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Uranium-Zirconium Hydride Nuclear Fuel Performance in the MARVEL Microreactor

MARVEL Technology Review Meeting

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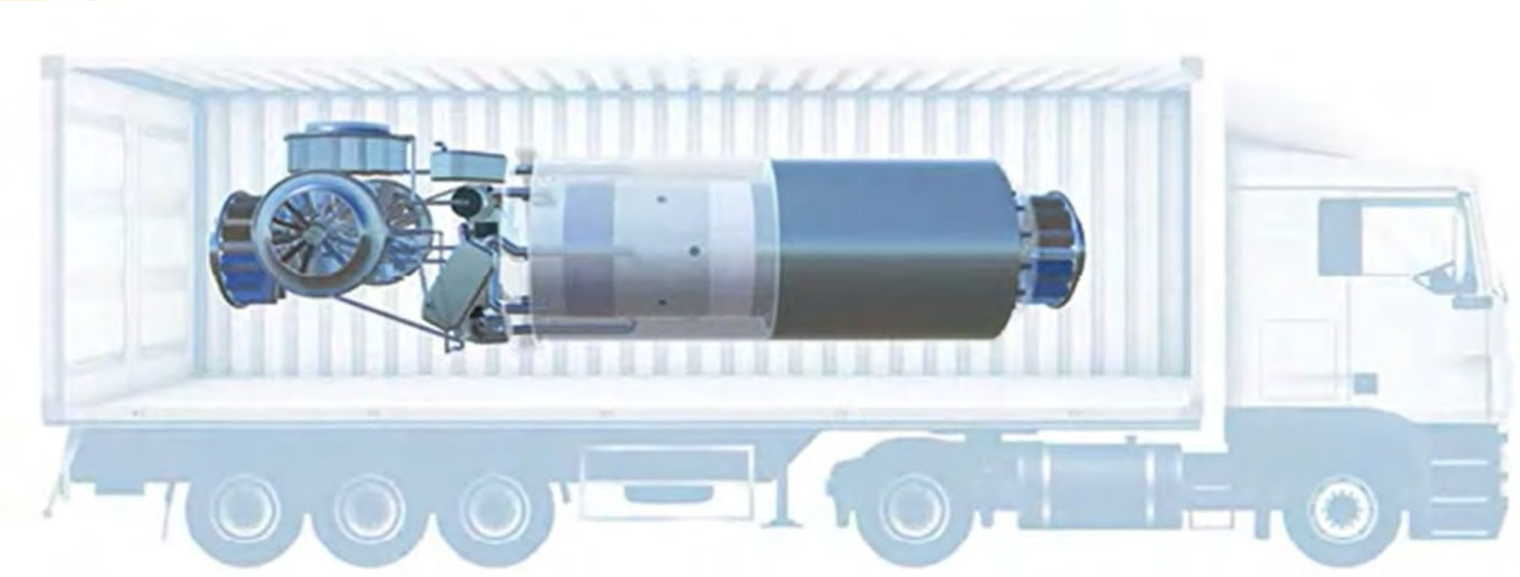
Background

MRP Microreactor Program

Nuclear Powered Microreactors



OKLO

X-energy

RADIANT

BWXT
BWX Technologies, Inc.

LOCKHEED MARTIN

Westinghouse

GENERAL ATOMICS

MRP Microreactor Program

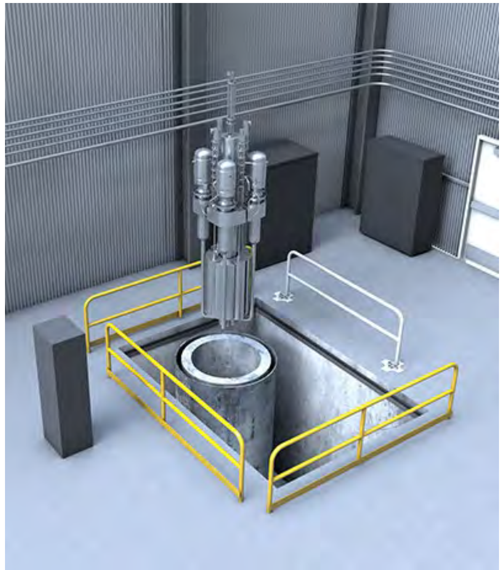
Factory Fabricated

Transportable (Before *And* After Service)

Self-Regulating

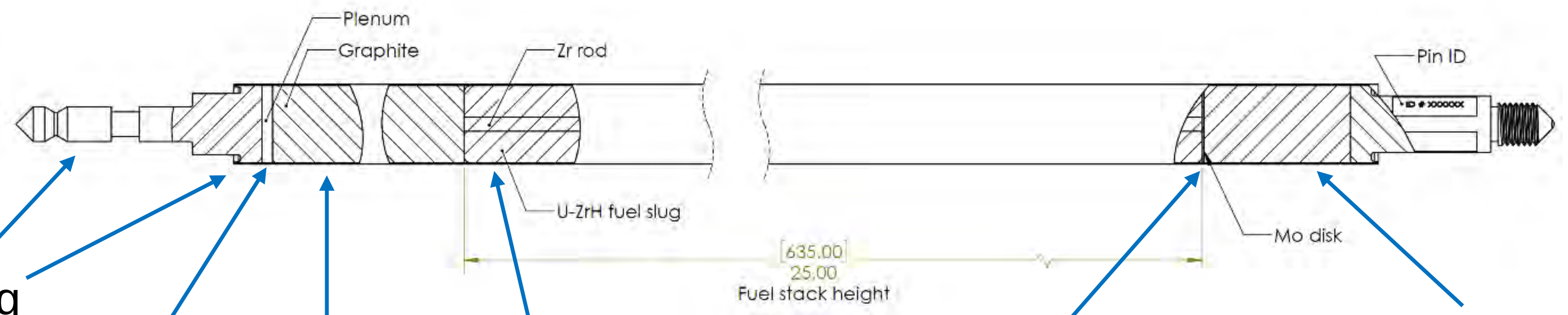
Microreactor Application Research, Validation and EvaLuation

- Rapid prototype Gen. IV microreactor, < 100 kW_{th}
- No pressurizer, but still high temperature coolant
  - MARVEL > 530 °C
  - LWR ~ 315 °C
- Liquid metal (NaK-78) cooled
- Produce combined heat and power (CHP)
- Integrate with intermittent power sources (solar and wind) in world's first functional nuclear-coupled microgrid
- Undertake the risk of "being the first"
- Share lessons learned with commercial developers
- Rapidly achieve:
  - Design
  - Authorization
  - Construction (at INL)
  - Testing
  - Operatation



Program

MARVEL Fuel Element Design



304 SS cladding and end-caps

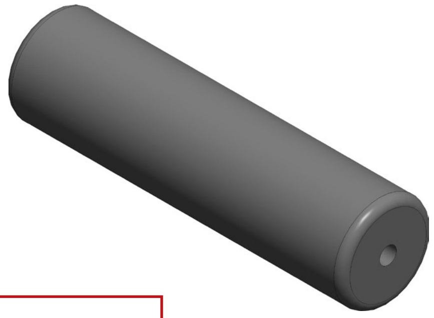
Plenum (ambient air)

Graphite neutron reflector

(5x) *Annular* **U-ZrH$_{1.6}$** fuel meat (30 wt% uranium, 19.75% enrichment) with central Zr rod

Mo diffusion barrier disc

Graphite neutron reflector



U-ZrH$_x$ contains both the fuel (uranium) *and* neutron moderator (hydrogen) in one, reducing the size requirement of the reactor core to achieve the desired neutron energy spectrum

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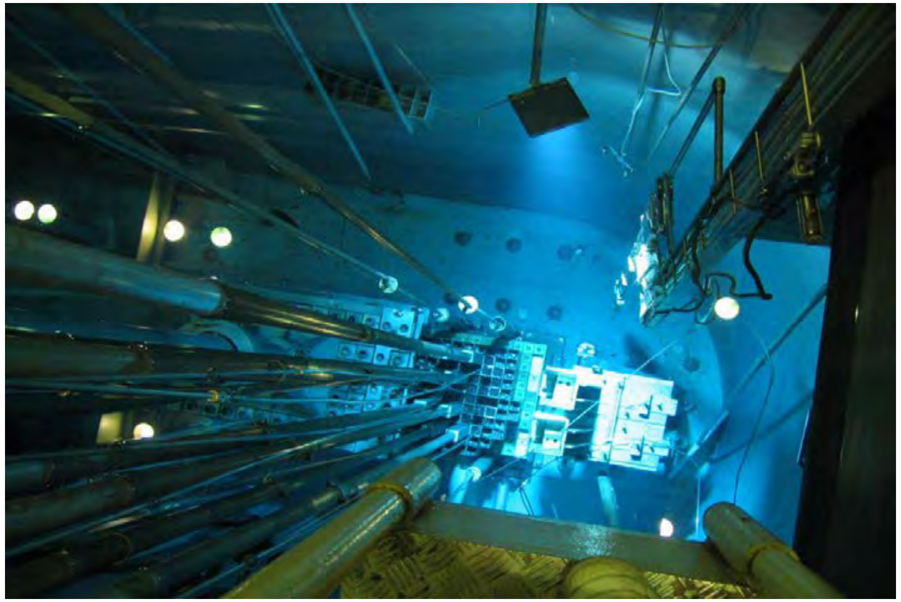
U-$ZrH_{1.6}$ Fuel Already Used in TRIGA Reactors

- TRIGA reactors have been licensed by US NRC since the 1950s
- TRIGA reactors use U-$ZrH_{1.60}$ fuel
- U-$ZrH_{1.60}$ fuel has been used previously in NASA space reactors (SNAP Program)
- MARVEL fuel will be fabricated and purchased from TRIGA International
  - Same materials, same fabrication processes, etc.



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

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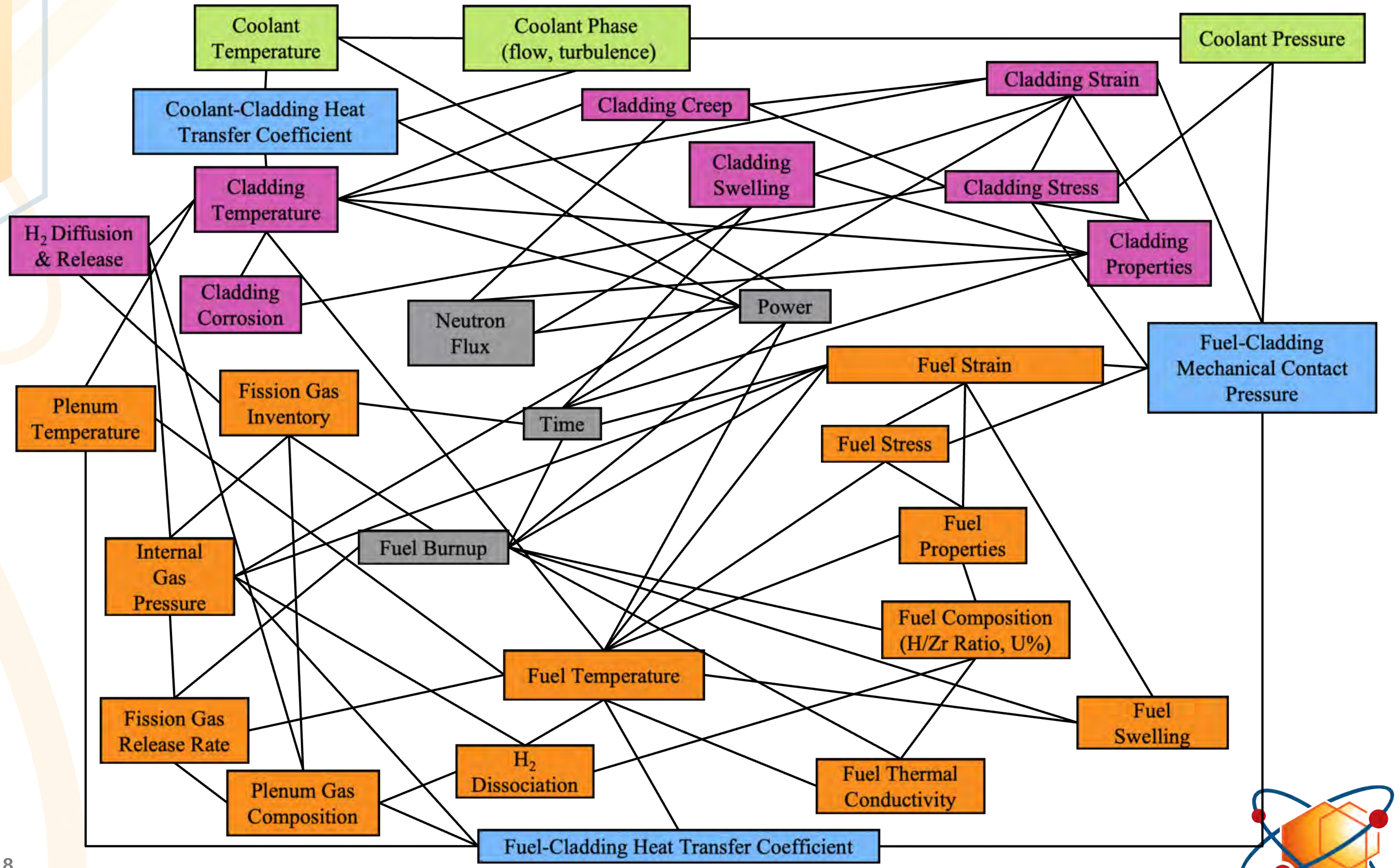
MARVEL Fuel Element Properties

Fuel Element Material Evolution is Complex



- Multiphysics
  - Thermo-mechanics
  - Mass transport
  - Chemistry
  - Neutronics
  - Thermal-hydraulics
- Multi-length scale
  - Important physics operate at level of microstructure
  - Need real predictions at engineering scale
- Multi-temporal scale
  - Long, steady operation
  - Short power ramps
  - Rapid transients

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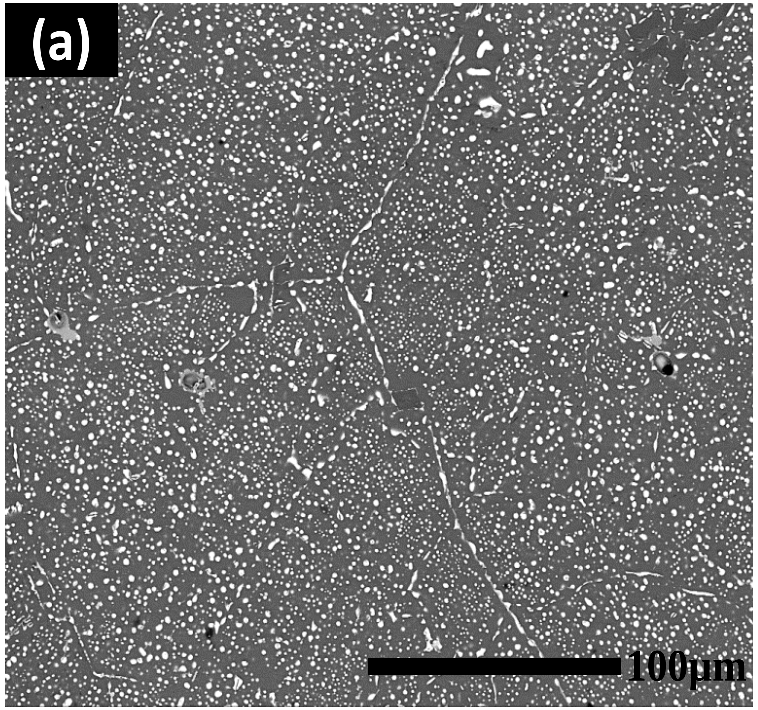
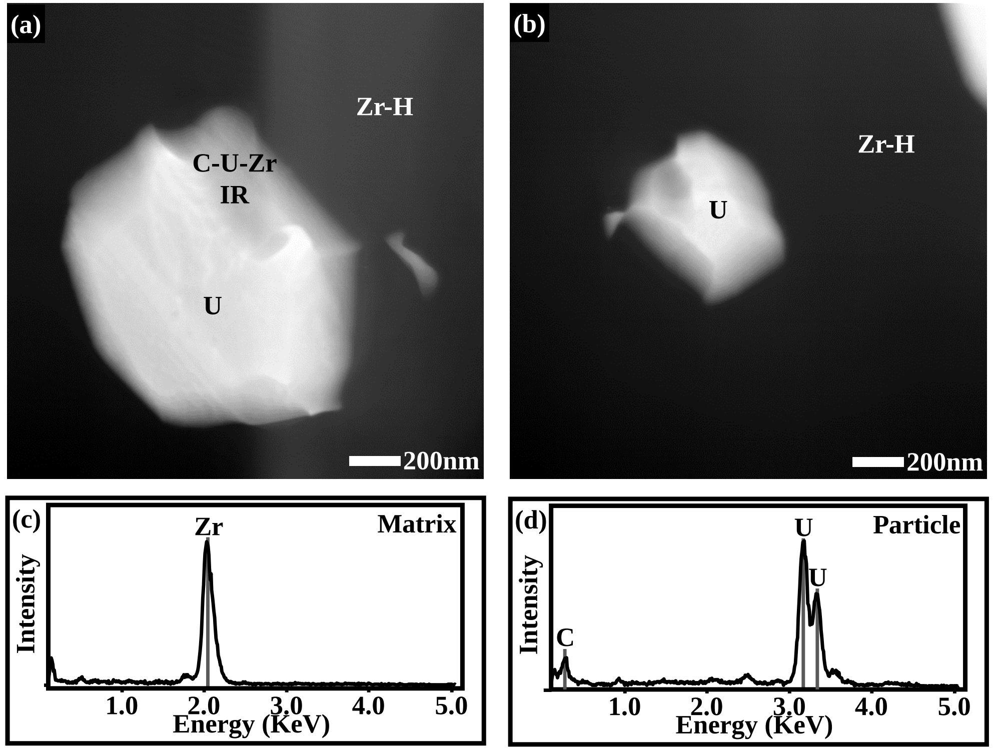
Adapted from D. Sunderland, Anatech – Nuclear Science and Technology Interaction Program (NSTIP), ORNL, July 8, 2011, reproduced from Lassman

MARVEL Fuel Meat Microstructure

- Microstructure of U-$ZrH_{1.6}$ confirmed
  - 30 wt% U
  - ~11 vol% U
- Uranium micro-inclusions embedded in $ZrH_{1.6}$ matrix
  - $ZrH_{1.6}$ is δ-phase (FCC)





[1] J.A. Evans et.al., *Uranium-Zirconium Hydride Nuclear Fuel Performance in the NaK-Cooled MARVEL Microreactor*, J Nucl Mater. *In Production.*

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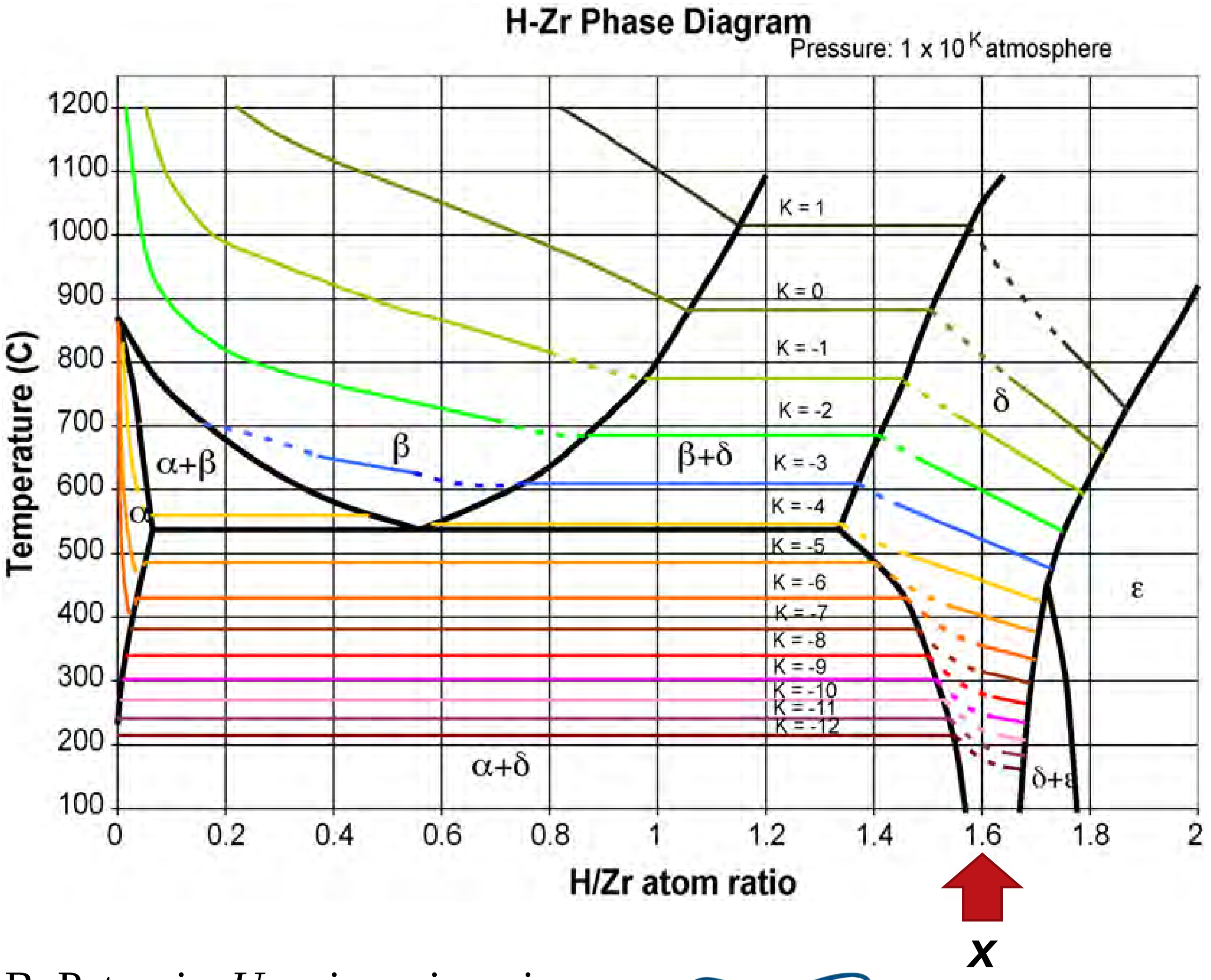
U-ZrH$_x$ Thermophysical Properties

- Matrix remains δ-phase up to > 1000 °C
  - FCC
  - Geometry is stable and predictable
- Cladding (and fuel) are compatible with NaK
- Design limits are based on *cladding rupture due to internal gas overpressurization (and FCMI, if present)*



[1] D. Olander, E. Greenspan, H.D. Garkisch, B. Petrovic, *Uranium-zirconium hydride fuel properties*, Nucl Eng Des 239(8) (2009) 1406-1424.

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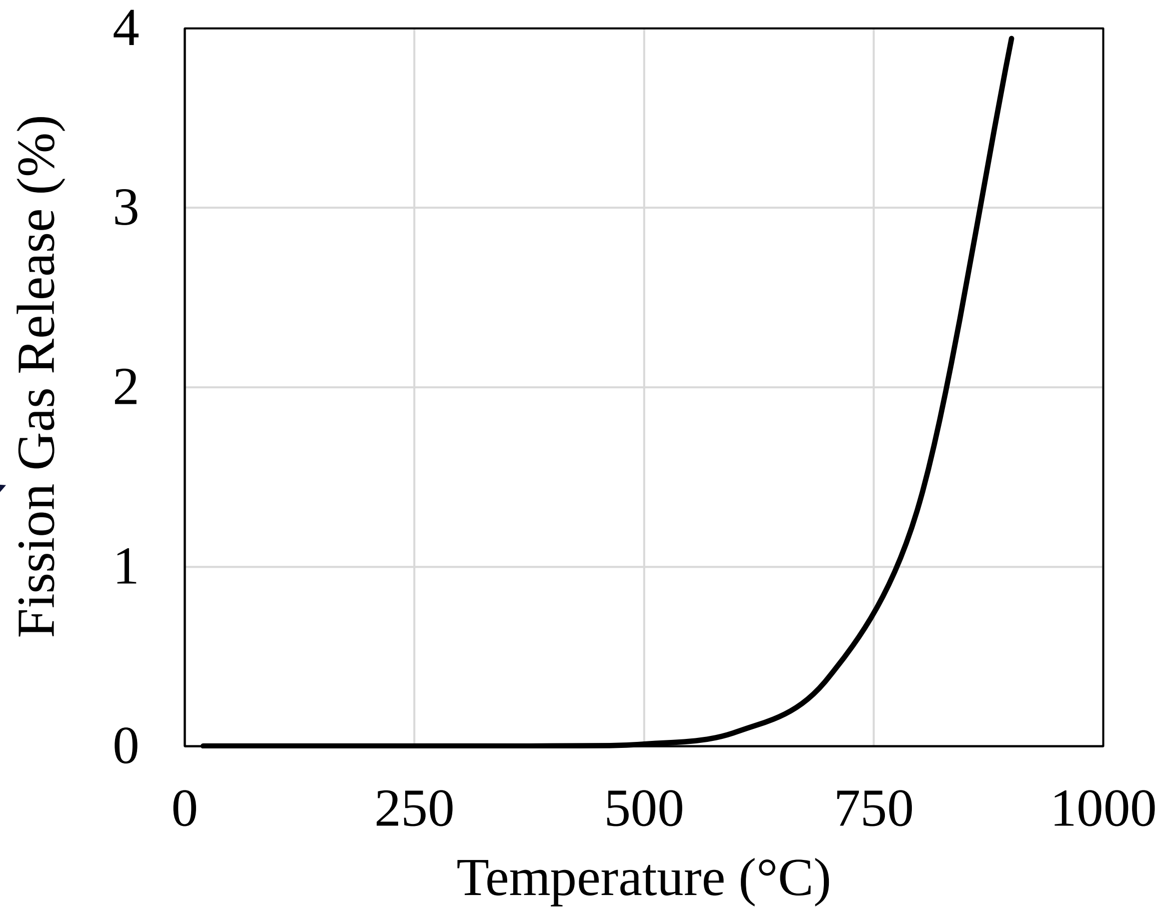
Fuel Element Internal Gas Gap/Plenum Pressure

- Air → $PV = nRT$
- Fission gas
  - Produced → [1] $\Omega_{FGP} \approx \frac{0.3FV_{fm}}{N_A}$
  - Released

[2] $$\Gamma_{FGR} = 1.5\cdot10^{-5} + 3600e^{\frac{-1.34\cdot10^{-4}}{T_K}}$$



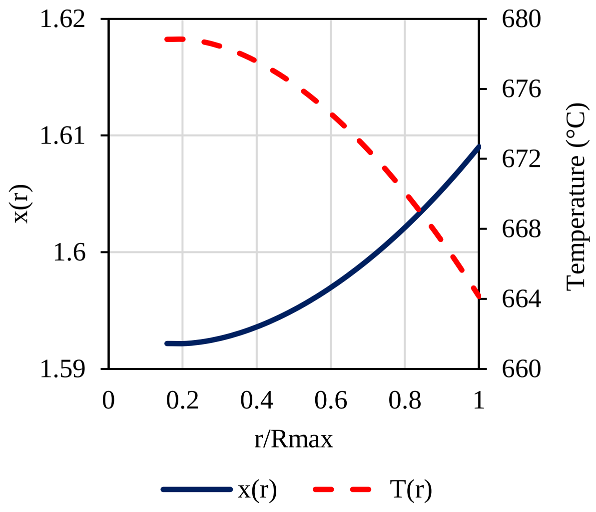
- Hydrogen Dissociation…

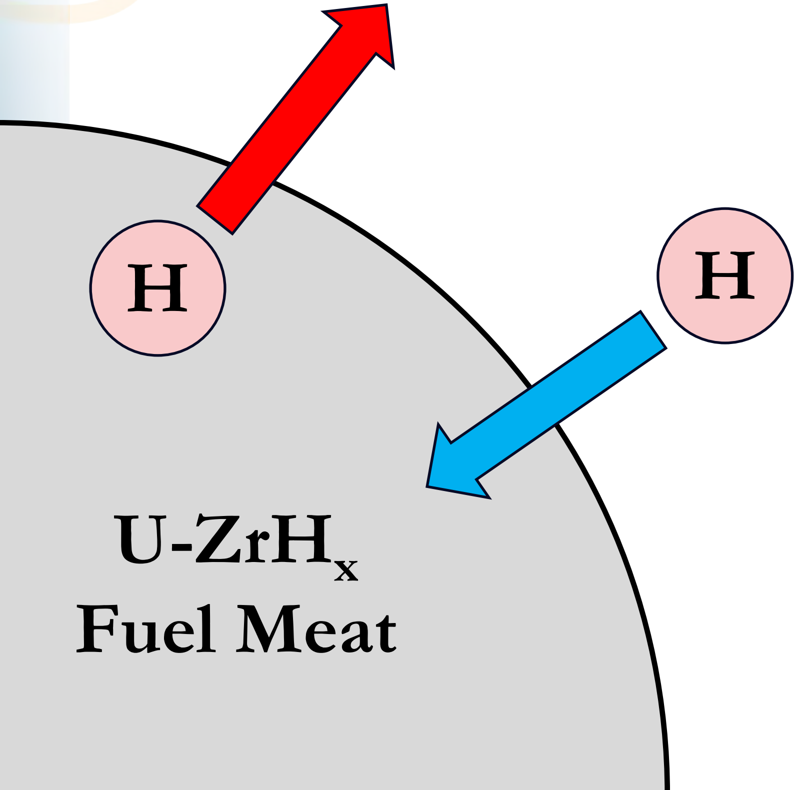
[1] M. Tonks, D. Andersson, R. Devanathan, R. Dubourg, A. El-Azab, M. Freyss, F. Iglesias, K. Kulacsy, G. Pastore, S.R. Phillpot, M. Welland, *Unit mechanisms of fission gas release: Current understanding and future needs*, J Nucl Mater 504 (2018) 300-317.

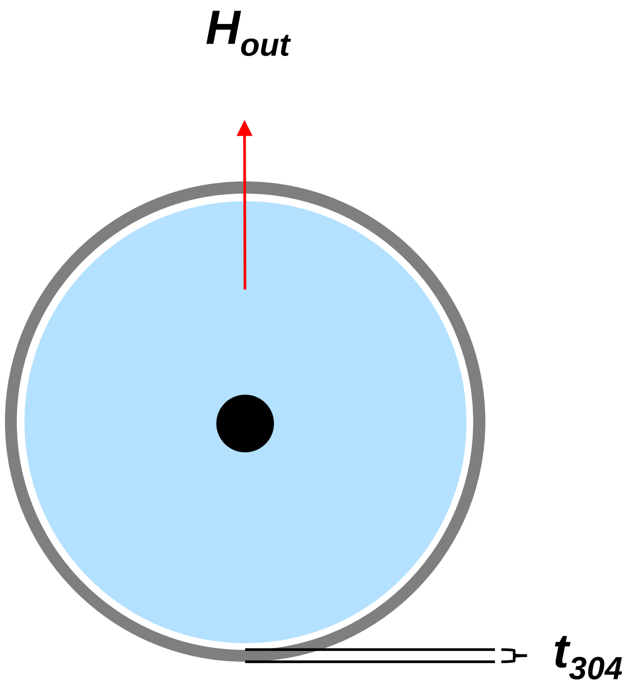
[2] M.T. Simnad, F.C. Foushee, G.B. West, *Fuel Elements for Pulsed TRIGA Research Reactors*, Nucl Technol 28(1) (1976) 31-56.

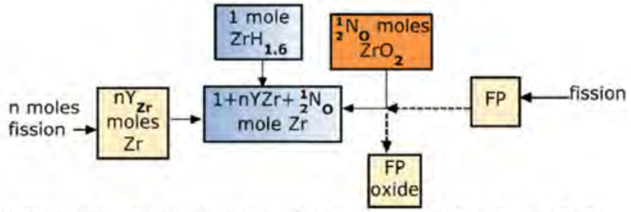
Summary of Hydrogen Evolution Mechanisms

1. Hydrogen diffusion and redistribution
2. Hydrogen dissociation (out of the fuel meat, into the gas gap)
3. Hydrogen leakage (through the cladding, into the coolant)
4. H/Zr evolution due to fission fragment oxidation reactions

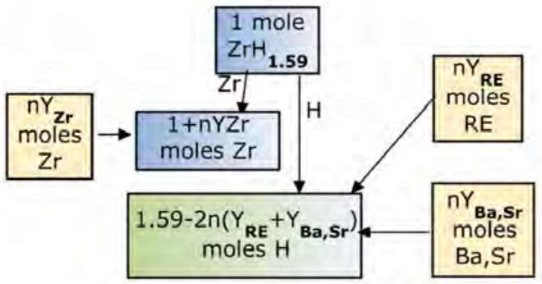








(a) Change of H/Zr ratio during transfer of oxygen from Zr to Re and Ba,Sr



(b) Reduction in H/Zr ratio with burnup

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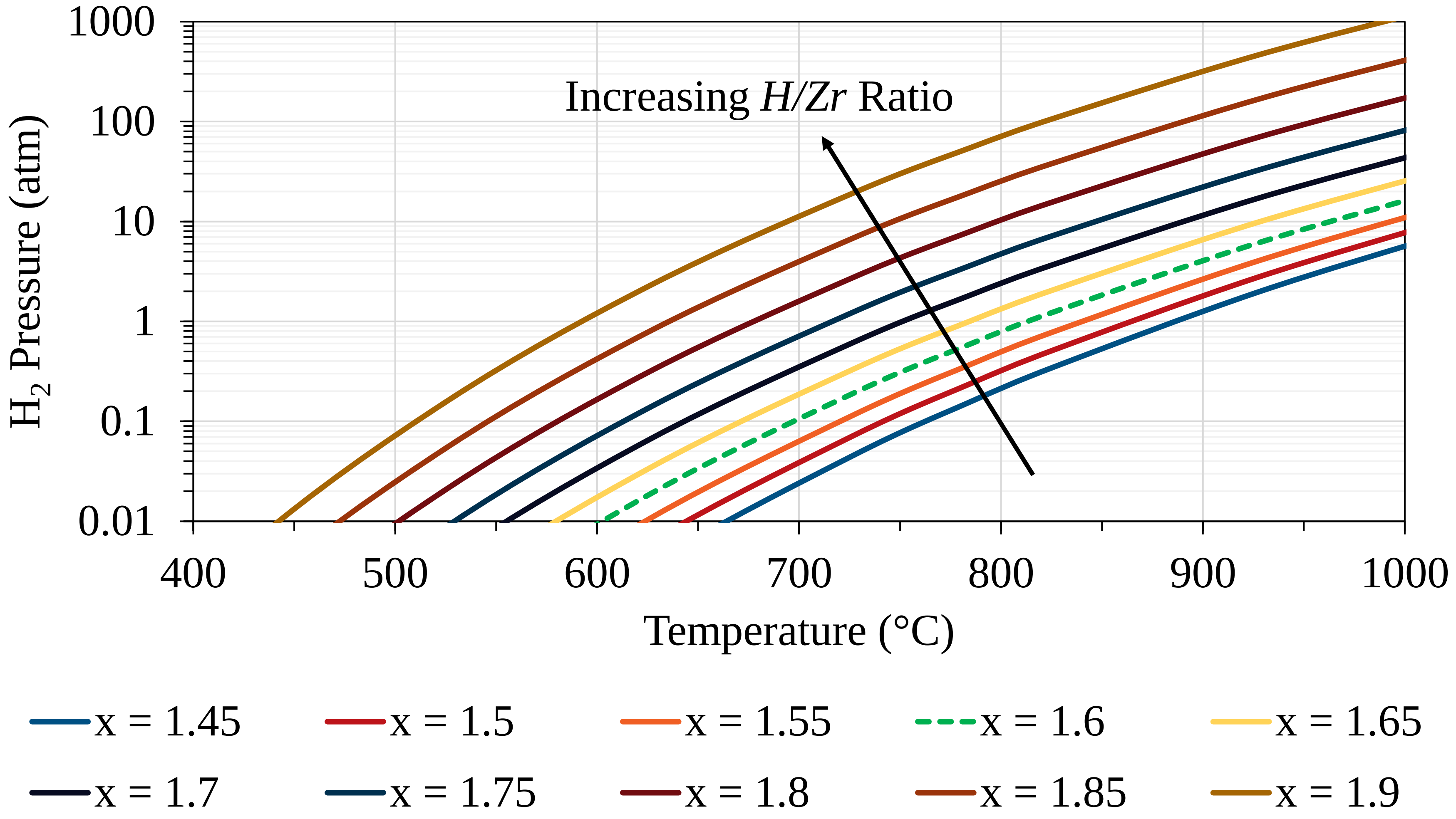
Hydrogen Dissociation Equilibria

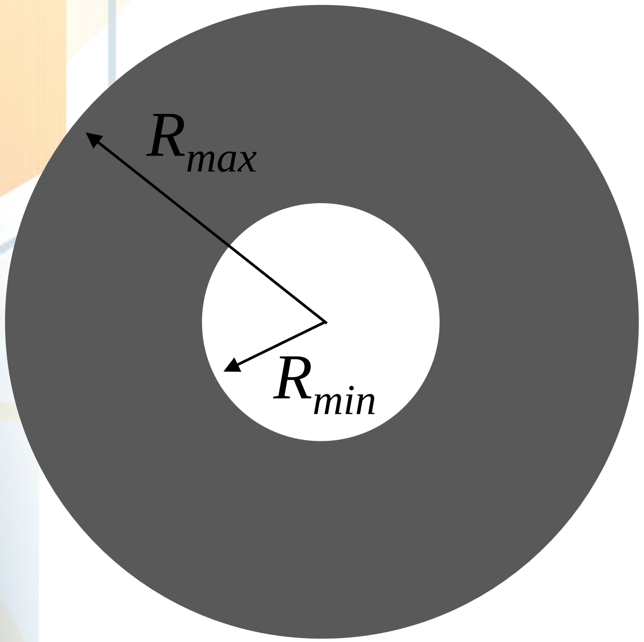
For MARVEL,

H/Zr_{nom} = 1.60

But the hydrogen dissociation pressure is dependent upon the temperature and H/Zr ratio ***at the fuel meat surface***…



Radial Hydrogen Redistribution in Annular Fuel – Steady State



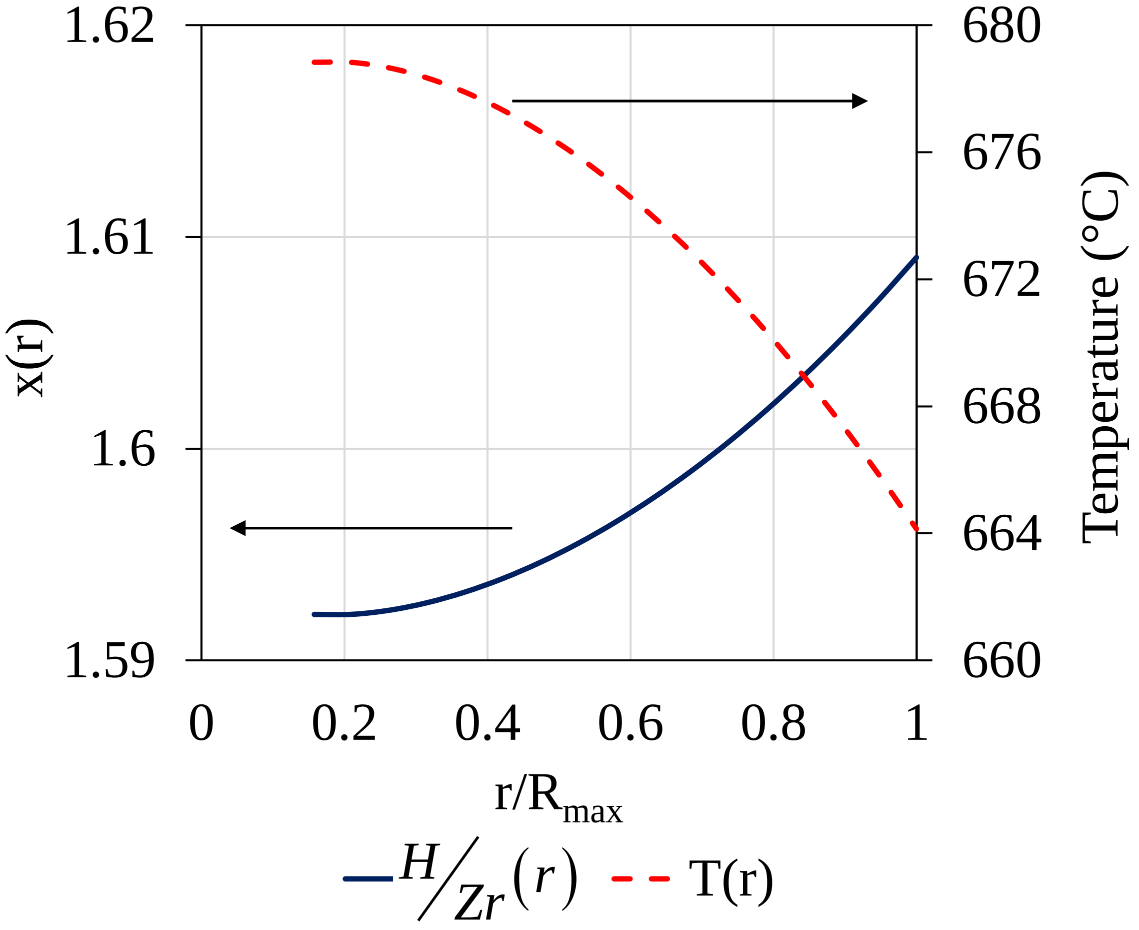
$$x(r) = Ae^{T_Q / T_K(r)}$$

T_Q = Soret heat of transport temperature

A = integration constant

$$T(r) = T_{peak} - \gamma r^2 \left(1 - \frac{R_{\min}^2}{r^2}\right) + 2\gamma R_{\min}^2 \ln\left(\frac{r}{R_{\min}}\right)$$

$$\gamma = \frac{T_{peak} - T_s}{R_{\max}^2 \left[1 - \left(\frac{R_{\min}}{R_{\max}}\right)^2 - \left(\frac{R_{\min}}{R_{\max}}\right)^2 \ln\left(\frac{R_{\max}}{R_{\min}}\right)^2\right]}$$



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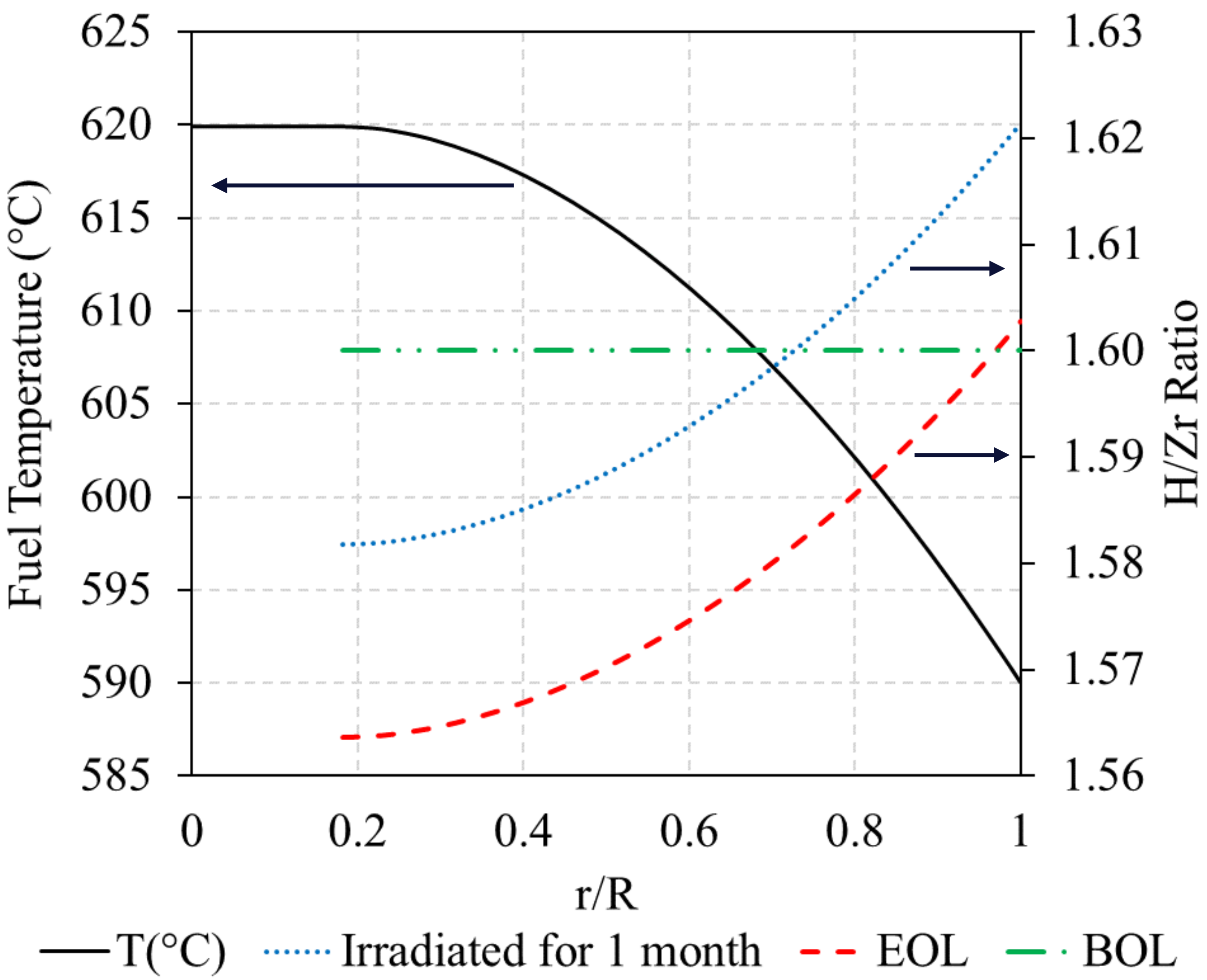
Hydrogen Redistribution in MARVEL Fuel Meat

- For fresh fuel, nominal H/Zr = 1.60
  - Flat green dash-dot
- Hydrogen redistribution reaches steady state in about a month
  - Blue dotted line
- By EOL, hydrogen loss mechanisms have had time to manifest
  - After reaching steady state, the H/Zr distribution has the same general shape as before, but x_{avg} has decreased
  - Red dashed line



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Severe Accident and Scoping Analyses

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Bounding Conditions – The Hypothetical Accident Scenario

- Two severe accident scenarios to consider are:
  1. Loss of Flow Accident (LOFA)
     - Something prevents the coolant from properly carrying heat away from the core
       - Probability of occurrence < 10^{-6} yr^{-1} (per ECAR 6332)
  2. Loss of Coolant Accident (LOCA)
     - Coolant pressure drops
       - (Although MARVEL doesn't use a pressurizer system like in an LWR, restricted thermal expansion of the coolant still results in ~3 atm of NaK pressure during normal conditions)
       - Probability of occurrence < 10^{-6} yr^{-1} (per ECAR 6332)

- The following analysis considers both accidents occurring *simultaneously* (probability of occurrence < 10^{-12} yr^{-1}) and *without human intervention*
- Peak values chosen for conservatism (ex. peak temperature, burnup, corrosion rate, etc.)

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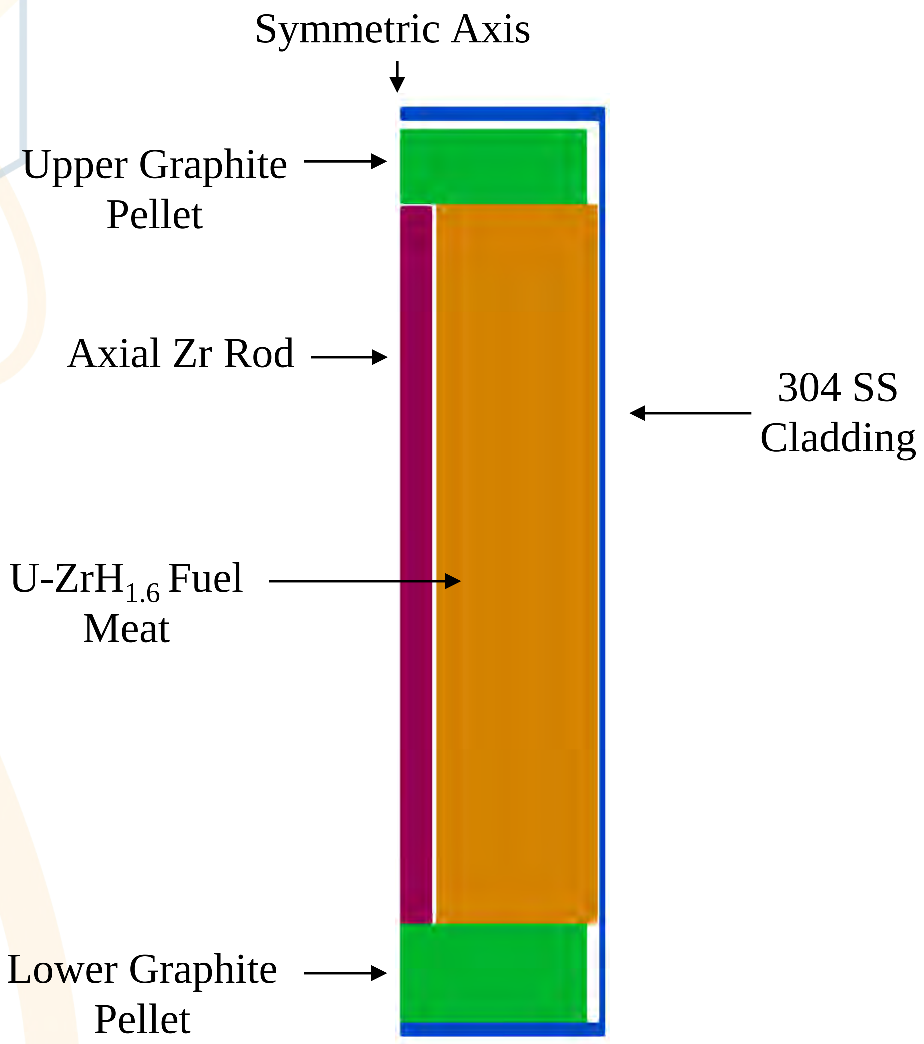
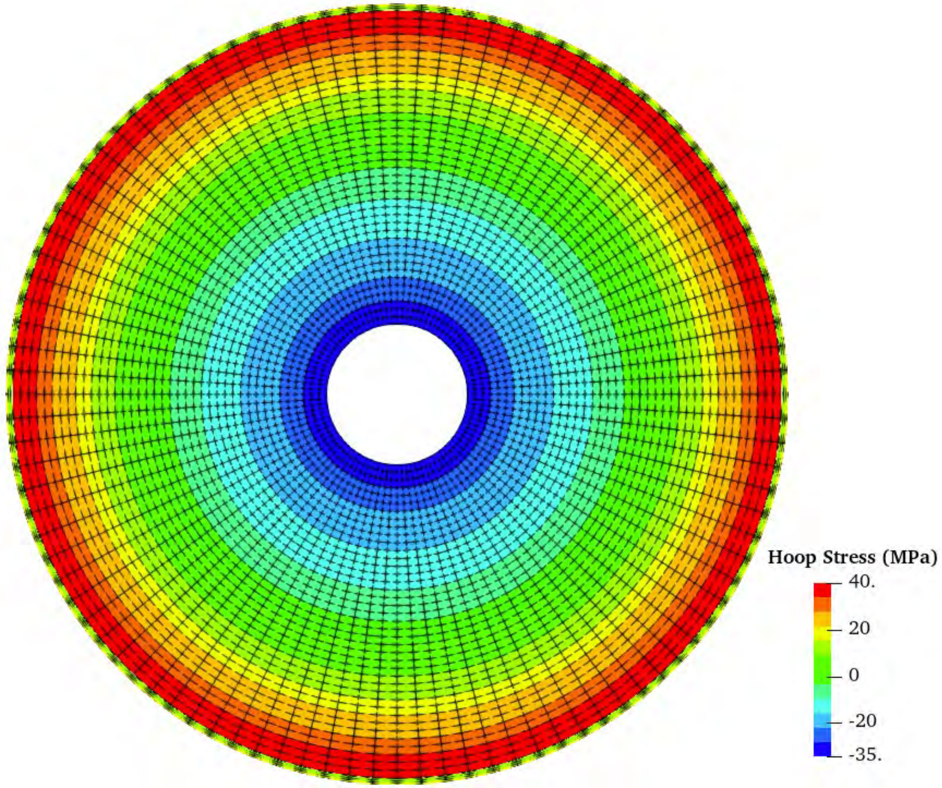
Fuel Performance During the Severe Accident

Peak Fuel Meat Temp ≈ 730 °C





BISON fuel performance simulation of hoop stress during accident is in excellent agreement with analytical calculations

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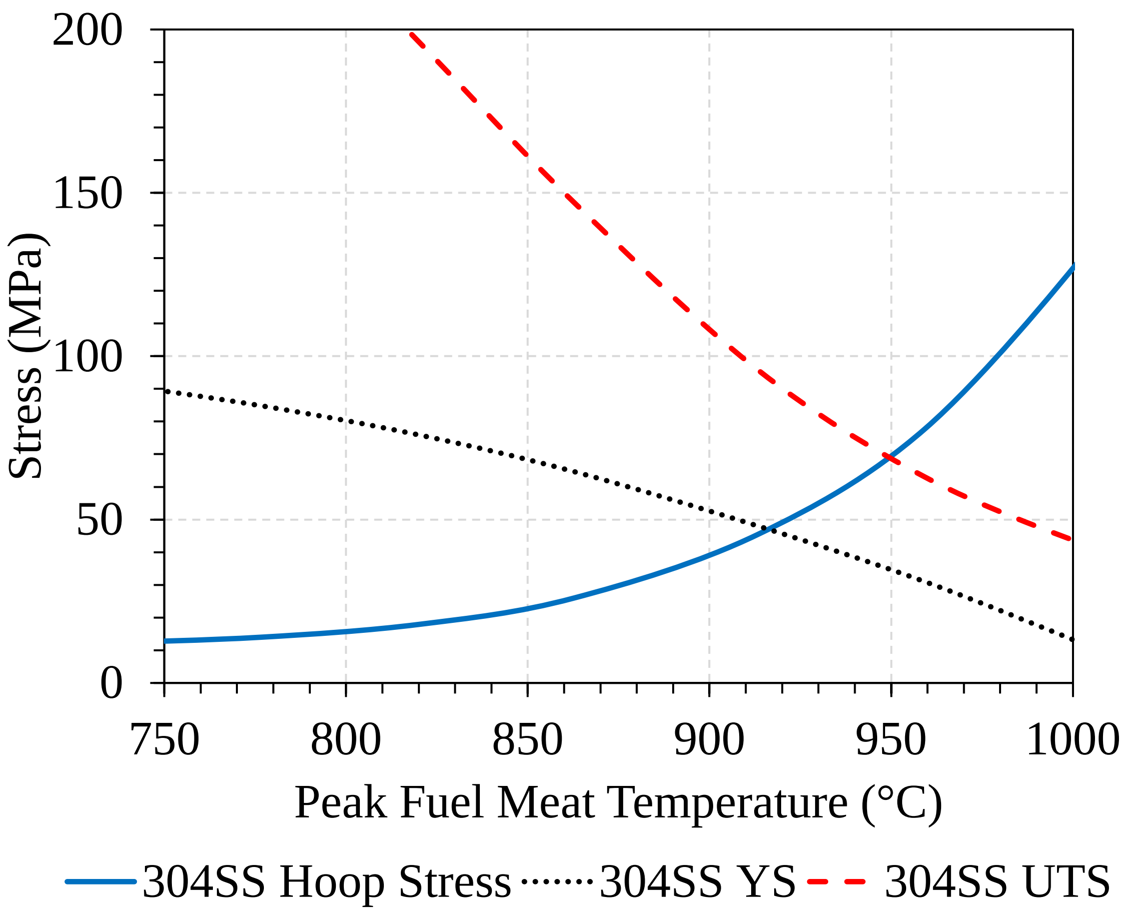
MARVEL Scoping Analysis: Fuel Safety Margin

- Peak fuel meat temp of 730 °C during the postulated "LOFA + LOCA" accident scenario
- The primary failure mechanism for MARVEL fuel is internal gas overpressurization (same as TRIGA)
- This is a function of fuel meat temp driven by hydrogen dissociation (same as TRIGA)
- Under the most conservative assumptions:
    - A peak fuel meat temp of 916 °C precludes fuel element damage
    - A peak fuel meat temp of 950 °C precludes fuel element rupture
- Rounding down for conservatism, we set the fuel element limit as a peak fuel meat temp of 900 °C
- We have a peak fuel meat temp margin of ~ 170 °C before challenging the integrity of the fuel element



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Conclusions

- No further qualification efforts are necessary for authorization per US NRC guidance (NUREG-1537)
- MARVEL reactor fuel performance is bounded by already-existing fuel licenses (ex. TRIGA reactor fuel)
  - Maintains structural integrity, geometric stability, and behavior is stable *and* predictable under bounding accident conditions
  - Bounding accident conditions (burnup, radiation damage, temperatures, pressures, etc.) are well below the functional limits of the fuel element
  - We find that a peak fuel temp of 900 °C precludes cladding damage
  - Safety margins are huge (~ 170 °C)

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