MARVEL Microreactor Overview and Fuel System

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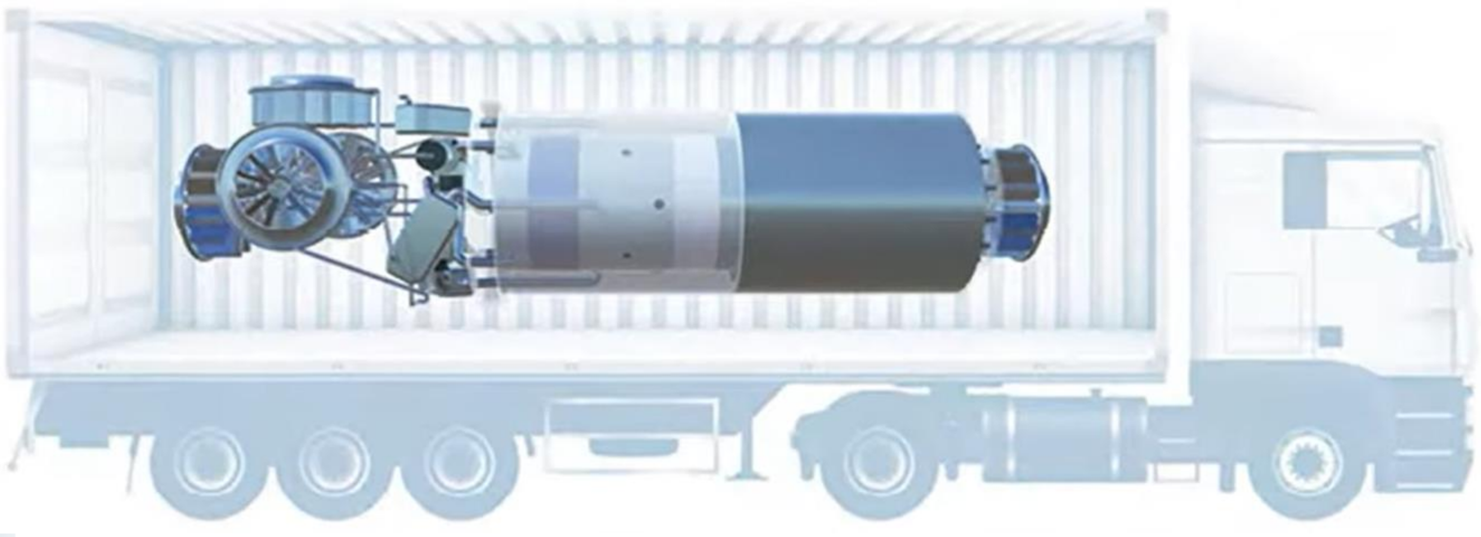
Overview

- Program Background
- Fuel System
- Material Interactions
- Summary

Nuclear Powered Microreactors in 5 Years



OKLO

X energy

RADIANT

BWXT
BWX Technologies, Inc.

LOCKHEED MARTIN

Westinghouse

GENERAL ATOMICS

MRP Microreactor Program

Factory Fabricated

Transportable (Before *And* After Service)

Self-Regulating

Microreactor Application Research, Validation and EvaLuation

- Rapid prototype microreactor, ~ 100 kW_{th}
- Integrate with intermittent power sources (solar and wind) to form a “first of its kind” nuclear coupled microgrid
- Share lessons learned with commercial developers
- Within **5 years**
  - Design
  - Licensing
  - Construction (at INL)
  - Testing
  - Operation

Critical Characteristics	
Reactor Thermal power	~100 kW
Nominal Electrical Output	~20 kWe
High-grade heat	~45 kWt at 450 ºC
Coolant, natural circulation	Sodium-Potassium eutectic (NaK)
Fuel	U-ZrH
Reactivity Control	4 control drums (B_4C)
Location	INL, TREAT Facility

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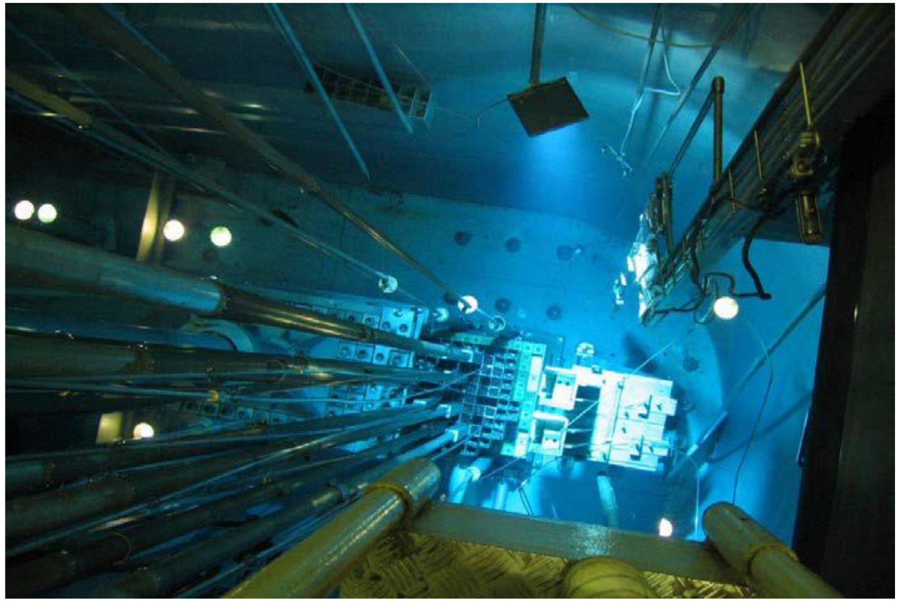
Background – MARVEL Fuel Selection

- The **304 SS-clad U-ZrH fuel system** has been selected for MARVEL (aka TRIGA reactor fuel)
- Fuel will be fabricated and purchased from TRIGA International
  - Same materials, same fabrication processes, etc.
- US NRC has licensed TRIGA reactors since the 1950s with this fuel system
- U-ZrH used previously in NASA space reactors (SNAP* program)



[1] *History, Development and Future of TRIGA Research Reactors*, International Atomic Energy Agency, Vienna, 2016.
*System for Nuclear Auxiliary Power

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Background – The MARVEL Fuel Element

- Fuel meat contains fissile (^{235}U) *and* neutron-moderating (^{1}H) species
- Excellent chemical stability in TRIGA reactor coolant (we'll discuss NaK in a moment)
- High fission product retentivity and high-temperature stability
- Fuel meat and cladding retain integrity under large reactivity insertions and frequent power cycling
- From NUREG-1282, fuel safety limit defined by gas over pressurization inside the element [1]

[1] *Safety Evaluation Report on High-Uranium Content, Low-Enriched Uranium-Zirconium Hydride Fuels for TRIGA Reactors*, NUREG-1282, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, (1987).

NRC Guidelines: NUREG-1537

- MARVEL fuel authorization strategy follows US NRC regulatory guidelines:
- Completed by MARVEL Program (see **INL/RPT-22-68555 *MARVEL Reactor Fuel Performance Report*** [2])
  - Describe history of fuel type (previous tests, qualifications, etc.)
  - Describe geometries, composition, thermophysical properties, etc.
  - Describe irradiation performance relationships
  - Determine operational limits
  - Assess risk of reaching limits
  - *Information and analyses "should be current"*

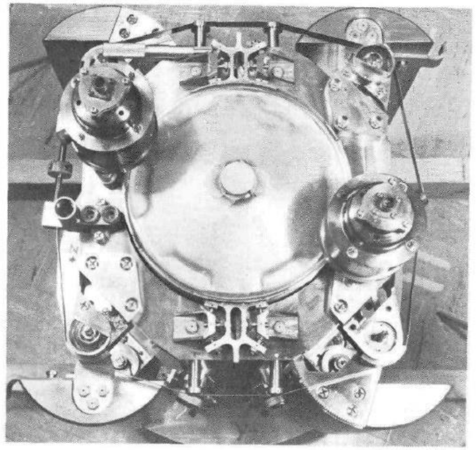
[1] NUREG-1537, *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors*, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, 1996.
[2] J.A. Evans, R.T. Sweet, J. Dennis D. Keiser, *MARVEL Reactor Fuel Performance Report*, INL/RPT-22-68555-Rev000, DE-AC07-05ID14517, US DOE Office of Nuclear Energy, (2023).

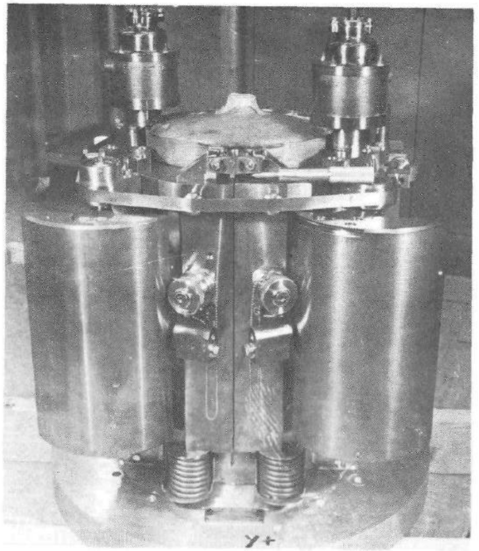
Background – Space Nuclear Auxiliary Power (SNAP) Program

- NASA's SNAP program developed nuclear reactors and RTGs for space missions in the 1950s and 1960s
- Post-irradiation examination following the SNAP-10A "extended BDBA test" (conditions held for 10,000 hours) showed no evidence of incipient failure

	MARVEL	SNAP-10A
Fuel Type	U-ZrH	U-ZrH
wt% U	30	10
Enrichment (%)	19.75	93
Gas gap	Air (1 atm)	He (0.1 atm)
Cladding	Type 304 SS	Hastelloy-N [a]
# Fuel Elements	36	37
Coolant	NaK	NaK
Fuel Temp (°C)	565	585
Power (kW_{th})	85	34
Control	BeO + poison (B_4C)	Be wedges

(a) Included a thin film (internal, 2-4 mils thick) of Solaramic (glassy coating BA)





[1] H. Dieckamp, *Nuclear Space Power Systems*, Atomics International, Canoga Park, California, 1967.

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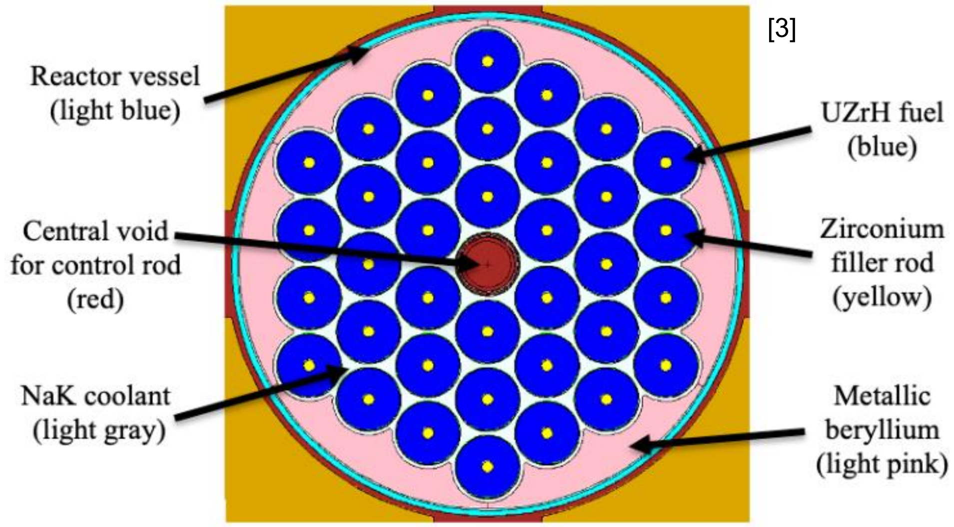
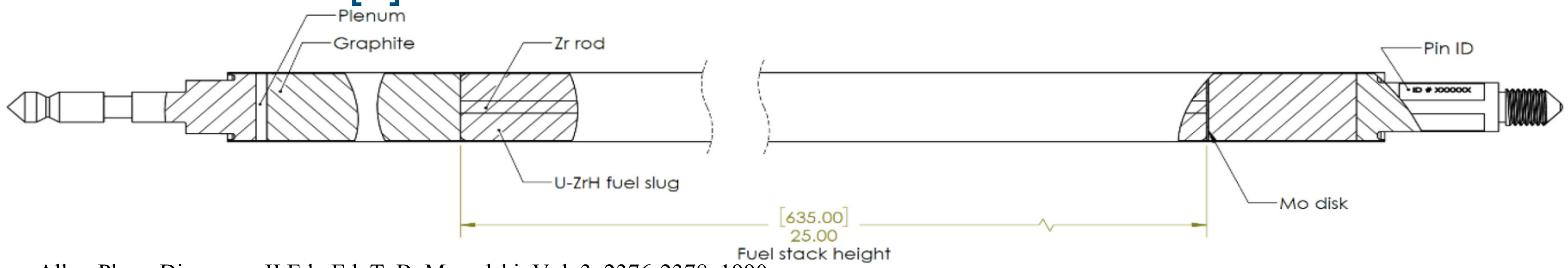
MARVEL Fuel System Overview

- 36 Elements each composed of:
  - 5 U-ZrH fuel meats clad in Type 304 SS
    - Annular with Zr rod
    - 30 wt% U, 19.75 % enriched
    - H/Zr: nominally 1.6
  - 2 graphite axial neutron reflectors
  - Peak cladding temperature: ~550 ºC
- Primary coolant: Sodium-Potassium (NaK) eutectic
  - 21 wt% Na, 79 wt% K [1]
  - Eutectic temperature: -13 ºC [2]
  - Boiling temperature: >785 ºC [2]



MARVEL Core schematic



[1] C. W. Bale, K-Na (Potassium-Sodium), Binary Alloy Phase Diagrams, II Ed., Ed. T. B. Massalski, Vol. 3, 2376-2378, 1990
[2] O. J. Foust, "Sodium-NaK Engineering Handbook: Volume I, Sodium Chemistry and Physical Properties", Gordon and Breach, 1972
[3] T. Lange, *et al.*, "MARVEL Core Design and Neutronics Characteristics", American Nuclear Society Annual Meeting, 2022

A Few Fuel Performance Phenomena to Consider

- Hydrogen redistribution and dissociation (fuel)
- Internal gas pressure
  - From as-fabricated air in gas gap, fission gas, hydrogen
- Oxygen interactions (with fission products, with graphite, coolant impurity)
- Geometric changes (Zr rod, fuel meat, cladding, and graphite reflectors)
  - Thermal expansion, fission/void growth, crystallographic changes of fuel as a result of H_2 redistribution, swelling, radiation-enhanced creep
- Radiation effects
  - Hardening, embrittlement, etc.
- Fuel-cladding mechanical interactions (FCMI)
- **Fuel-cladding chemical interactions (FCCI)**
- **Coolant-cladding interaction**
- Hydrogen embrittlement (cladding)

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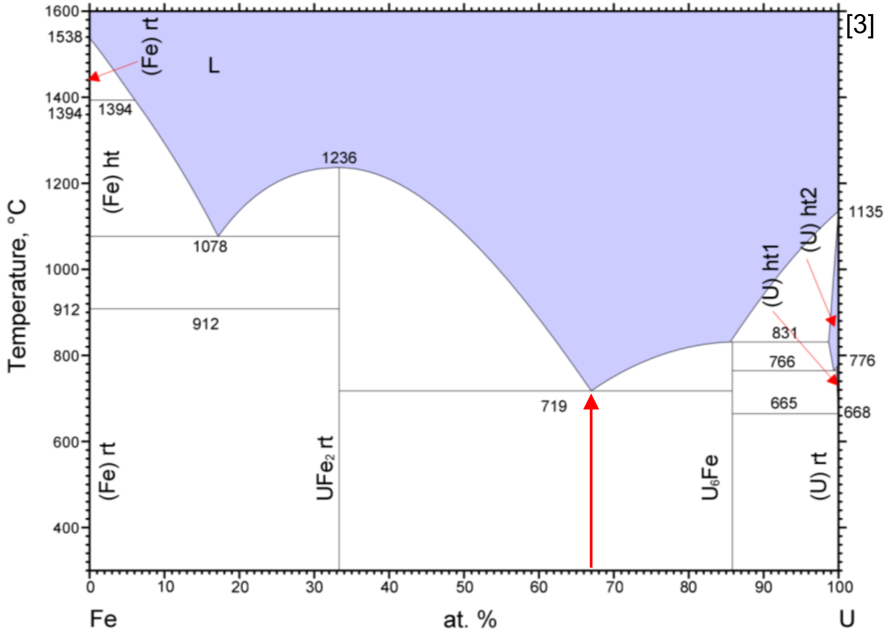
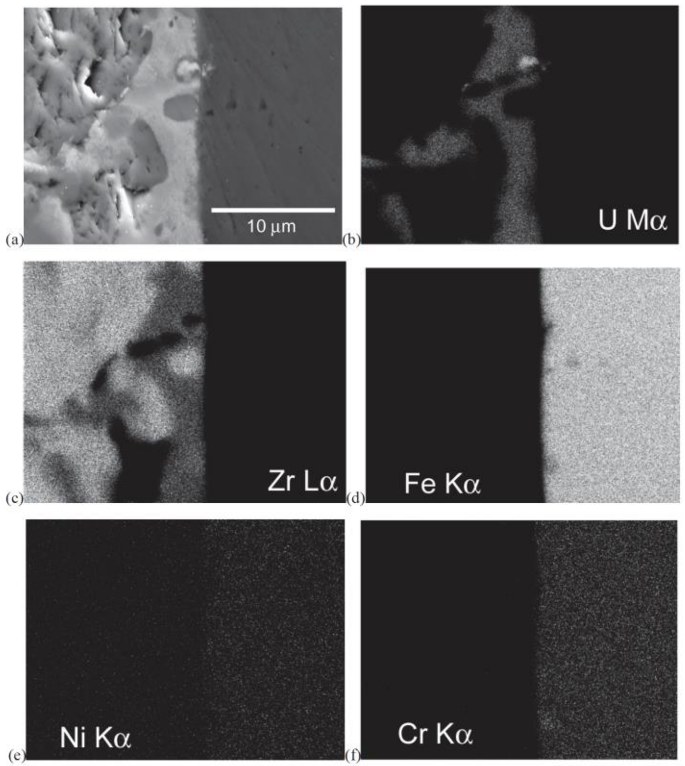
Fuel-Cladding interaction: As-fabricated and irradiated

- At 730 and 800 °C, for as-fabricated TRIGA fuel (U-ZrH, Type 304 SS) [1]
  - Of primary concern: Fe-U eutectic (719 °C)
  - No evidence of eutectic formation after a 1-hour soak

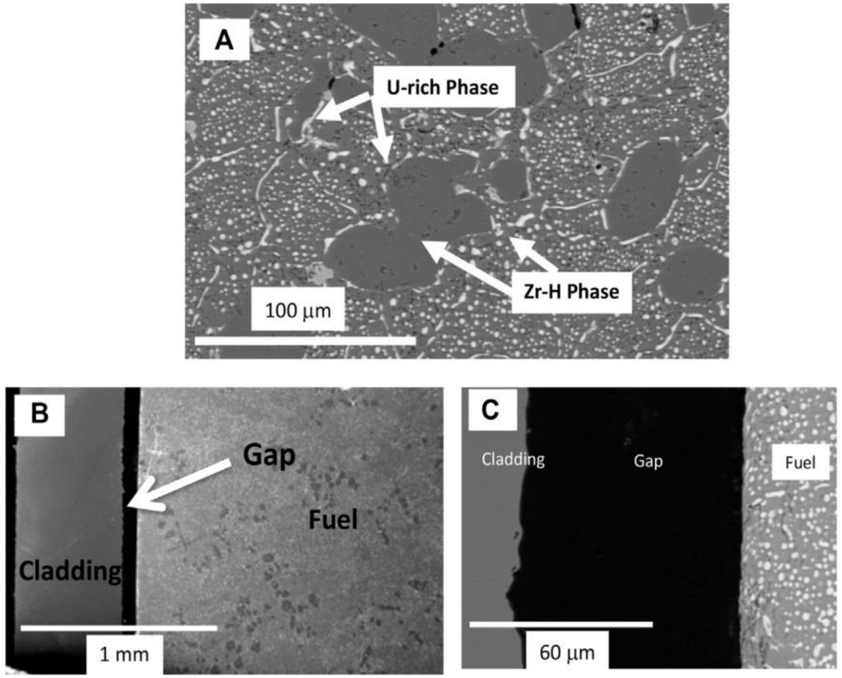
- As-irradiated TRIGA Fuel Analysis (20% burnup) [2]
  - No evidence of FCCI or FCMI was observed



Fe-U eutectic
- 719 ºC
- ~90 wt% U, 10 wt% Fe



U-ZrH / SS 304 diffusion couple
800 ºC, 1 hour [1]



As-irradiated 30/20 TRIGA fuel [2]

[1] D. D. Keiser, *et al.*, “High temperature Chemical Compatibility of As-Fabricated TRIGA Fuel and Type 304 Stainless Steel Cladding”, INL/EXT-12-27153, 2012
[2] D. Keiser. Jr., J.-F. Jue, F. Rice, E. Woolstenhulme, Post irradiation examination of a uranium-zirconium hydride TRIGA fuel element, Front Energy Res 11 (2023) 12.
[3] Chatain S., Guéneau C., Labroche D., Rogez J., and Dugne O., Thermodynamic Assessment of the Fe-U Binary System, J. Phase Equilib., Vol. 24, 2003, p 122-131

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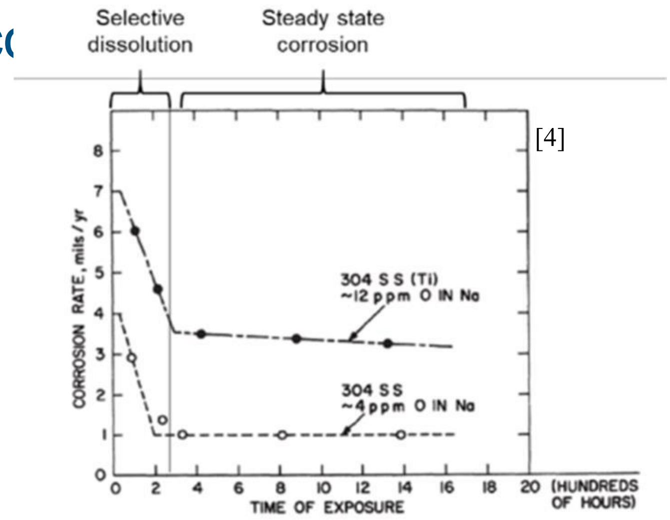
MARVEL Fuel Meat and Cladding Compatibility with Hot NaK Coolant

- Fuel Meat / NaK
  - No physical or microstructural changes of U-ZrH fuel were observed in NaK up to ~540 °C [1]
- Cladding / NaK
  - At temperatures above the peak cladding temperature for MARVEL
    - Intergranular corrosion, pitting corrosion, and general corrosion observed [2, 3]

Time [h]	Temperature 650 °C		Temperature 760 °C	
	Attack depth [μm]	Observation	Attack depth [μm]	Observation
1500	0	No observable attack	0	Slight evidence of decarburization
2500	35.5	Intergranular	35.6	pitting corrosion
3500		General corrosion	33	intergranular corrosion
4500	338.1	Pitting	58.4	decarburization

Corrosion of Type 304 SS in liquid NaK-78, O_2content: <20ppm



Corrosion rates of Type 304 SS in high-velocity sodium at 760 °C

[1] J. Vetrano, *Delta-Phase Zirconium Hydride as a Solid Moderator*, BMI-1243, Battelle Memorial Institute, Columbus, Ohio, 1957.
[2] C. A. Zimmerman, “Corrosion of Type 316 Stainless Steel in NaK Service – A Literature Survey”, IDO-146651.
[3] M. A. Perlow, “SNAP-2 Primary Coolant Development”, NAA-SR-6439, North American Aviation, 1961.
[4] Weeks, J.R. and H.S. Isaacs, Corrosion and Deposition of Steels and Nickel-Base Alloys in Liquid Sodium, in Advances in Corrosion Science and Technology, M.G. Fontana and R.W. Staehle, Editors. 1973, Springer US: Boston, MA. p. 1-66.

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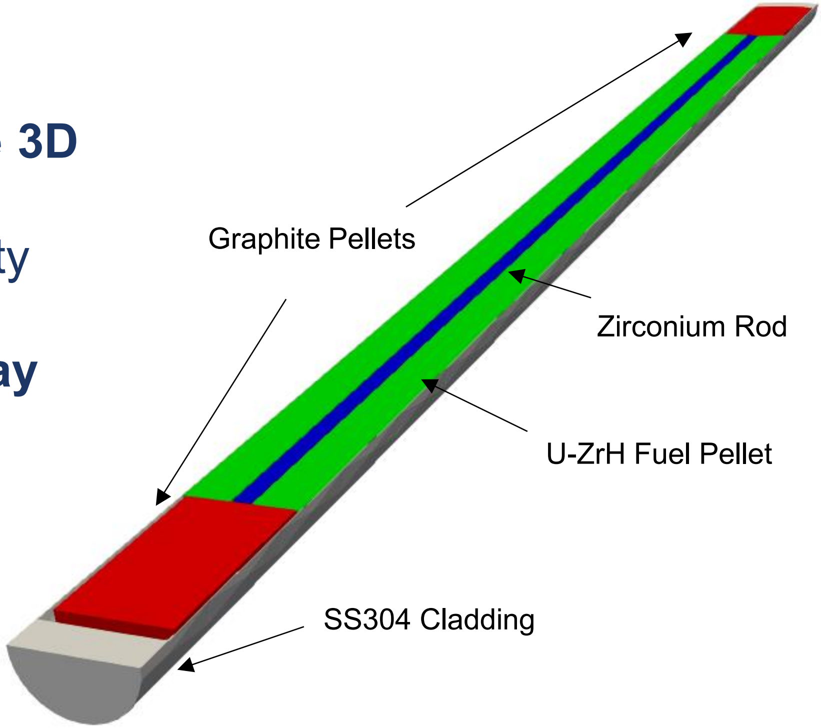
Ongoing analyses include 3-dimensional, time-dependent conditions

In order to show how the fuel rod pitch will change with extreme temperature/irradiation (flux/fission rate) gradients, a representative 3D model is used.

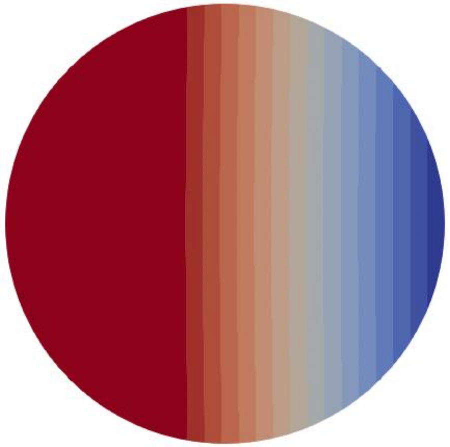
- Azimuthally- and axially-varying temperature/irradiation capability



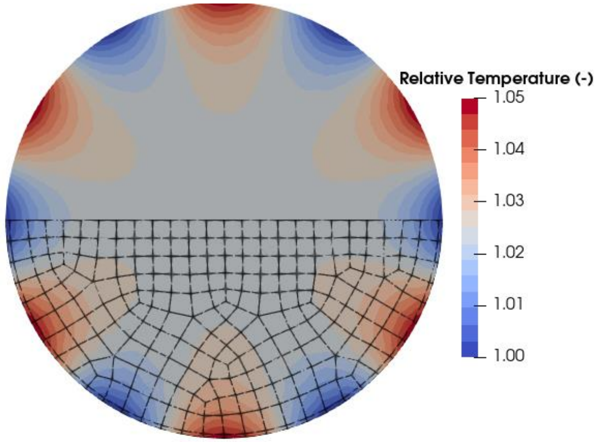
180˚-symmetric TRIGA fuel element model

Hydrogen redistribution in the fuel (i.e. evolution of the H/Zr ratio) may alter fuel behavior

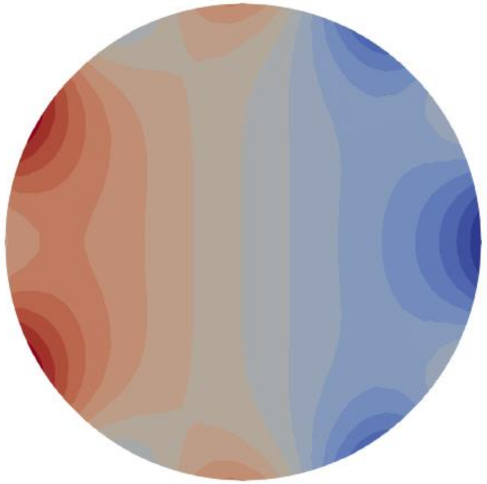
- Constitutive properties (including H/Zr dependance) are used.
- Hydrogen diffusion model is currently being investigated



180˚ variation after core radial power profile



30˚ variation after nearest neighbor rods



Resulting composite temperature variation

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Summary

- The MARVEL Reactor has design based on TRIGA reactors and the SNAP experiments
- MARVEL fuel authorization strategy follows NUREG-1537 guidance
- MARVEL reactor fuel performance is bounded by already-existing fuel licenses
  - Maintains structural integrity, geometric stability, and behavior is stable *and* predictable under bounding accident conditions
- MARVEL will be constructed and deployed at the Idaho National Laboratory
- MARVEL will be integrated into a “first of its kind” nuclear-coupled microgrid

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