Additive Manufacturing of Gyroid Fuel Elements for Nuclear Thermal Propulsion

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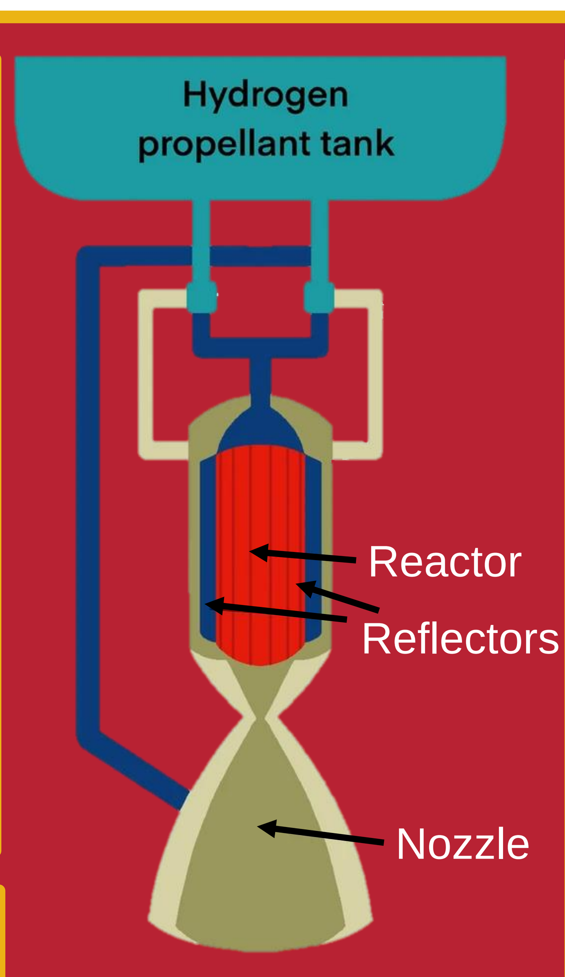
Overview

- **Research Goal:** Develop nuclear thermal propulsion fuel models with complex propellant flow channels.
- **Focus:** Analyse microstructural changes and assess fabrication quality.
- **Material:** Zirconium-Vanadium (Zr-V) alloy as fuel element matrix (no active fuel included).
- **Characterisation Methods:** Optical Microscopy, Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Energy-Dispersive X-ray Spectroscopy (EDS).

1. Nuclear Thermal Propulsion (NTP)

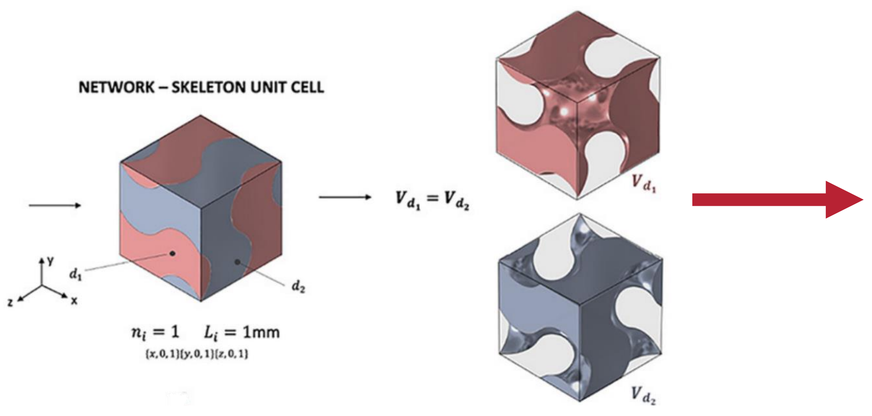
- Utilises controlled nuclear fission to produce thrust (2-3 times that of chemical propulsion).
- **Mechanism:** Pumps liquid propellant through the reactor core, heating it rapidly to a gas, which expands and is forced through the rocket nozzle, generating high thrust.
- **Notable Program:** U.S. ROVER/NERVA initiative.
- **Importance:** Critical for reducing flight times in Mars missions.
- **Operating Temperatures:** Exceeding 3000K.
- **Design Limitation:** Efficiency depends on materials' ability to withstand high temperatures.



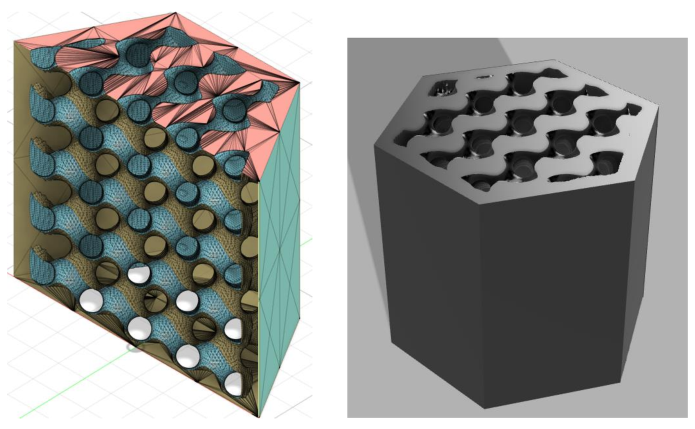
A. Schematic of NTP assembly [1]

2. Fuel Element Design

- **Fuel Element:** Serves as a self-regulating reactor, heat exchanger, and structural component with integrated flow channels.
- **CERMET Configuration:** Combines metal matrix with ceramic active fuel.
  - **Advantages:** Thermal cycle durability; potential to exceeds 40-hour operational life.
- **Gyroid Design:**
  - Selected for space reactor fuel element.
  - A type of triply periodic minimal surface (TPMS) with zero curvature.
  - **TPMS Structures:** Created using surface equations; skeletal structures form solid volumes with interconnected pores when one domain is removed.
  - **Benefits:** Maximises surface area for heat transfer and optimises strength-to-weight ratio



B. Gyroid TPMS generation [2]

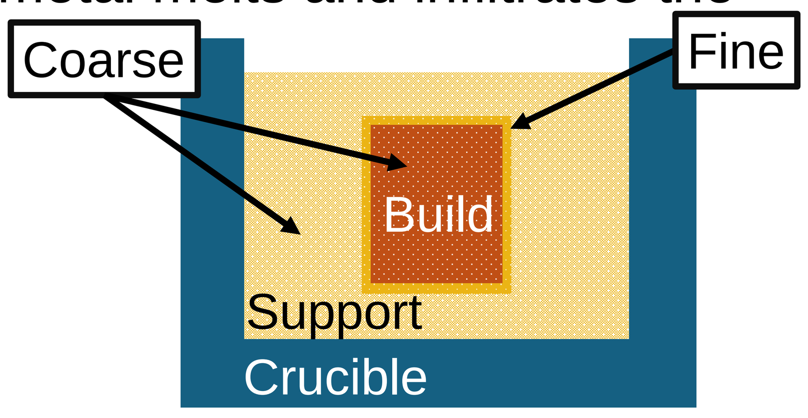


C. CAD Gyroid fuel element cross-section & render

3. Selective Powder Deposition (SPD)

- An additive manufacturing, layer-based sand-casting technique.
- Uses coarse and fine silica sand as scaffolding for Zr-V build powder.
- **Two Techniques:**
  - **Dry Sintering:** Without additional material.
  - **Infill:** Additional metal melts and infiltrates the build powder.

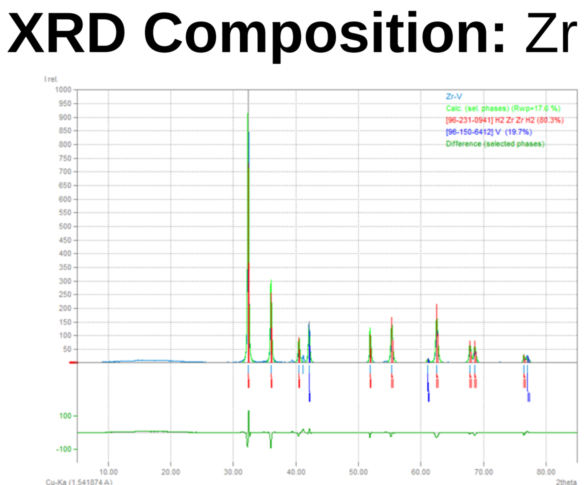
D. Iro3D printer [3]



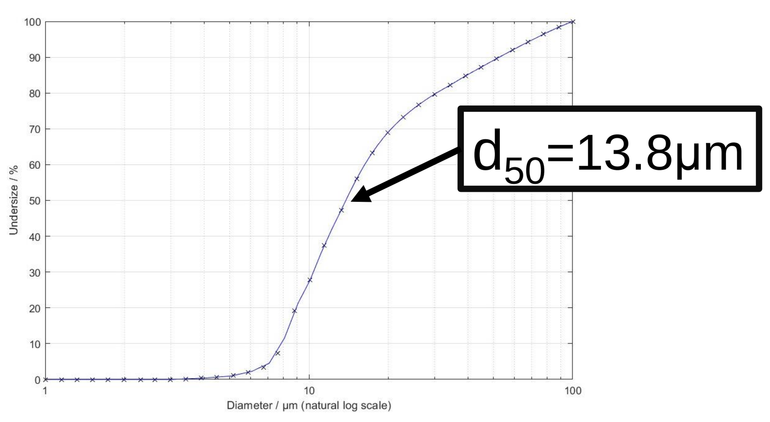
E. SPD schematic

4. Powder Feedstock

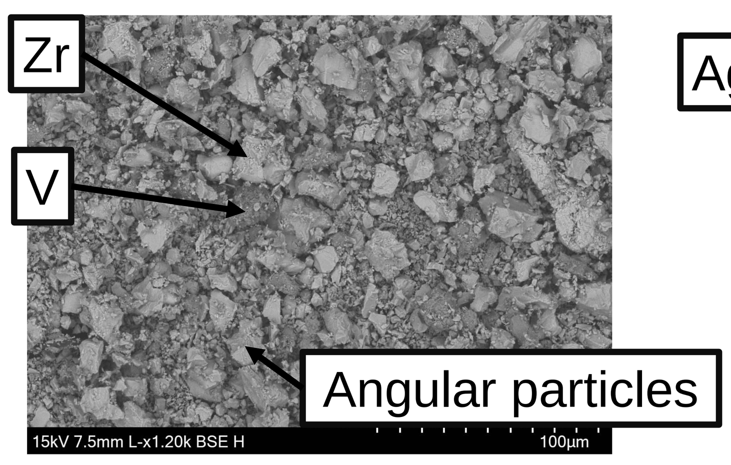
- **Iro3D Printer Specifications:**
  - Fine powders: 40-90 µm, coarse powders: 90-190 µm
- **Zr-V Alloy Powder:** Sourced from Nanochemazone (Canada); characterised by XRD, particle size distribution (PSD), and SEM.
- **Silica Sand:** >99% pure.
- **XRD Composition:** Zr – 70%, V – 30% atomic percent.



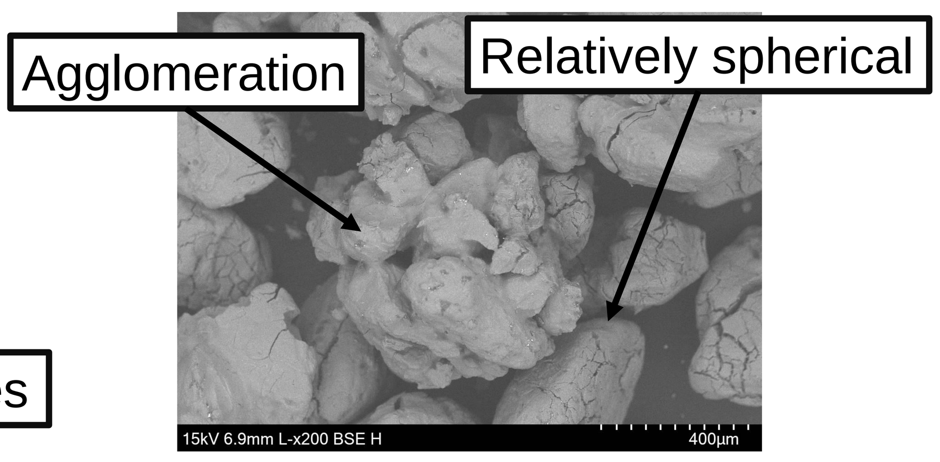
F. Zr-V powder XRD pattern



G. Zr-V powder PSD



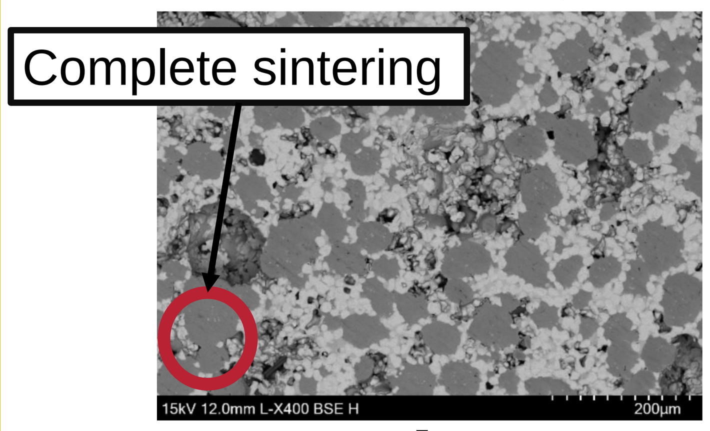
H. SEM image of Zr-V powder



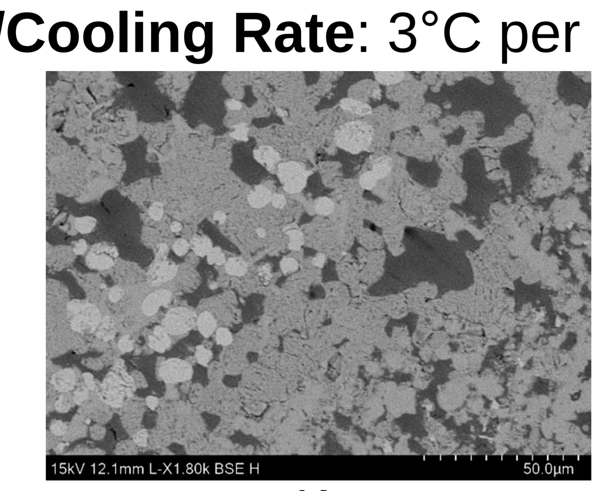
I. SEM image of coarse silica sand

5. Microstructure Evaluation of Zr-V Alloy & TRL

- **Preparation**: Zr-V alloy powder placed on silica (SiO_2) sand bed, slightly compacted to form a green body.
- **Sintering Conditions**:
  - **Furnace Type**: Vacuum furnace, **Temperature**: 1500°C, **Sintering Duration**: 1 hour, **Heating/Cooling Rate**: 3°C per minute.

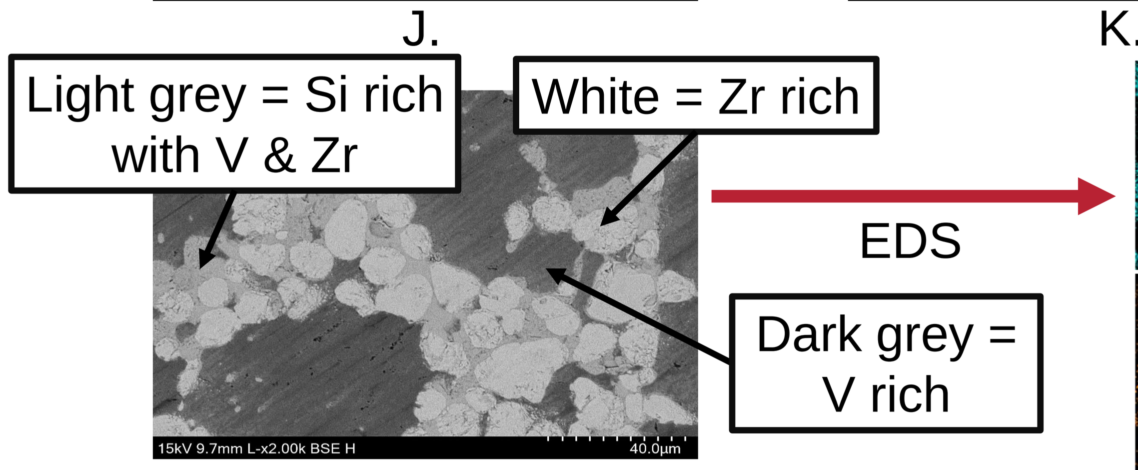


J.

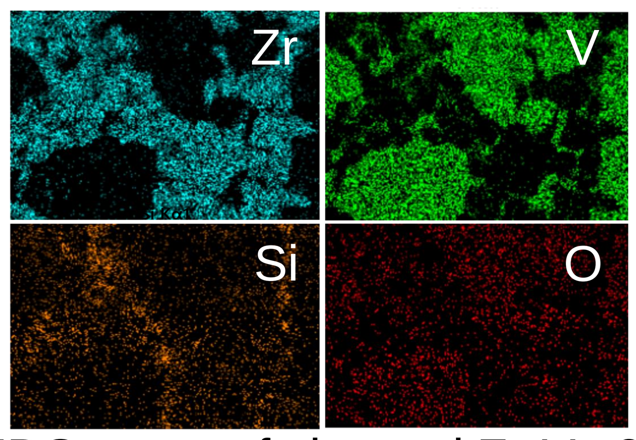


K.

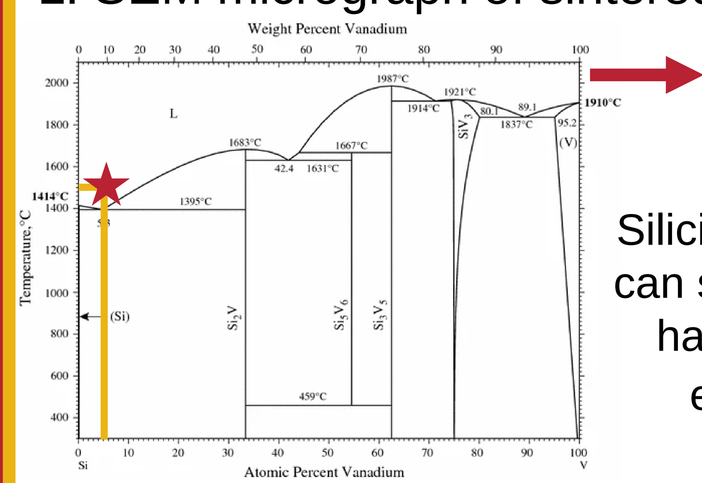
SEM micrographs of sintered Zr-V at J. 400x and K. 1,800x



L. SEM micrograph of sintered Zr-V x2,000



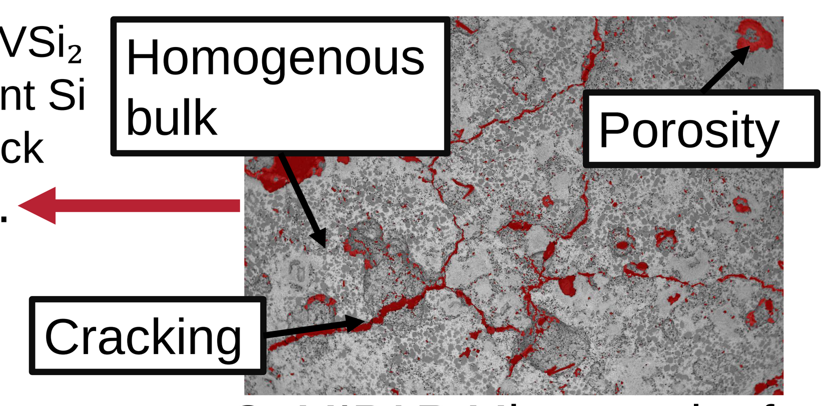
M. EDS maps of sintered Zr-V x2,000



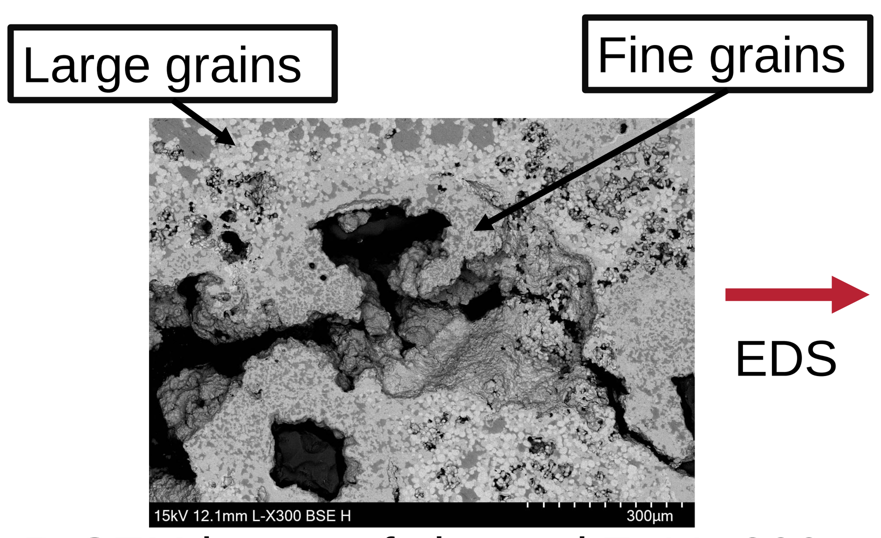
N. Si-V phase diagram [4]

Thermodynamically, the sintering temperature of 1500°C is above the eutectic temperature of 1414°C at 5 at.% V

Silicide phases such as VSi_2 can solidify once sufficient Si has diffused to the crack edges of the sample.

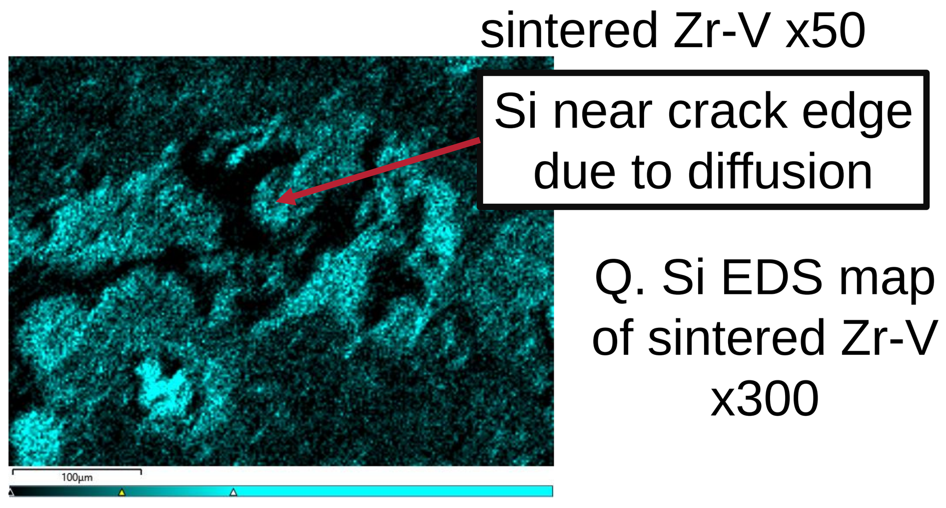


O. MIPAR Micrograph of sintered Zr-V x50



P. SEM image of sintered Zr-V x300

EDS



Q. Si EDS map of sintered Zr-V x300

- Silica sand leads to embrittlement near crack edges due to high concentration of **Si-precipitates** and **secondary oxidation**, therefore cracking and degrading the sample.
- SPD application to NTP fuel element manufacture is estimated at the 2-3 TRL level.
- Future work will look at replacing the support powder from silica sand to a non-oxidising and non-degrading material.

Figure References

[1] – Hirschhorn, J.; Hilty, F.; Tonks, M. R.; Rosales, J. Review and Preliminary Investigation into Fuel Loss from Cermets Composed of Uranium Nitride and a Molybdenum-Tungsten Alloy for Nuclear Thermal Propulsion Using Mesoscale Simulations. *JOM* **2021**, *73* (11), 3528–3543.
[2] – R. Pugliese and S. Graziosi, 'Biomedical scaffolds using triply periodic minimal surface-based porous structures for biomedical applications', *SLAS technology*, vol. 28, no.3, pp. 165-182, 2023.
[3] – iro3d. *Metal 3D printer*. Iro3d.com. https://iro3d.com/index.html#method (accessed 2024-08-26).
[4] – Okamoto, H. Si-V (Silicon-Vanadium). *Journal of Phase Equilibria and Diffusion* 2010, *31* (4), 409–410.

6. Acknowledgements

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