Lightbridge Fuel™ Overview

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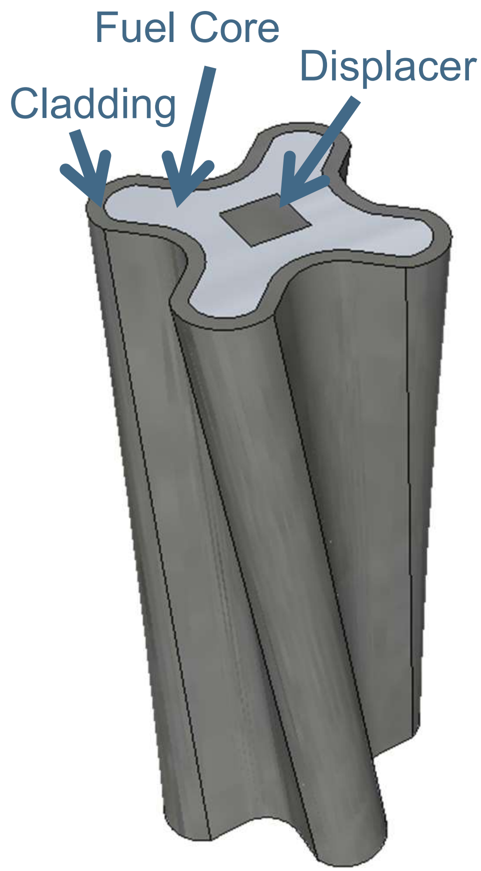
Lightbridge’s Metallic Fuel Rod

- Solid metallic fuel rod utilizes a unique composition and geometry to provide significant advantages compared to conventional fuels.
- Three-component fuel rod:
  - Alloy fuel core (δ-phase UZr_2)
  - Central displacer reduces T_{cl} and allows for incorporation of burnable absorber material (e.g. Er, Gd)
  - Zr-1Nb cladding is metallurgically-bonded to fuel core, no plenum or gas gap
- Helically twisted rod geometry
  - 30-40% Increased surface area for heat transfer
  - Inherent coolant mixing in the assembly
  - Circumscribed diameter = pin-to-pin pitch



Evolutionary LWR Fuel Design

Lightbridge’s metallic fuel is based on previous fuels used in icebreaker reactors:

- Uranium-zirconium alloy fuel, metallurgical bond, twisted rod geometry, self-spacing assembly
- High power density and ramp rate
- Ability to withstand high burn-ups in water cooled reactor

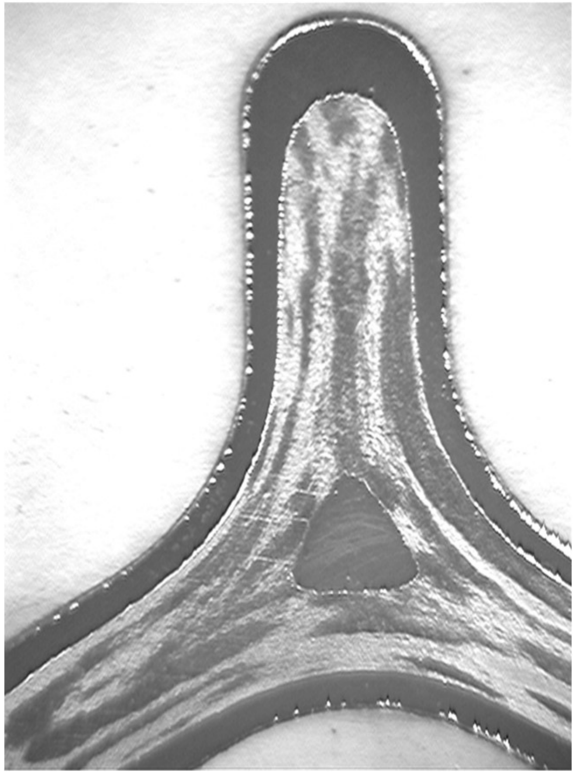
Maritime reactor fuel experience:

- Irradiated ~3,100 fuel assemblies
- Average burn-up ~ 200 GWd/MTU
- Nominal irradiation period – up to 7 years
- Length of operation at nominal power – 30,000+ hours

The icebreaker fuel program provides high confidence in the performance and behavior of Lightbridge’s metallic fuel. Lightbridge’s development program is based on modern U.S. nuclear standards & QA requirements.

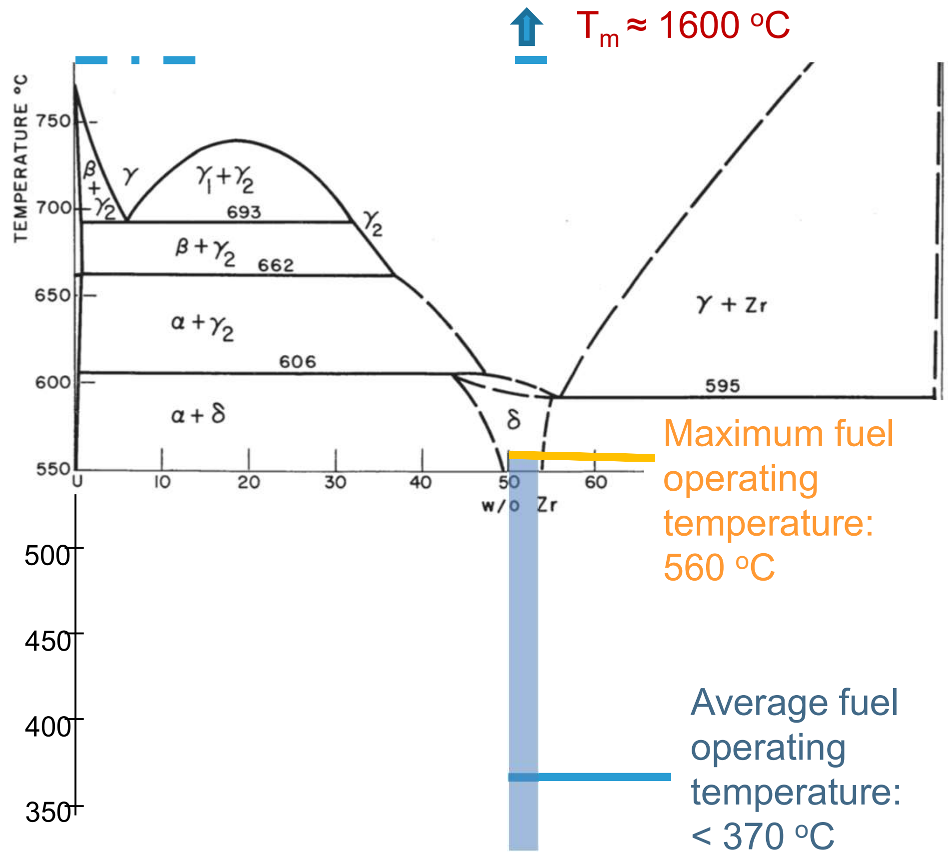
Robust Fuel Rod Design

- **Metallurgical bond** between fuel material and cladding reduces cladding breach due to fuel-cladding mechanical interactions and limits fuel washout in event of breach;
- **Monolithic fuel rod** and **self-spacing** assembly design provide increased strength to resist bowing and lateral loading;
- **Absence of spacer grids** eliminates grid-to-rod fretting and reduces the potential for debris fretting;
- **Increased cladding thickness** at lobes increases the durability of the fuel at the contact points;
- **Absence of fuel-clad gap** eliminates mechanism for rapid FG release and widespread coolant-cladding interaction on the inner cladding surface in the event of a breach;
- **Fuel rod extrusion process** eliminates several sources of manufacturing defects (e.g., pellet chipping).



δ-phase UZr_2 Alloy Fuel

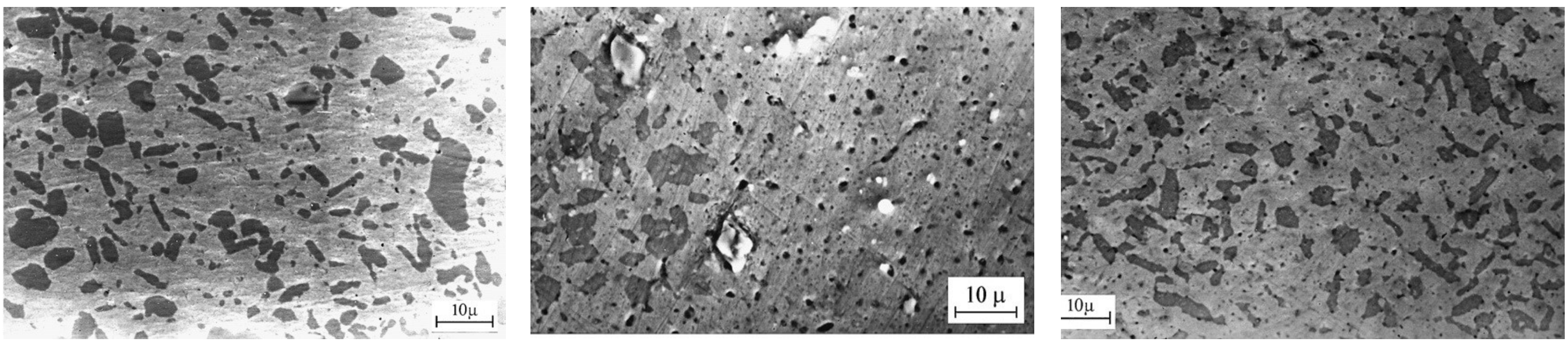
- Absence of α-U reduces irradiation-induced fuel swelling.
- Low operating temperature limits diffusion of fission products; reducing the potential for FCCI-related failures .
- Due to low operating temperature fission gases behave like solid fission products and remain where they are created; limited bubble formation and no gas accumulation for release in the event of cladding breach.



Uranium-Zirconium phase diagram. “Constitution of the Uranium-rich U-Nb and U-Nb-Zr systems”, Dwight & Mueller, ANL-5581 (modified).

Improved Fission Product Retention

- At the low fuel operating temperature fission gases behave like solid fission products and have significantly less mobility. The fuel core acts as part of the barrier to fission product release;
- Large fission gas bubbles do not form in the metallic fuel and the microstructure is comparatively stable (i.e., no cracking, interconnected porosity)
- Small, isolated fission gas bubbles may form depending on the fuel temperature, power history, and burnup; these bubbles are not mobile and remain isolated up to very high burnup and do not lead to FGR.

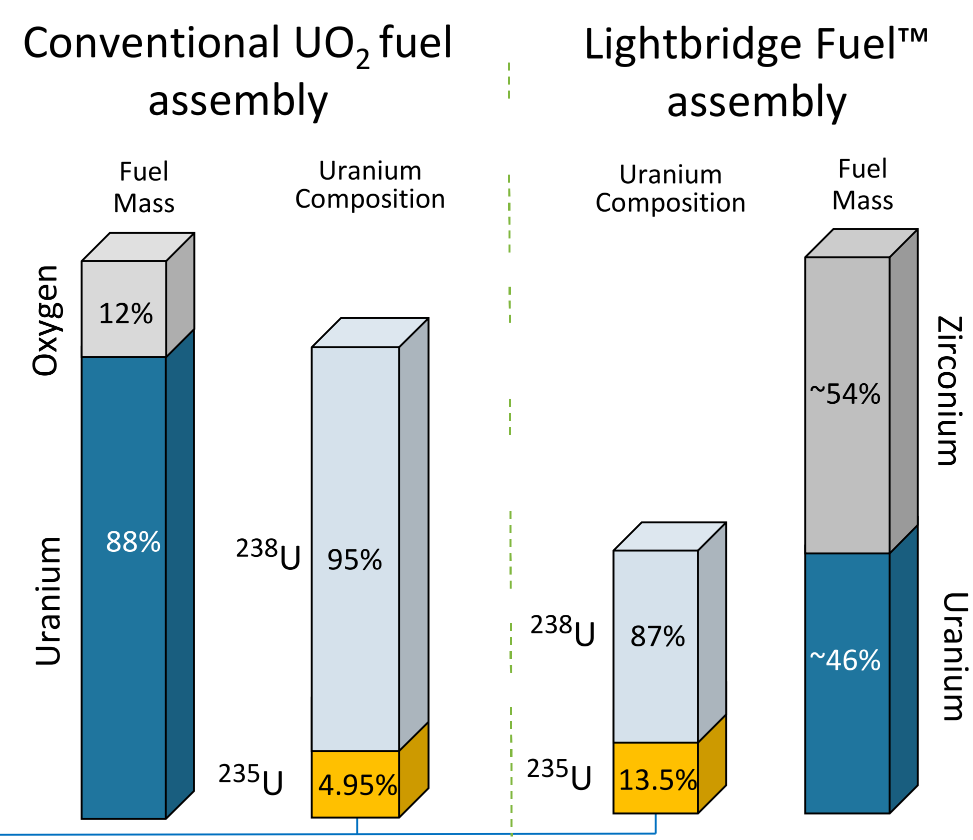


Microstructure of Zr-40U metallic fuel with burnup of (a) ~100, (b) ~200, and (c) ~260 MWd/kgHM

"Measurement of the specific heat of Zr–40 wt%U metallic fuel," by Byung-Ho Lee et al, J Nuc Mat. v.360, pp 315-320, 2007

High Assay Low Enriched Uranium (HALEU)

- Lightbridge's fuel utilizes HALEU to compensate for the reduction in total U of the fuel and a reduction in fission from Pu.
- Reduced total U content must be considered when comparing fuel metrics to other fuel forms (e.g. MWd/kgHM)

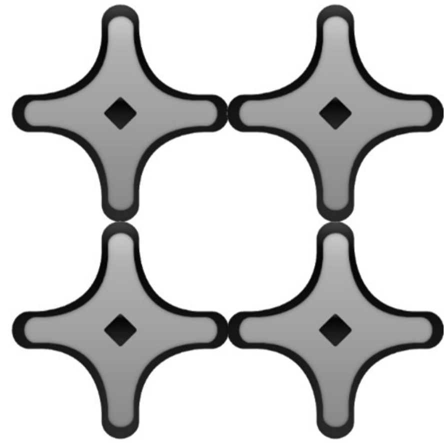


Lightbridge Fuel™ with 13.5% enriched uranium has the same ^{235}U mass as UO_2 fuel enriched to 4.95%.

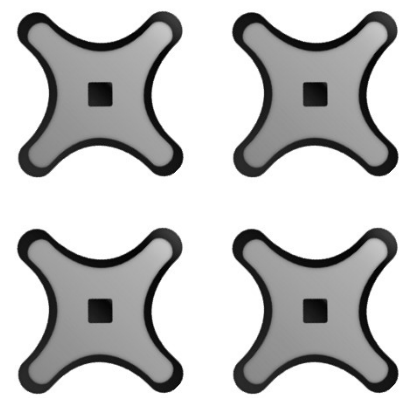
Lightbridge Fuel™ with 19.7% enriched uranium has approximately the same mass of ^{235}U as conventional UO_2 fuel enriched to ~7.2%.

Helical Cruciform Geometry

- Fuel rod surface area is ~35% greater than cylindrical fuel
  - Increased heat crisis margin (DNBR) allows for higher power density operation without reducing fuel failure margin;
- Helical twist allows for self-spaced fuel rods and inherent coolant mixing in fuel bundles;
  - Fuel assemblies require no mixing vanes; reduces ΔP_{core} and debris trapping
  - Coolant mixing is continuous along the length of the fuel rod and mitigates the development of hot spots.



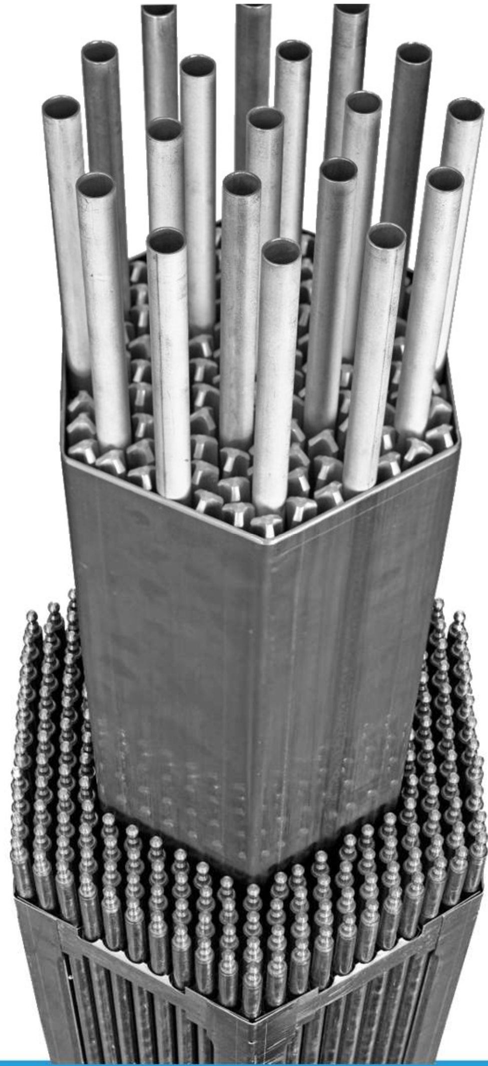
Self-spacing Plane

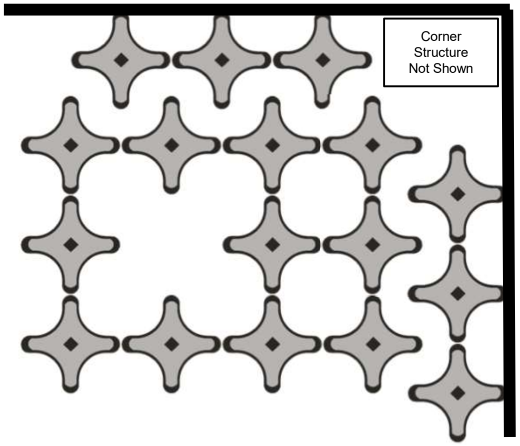


Half-Rotation Plane

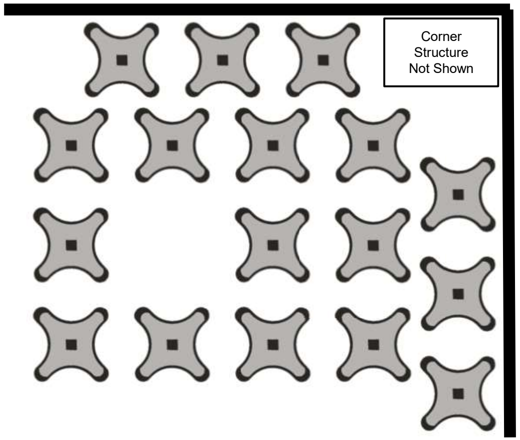
Self-Spacing Fuel Rod Array Examples

Lightbridge's tri-lobe metallic fuel rod forms the seed region of the Th-SBU hexagonal fuel assembly.





17x17 Self-spacing Plane



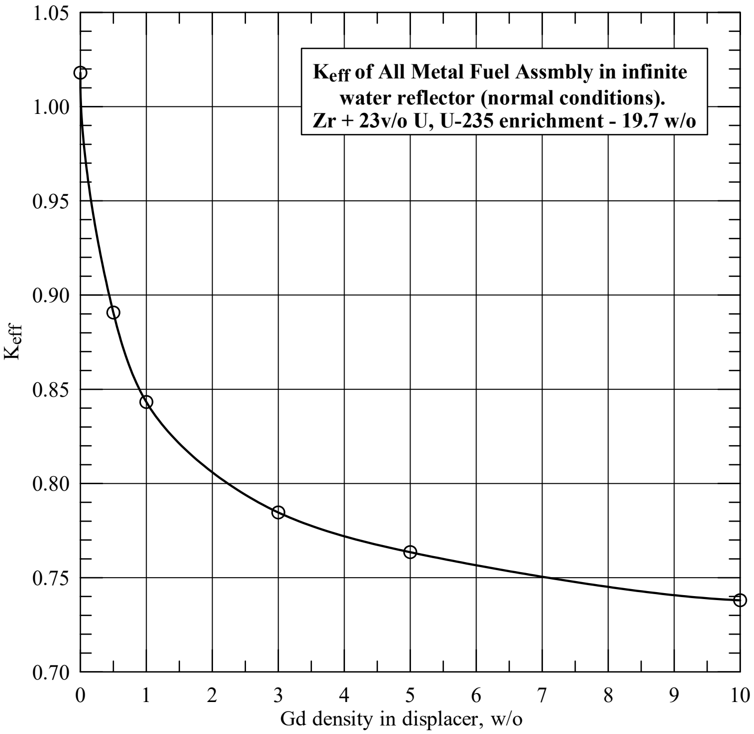
17x17 Half-Rotation Plane

Fuel Mass & Enrichment Comparison

Fuel Assembly Uranium Loading	4-loop PWR, UO_2	LTBR 0% Uprate, 18mo Cycle	LTBR 10% Uprate, 24mo Cycle
Total Mass of Fuel Rods, kg *	630	540	540
Assembly kgU	465	166	166
Assembly kgU^{235}	19	22	31

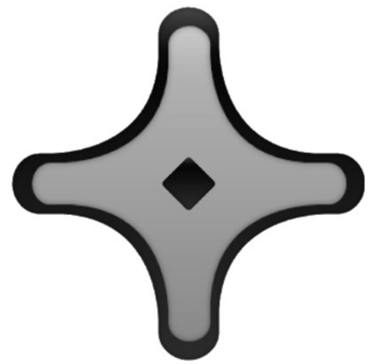
* Mass of fuel rods, excluding assembly hardware

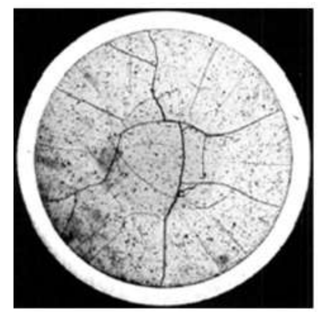
Mockup of 4-lobe helical cruciform fuel rods.



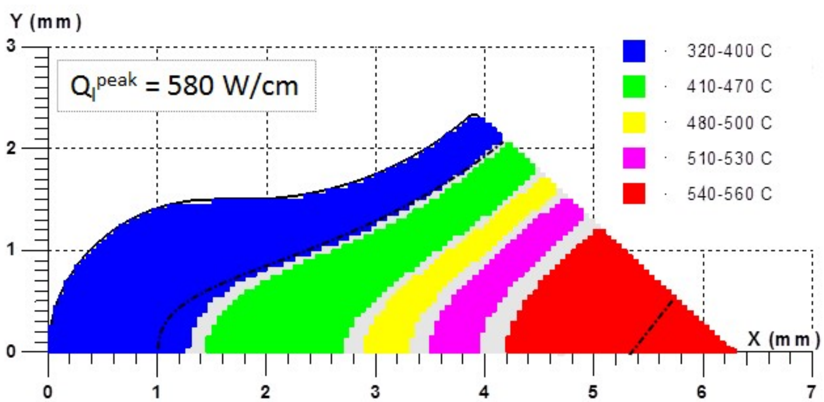
“Cold” Fuel Operating Temperatures

- Thermal conductivity of metallic fuel is ~ 3x higher than that of UO_2.
- Thermal conduction pathway from fuel to coolant is continuous and ~40% shorter than cylindrical fuels.
- Low thermal inertia of metallic fuel; reduced sensible heat stored in the fuel is lower and heat can be transferred out of the fuel more quickly.





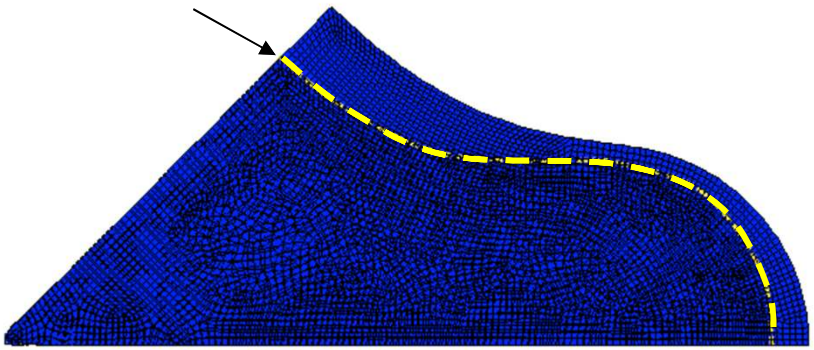
N. Marchal, et al. “Finite elements simulation of PCI in nuclear fuel rods.” Comp Mat Sci, vol 45, No 3, 2009



Temperature distribution of peak rod operating with coolant inlet temperature of 300 ^oC at 17.7 kW/ft.

Fuel Swelling During Operation

- Majority of fuel swelling occurs at the interior region of the fuel lobes, near the central region of the fuel element as the fuel rod attempts to become cylindrical.
- Results in an expansion of the central region of the fuel and thickness of the lobes without significantly increasing the circumscribed diameter of the fuel rod.
- Swelling decreases the area available for coolant flow; preliminary analysis and previous experience show that adequate coolant flow is maintained over the life of the fuel.



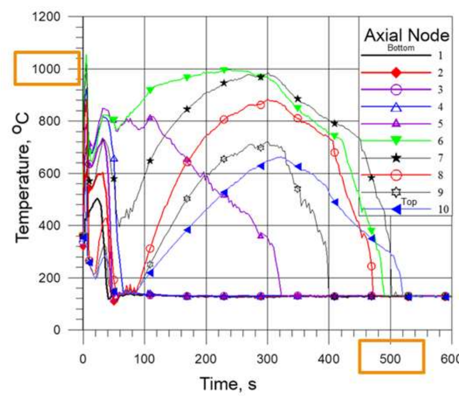
Unconstrained swelling in four-lobe fuel rod.

Benefits of Lightbridge Fuel

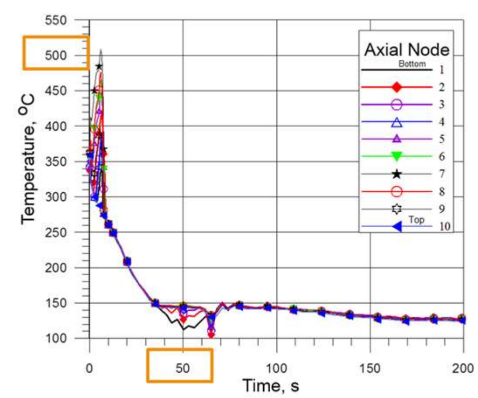
Lightbridge's metallic fuel rod enables the design of LWR fuel systems which can have the following benefits compared to UO_2 fuels:

- Increased power uprate
- Extended fuel cycle length
- Enhanced natural circulation
- Improved safety in normal operation and DBA
- Faster ramp-rate enables to facilitate load following
- Improved proliferation resistance

Fuel Product	Potential Markets		Key Attributes		
	Existing Plants	New Plants	Power Uprate	Fuel Cycle Length	Spent Fuel Reduction (per kWh)
10% Uprate	✓	✓	10%	24 months	Up to 9%
17% Uprate	✓	✓	17%	18 months	Up to 16%
30% Uprate		✓	30%	18 months	Up to 25%



VVER-1000 UO_2 fuel – 448 W/cm (13.6 kW/ft)



Lightbridge tri-lobe fuel – 550 W/cm (16.7 kW/ft)

Lightbridge Fuel Manufacturing

- Primary forming process is high temperature co-extrusion
  - Co-extrusion billet contains displacer, fuel core, and cladding
  - Co-extrusion forms the fuel rod in a single step;
  - Extrusion forms the rod geometry and metallurgical bond;
- Reduced fabrication facility footprint and less equipment;
- Fewer process steps reduces QC burden.

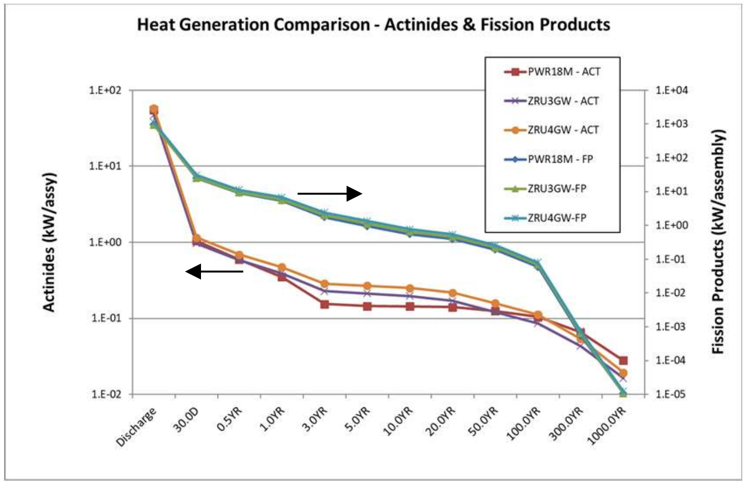
U-Zr Ingot Casting → Primary Hot Working → Billet Assembly → Co-extrusion → Finishing Operations → NDE & Final Inspection

Ongoing & Near-Term Development Activities

- Ongoing fabrication process development & demonstration activities:
  - Production of surrogate (i.e., non-U) fuel rod simulators
  - Co-extrusion process FEM simulation validation
  - Corrosion testing and hydride evaluation of as-fabricated cladding alloys
  - Awarded DOE GAIN voucher with PNNL to demonstrate U-Zr casting process (work to commence in Q2 '21)
- Ongoing fuel demonstration activities:
  - Awarded DOE GAIN voucher with INL to design U-Zr irradiation test (expected completion in 2021)
- Near-term demonstration activities:
  - U-Zr irradiation test and PIE (2-3 yr)
  - Prototypic fuel rod irradiation test in the ATR (4-5 yr)

Considerations for Used Fuel Management

- Based on the monolithic rod design, stability of the fuel microstructure during irradiation, and absence of fission product gases in a gap/plenum, Lightbridge anticipates the metallic fuel will meet or exceed the performance of conventional pellet-in-tube fuels during storage and transport in both fresh and used fuel conditions.
- Compatibility with existing dry storage solutions will be confirmed at a later stage but no show-stoppers have been identified regarding:
  - Fuel rod integrity
  - Fuel assembly geometry or mass
  - Fuel handling
  - Dry canister integrity
  - Subcriticality
  - Retrievability of used fuel



Comparison of 4-loop PWR (18 mo cycle) used fuel heat rates for UO_2 fuel and LTBR fuel design with no power uprate (ZrU3GW) and 17% power uprate (ZrU4GW).

Thank you!

Questions?