Stabilizing Uranium-Yttrium Hydride (U-YH_x) Fuel Using Nuclear Nanotechnology

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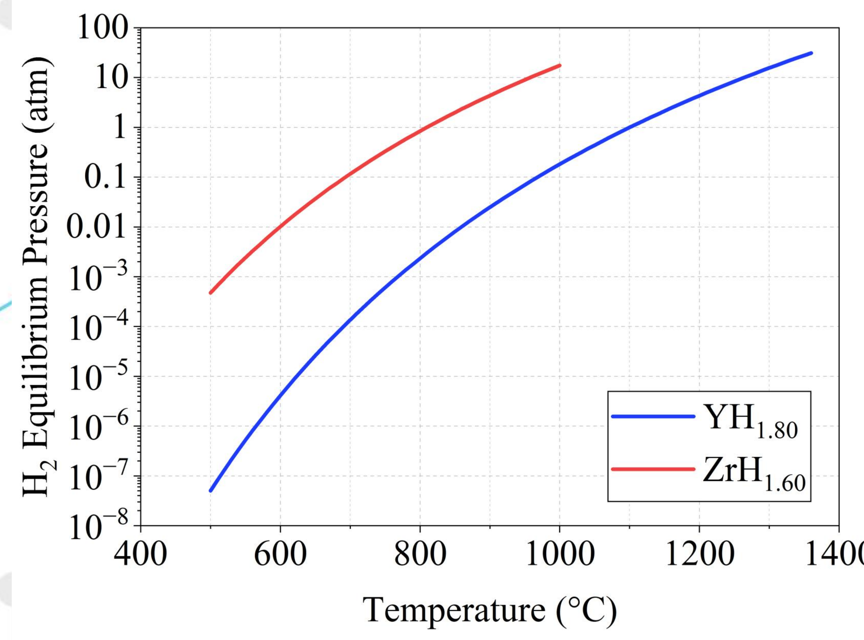
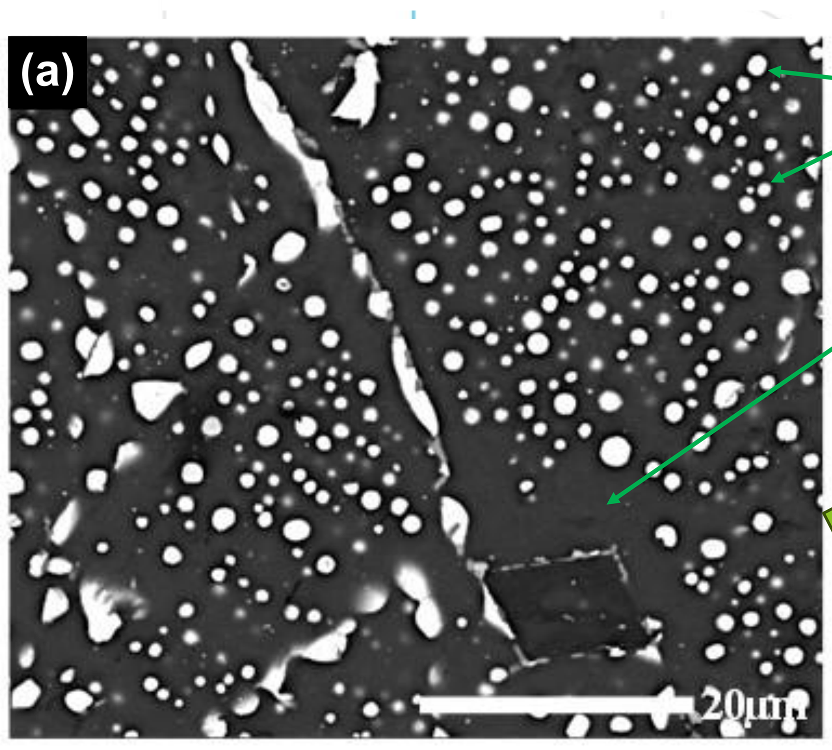
Motivation

Metal hydride nuclear fuels, like uranium-zirconium hydride (U-ZrH_x), combine the neutron moderator (hydrogen) and fuel (uranium) into one material, enabling a thermal neutron spectrum from the fuel alone. This improves reactor economics and transportability by reducing core size, mass, and complexity; this was accomplished for the liquid metal cooled Microreactor Applications Research Validation and EvaLuation (MARVEL) reactor at Idaho National Laboratory (INL) using U-ZrH_x [1]. Unfortunately, U-ZrH_x is not a practical fuel for commercial power production even after fuel optimization [2] due to hydride destabilization. Yttrium retains hydrogen in solid phase at high temperatures better than any other known element. YH_x and U can be separated into different moderator/fuel pins, but doing so can result in a positive reactivity coefficient [3]. The uranium-yttrium hydride (U-YH_x) system has been recognized as the "ultimate" self-moderating nuclear fuel since at least the 1970s, but uranium and yttrium are immiscible (like oil and water) [4,5], leading to rapid fuel degradation and crumbling during service [6]. Stabilizing this fuel system has game-changing disruptive potential for small/transportable nuclear reactor technologies.

Stabilization Mechanism

- **Grain boundary energy** increases substantially at the nano-scale
- **Nano-grain boundary locking** can stabilize immiscible binaries
  - YH_x nano-grains prevent U nanoparticle agglomeration
  - U nanoparticles prevent YH_x grain growth and recrystallization

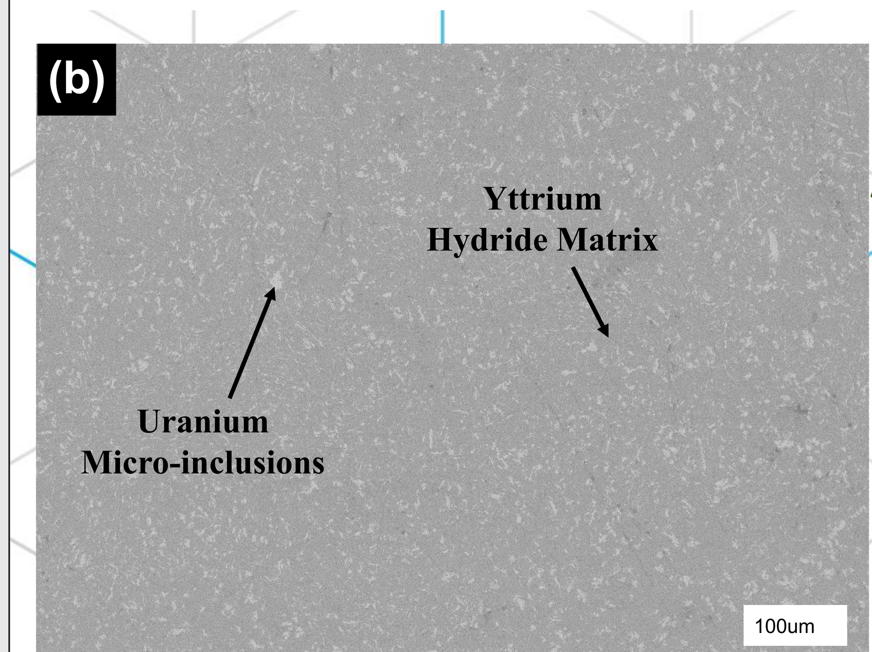




Uranium Micro-Inclusions

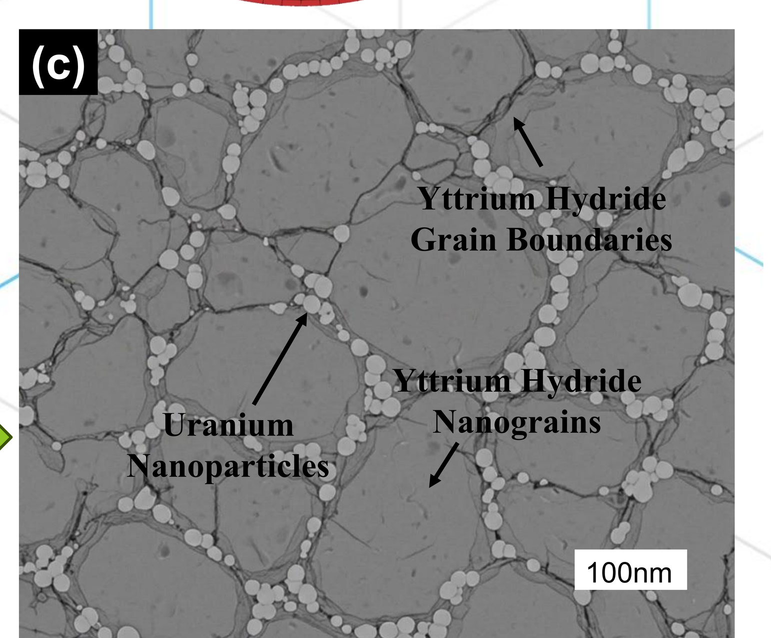
Zirconium Hydride Matrix

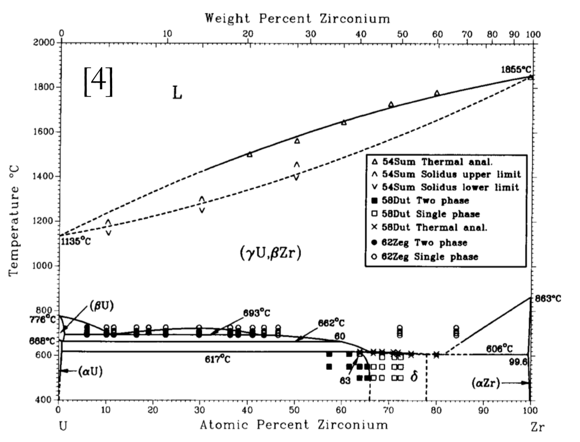
MARVEL Fuel (U-ZrH_x) [1]

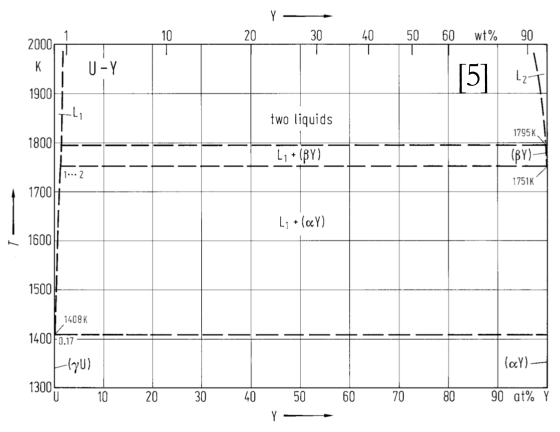


U-YH_x via Hot Isostatic Pressing (HIP)

Nano-Stabilized U-YH_x via High Temperature Equal Channel Angular Extrusion



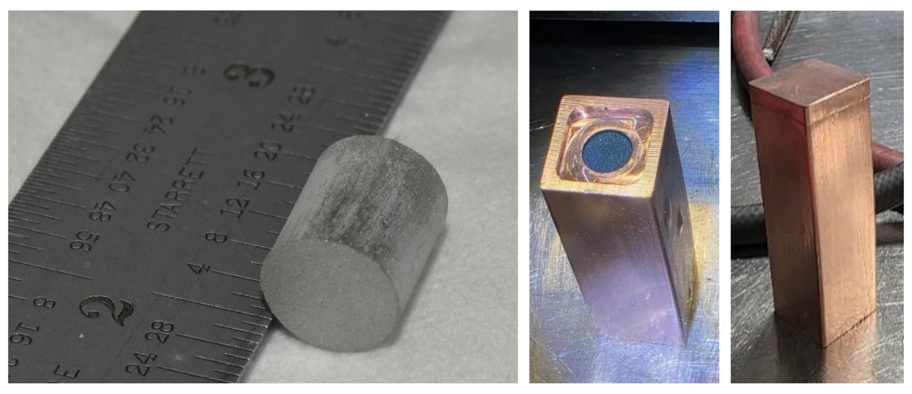


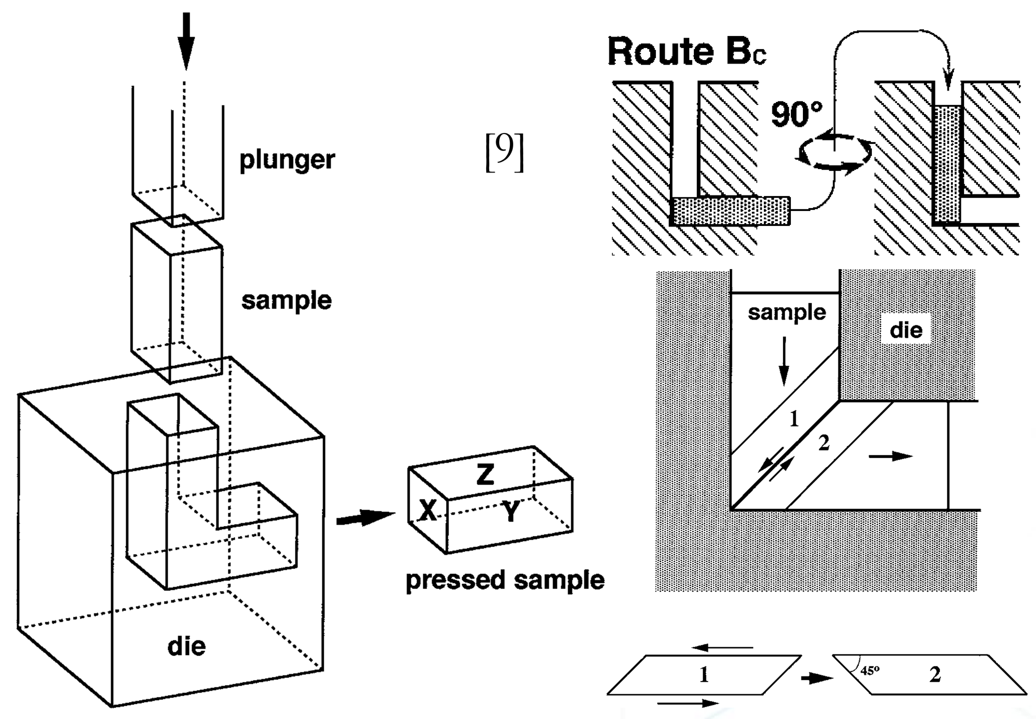


Experimental Methods

Bulk nano-stabilized U-YH_x manufacturing steps [7]:

1) **Mixing and milling** of elemental U, Y, and rare earth powders (Gd, Er, etc., if burnable neutron absorbers [8] are desired);
2) **Equal channel angular extrusion** (ECAE) at high temperature (HT-ECAE) for simultaneous co-consolidation and grain/particle nano-refinement;
3) **Hydriding** under conditions where Y is preferentially hydrided to δ-YH_x (following the isochore for $x \approx 1.80$)



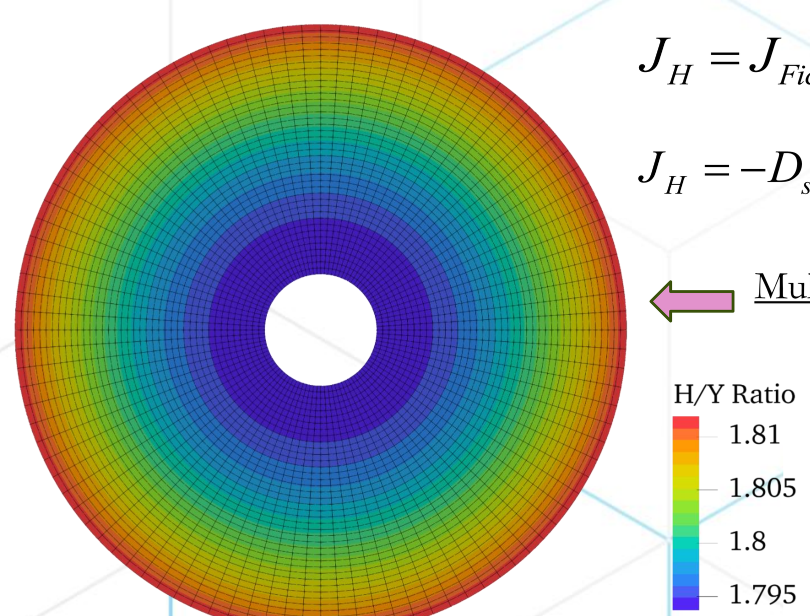


Computational Methods

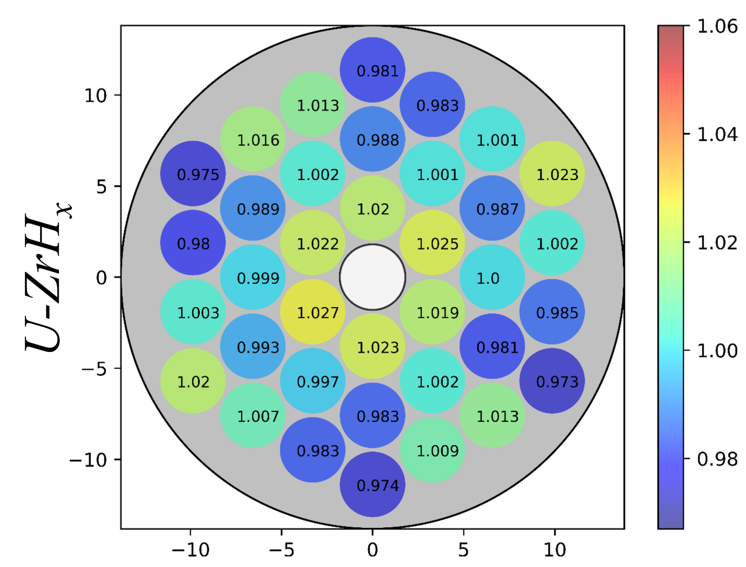
- **BISON**: Thermomechanics
- **MCNP**: Neutronics and nuclear physics
- Results shown here are under MARVEL conditions
- Comparisons under commercially relevant conditions ongoing

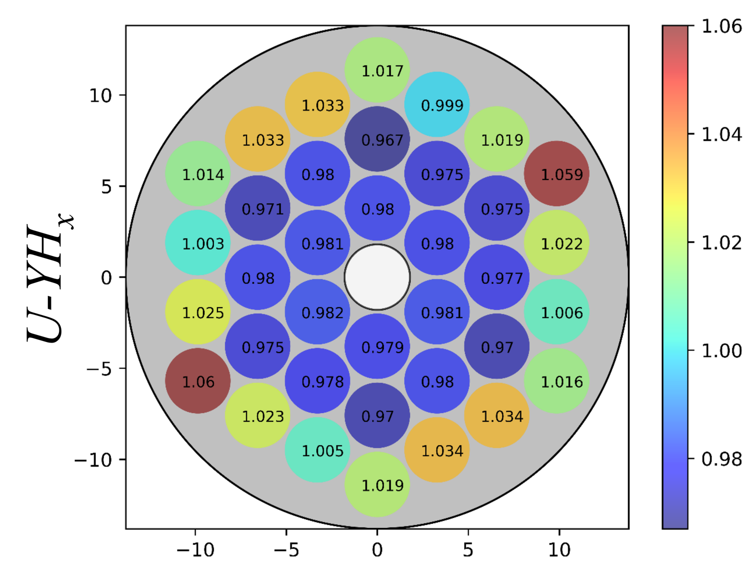
$$J_H = J_{Fickian} + J_{Soret} + J_{Stress}$$

$$J_H = -D_s \nabla C_H - \frac{D_s C_H Q}{RT^2} \nabla T + \frac{D_s C_H V_H}{RT} \nabla \sigma_H$$



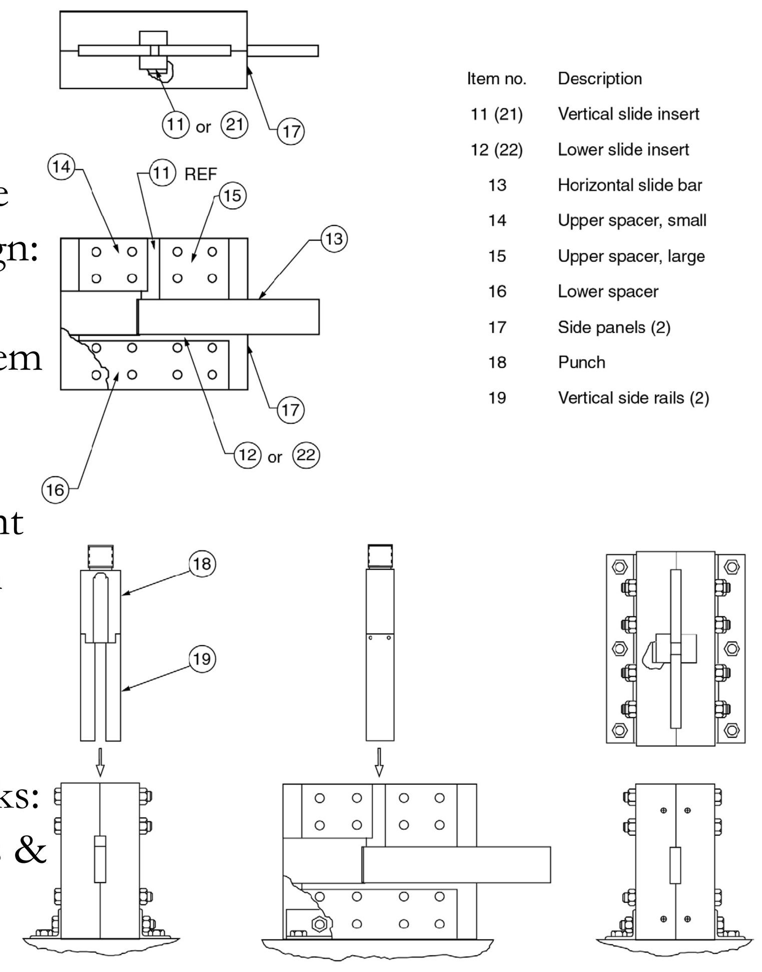
Multiphysics Problem: Hydrogen redistributes under temperature gradients, which changes the spatial neutron spectrum, which changes the local power/temperature profiles.

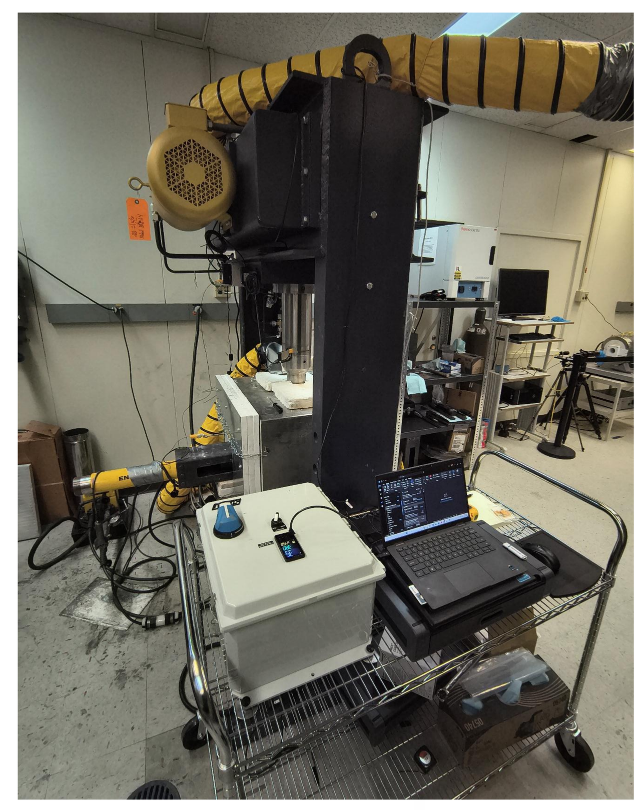




Progress & Future Work

- Retrofitted a 150-ton press at INL for high temp. ECAE with auxiliary backpressure
- INL HT-ECAE design:
  - 90° ECAE Die
  - Backpressure System
  - Billets
  - Furnace System
  - Laser Displacement
  - Ventilation System
- BISON and MCNP simulation models developed [10]
- FY27 Remaining Tasks:
  - Publish neutronics & thermomechanics
  - Optimize ECAE process parameters
  - Stability testing
  - Characterization
- Other new nano-fuels/materials!
- Fuel qualification?
- New reactor designs?





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Intellectual Property: Patent no. 2939-P17703US [7]

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Stabilizing Uranium-Yttrium Hydride (U-YH_x) Fuel Using Nuclear Nanotechnology

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Neutron moderation, or the slowing down of neutrons born from fission, is important for compact transportable nuclear reactors because it reduces both neutron leakage and critical mass. Hydrogen is an extremely effective neutron moderator. Most nuclear reactors use water as primary coolant, which also serves as the moderator due to its hydrogen abundance. In mobile reactor designs, minimizing the volume and mass of the system is a high priority in order to achieve the desired thermal neutron spectrum, which prohibits the use of water coolant due to its associated containment and pressurization system requirements. Metal hydride nuclear fuels, like uranium-zirconium hydride (U-ZrH_x), combine the neutron moderator (hydrogen) and fuel (uranium) into one material, enabling a thermal neutron spectrum from the fuel alone. This improves reactor economics and transportability by reducing core size, mass, and complexity; this was accomplished in the U.S. Microreactor Program's liquid metal cooled Microreactor Applications Research Validation and EvaLuation (MARVEL) reactor at Idaho National Laboratory (INL) using U-ZrH_x. Unfortunately, U-ZrH_x is not a practical fuel for commercial power production even after fuel optimization due to hydride destabilization. Yttrium retains hydrogen in solid phase at high temperatures better than any other known element (roughly 1000× better than zirconium under comparable conditions). Designs have been proposed whereby YH_x and U are separated into different moderator/fuel pins, but doing so can result in a positive reactivity coefficient. The uranium-yttrium hydride (U-YH_x) system has been recognized as the "ultimate" self-moderating nuclear fuel since at least the 1970s, but uranium and yttrium are immiscible (like oil and water), leading to rapid fuel degradation and crumbling during service. This presentation introduces the theory, thermophysics, neutronics, manufacturing, and current progress of the stabilization of the U-YH_x system using a novel grain boundary locking mechanism enabled by nuclear nanotechnology. Stabilizing the U-YH_x fuel system has enormous game-changing disruptive potential for the nascent microreactor industry and was selected for patenting in 2025.