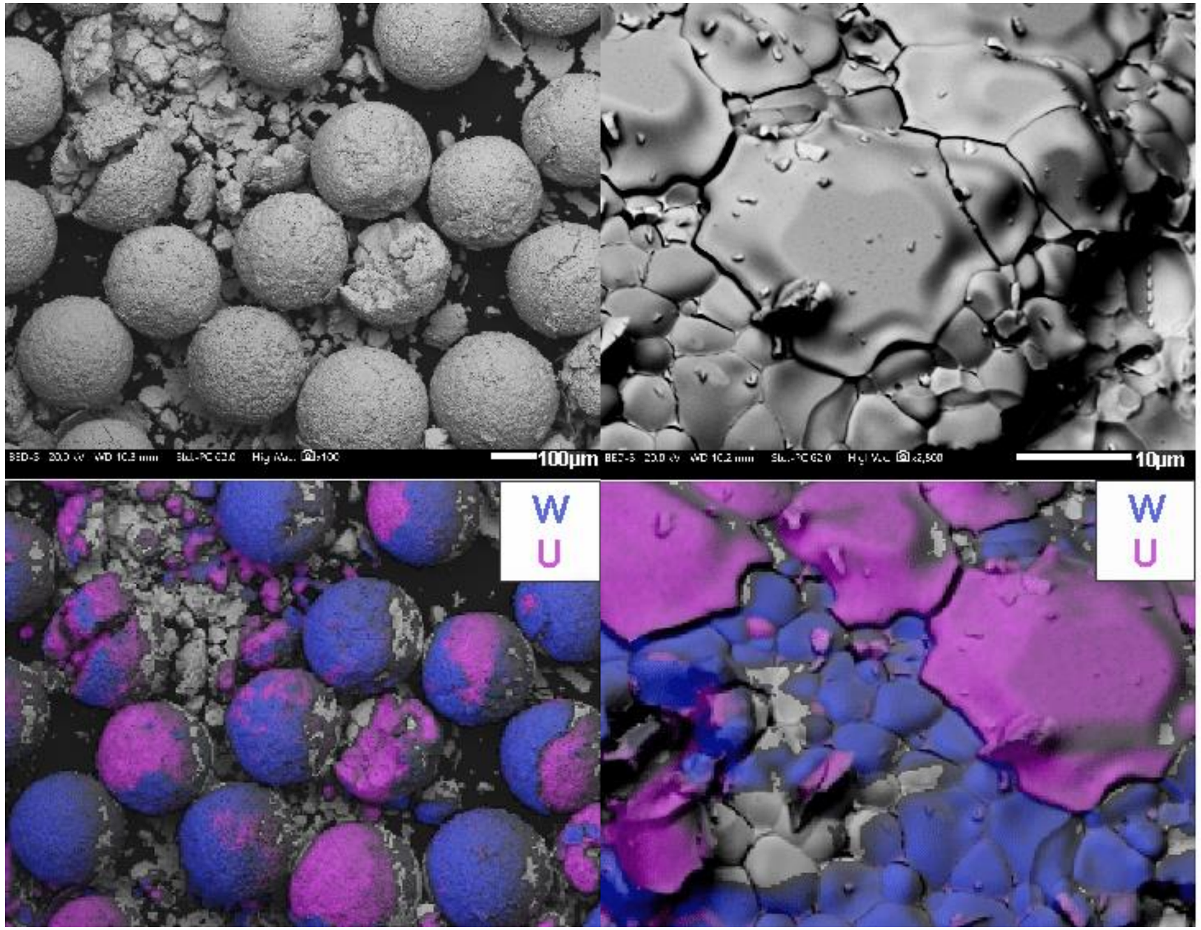
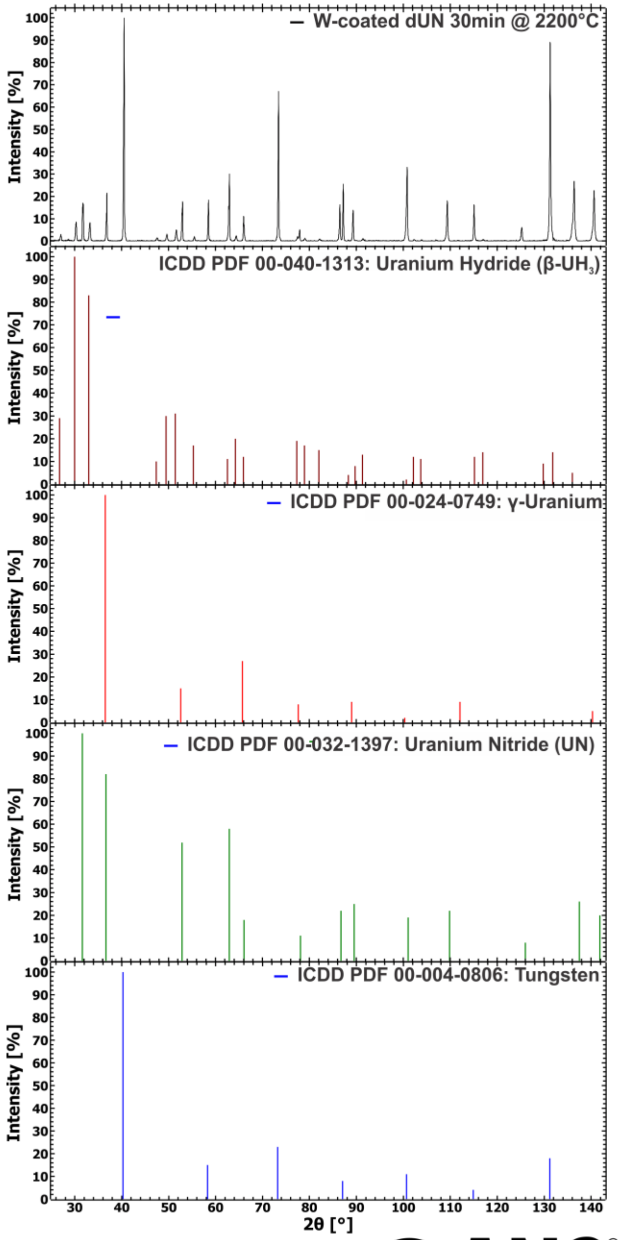
Processed at 2200°C for 30min

- Some kernels are broken into frag-ments
- EDS maps shows even more U melt on the kernel surface
- CFEET chamber window was radio-active
- XRD scan shows some UN/γ-U, β-UH_3, and traces of d_H^{IV} -W nitride
- Mass loss: 1.04%





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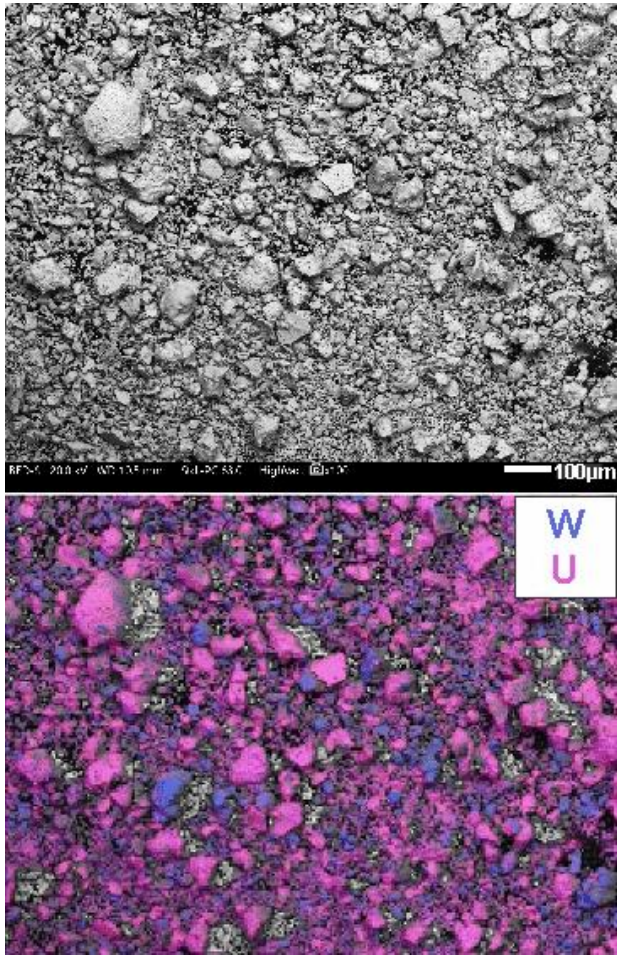
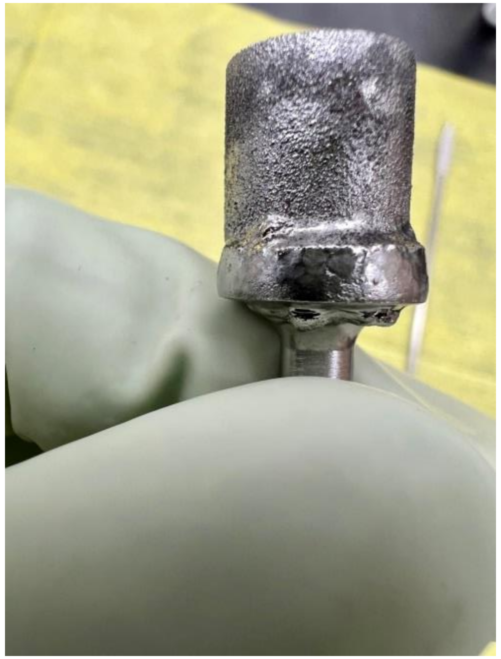
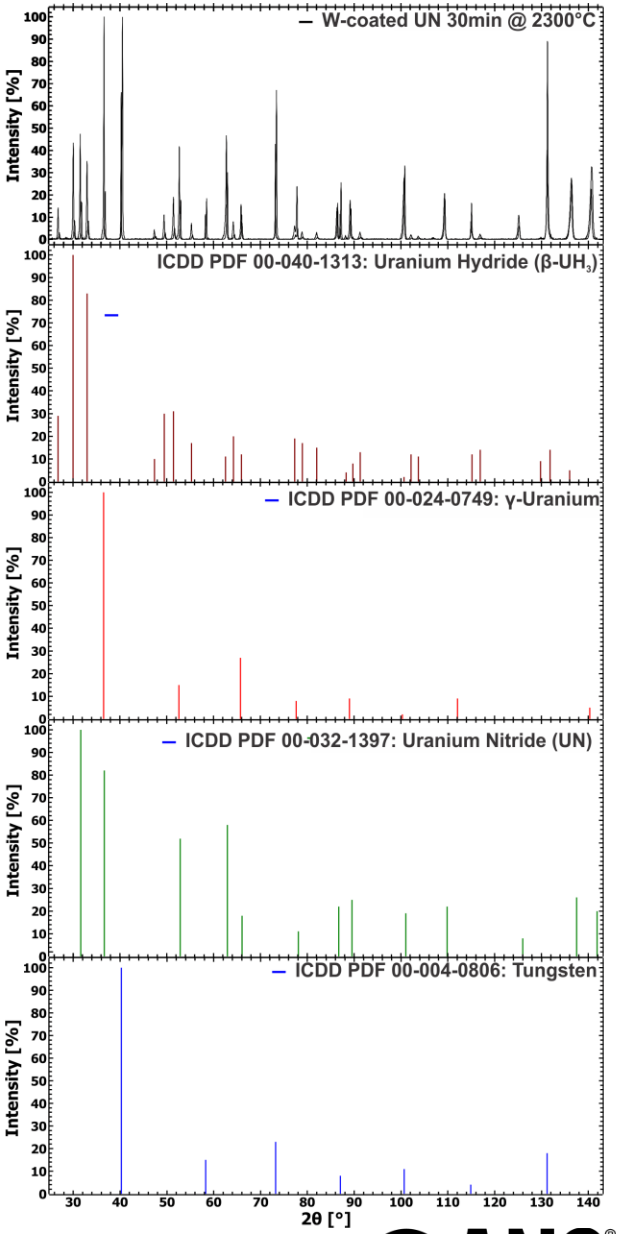
Processed at 2300°C for 30min

- **Liquid U seeped through crucible walls/bottom[5]; remaining kernel fragments are brown**
- **SEM image and EDS map show complete-ly destructed kernels**
- **CFEET chamber window was radio-active**
- **The XRD scan shows UN, γ-U, and β-UH_3 in addition to W**





[5] M. KUZNIETZ, Z. LIVNE, C. COTLER, and G. EREZ, "Effect of liquid uranium on tungsten foils up to 1350°C," *J. Nucl. Mat.*, **160**, 69 (1988)



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Summary and Conclusions

- Hot Hydrogen tests of W-coated UN kernels were performed at temperatures from 1800°C to 2300° in the CFEET facility at NASA MSFC
- Mass loss and the appearance of uranium on the kernel surface starts already at 1800°C
- At 2000°C and 2200°C mass loss increases and molten areas of uranium can be seen on the kernel surfaces. At 2200°C some kernels break up, and XRD indicates the formation of β-UH_3
- 2300°C leads to catastrophic loss of the integrity of all kernels and the formation of a macroscopic uranium melt

➢ Dissociation of UN starts at 1800°C or below and is <u>not</u> prevented by the W coating

➢ Nitrogen either escapes through cracks and grain boundaries in the coating, or is temporarily bound as tungsten nitride at temperatures of 2200°C or lower, resulting in the formation of molten uranium

➢ Molten uranium readily infiltrates the tungsten grain boundaries and releases the grains (as reported in earlier literature[5]), leading to a runaway process of dissociation, melting, and finally catastrophic failure

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