LIGHTBRIDGE CORPORATION'S ADVANCED METALLIC FUEL

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Abstract: Lightbridge Corporation is developing a metallic nuclear fuel which utilizes an innovative fuel rod geometry and composition to improve power plant economics and enhance the performance and safety of commercial light water reactors. The versatile fuel can utilize uranium or plutonium as the fissile component. The fuel is fully compatible with existing light water reactor designs and requires no major changes to reactor operations. The metallic fuel provides a durable solution that is also capable of operating at higher power density than existing fuels allowing for increased power output and cycle length compared to conventional oxide fuels.

Lightbridge's patented nuclear fuel technologies are designed to significantly enhance nuclear power industry economics and increase power output by: 1) extending fuel cycle length to 24 months or longer while simultaneously increasing power output by 10% or increasing power output by up to 17% with 18-month fuel cycles in existing pressurized water reactors (PWRs); 2) enabling increased reactor power output of up to 30% without changing core size in new-build PWRs; and 3) reducing the volume of used fuel per kilowatt-hour as well as enhancing proliferation resistance of spent fuel.

Keywords: *metallic nuclear fuel, light water reactor*

INTRODUCTION

Lightbridge Corporation is developing a metallic nuclear fuel rod that provides increased safety margins and improved economics for Light Water Reactors (LWRs) compared to conventional oxide fuel. The fuel utilizes a unique rod geometry and fuel composition that, combined, allow for increased heat transfer to the reactor coolant and significantly reduced fuel operating temperatures. The fuel is monolithic and consists of three primary components which are metallurgically bonded during the fabrication process. Compared to an equivalent cylindrical fuel rod, Lightbridge's® metallic fuel is capable of operating with a linear power density increase of up to 30%. Coupled with the microstructural stability of the fuel during irradiation, this allows for power uprates and cycle length extensions beyond the current capabilities of pellet-in-tube oxide fuels while maintaining or improving existing margins to fuel failure.

Fuel assemblies incorporating the metal fuel are being designed as a one-to-one replacement for conventional oxide fuel assemblies such that they are fully compatible with existing plant control and safety systems.

This paper provides a review of the fuel rod design and its performance in a typical 17x17 pressurized water reactor (PWR).

FUEL COMPOSITION & GEOMETRY

Three main components make up the fuel rod: a fuel core, exterior cladding, and a central displacer. As mentioned, these components are metallurgically-bonded during the fabrication process and result in a solid metal rod with no internal gaps or plenums. As a result of this monolithic construction, all fuel rod components contribute to the mechanical strength of the fuel rod, unlike pellet-in-tube fuels wherein the thin-walled cladding acts as both the primary barrier to radionuclide release and the primary rod structural component.

The fuel core utilizes a δ-phase zirconium-uranium alloy with zirconium content near 50 w/o. The fuel contains no α-phase uranium metal, which is known to undergo severe swelling in an irradiation environment [1]. The absence of α-phase uranium and the low operating temperature of the fuel significantly reduce fuel rod swelling during operation. Compared to pellet-in-tube oxide fuels, the solid metal fuel rod has greater heat conduction properties as the components are all metallic and the heat conduction pathway from the fuel to the cladding surface is continuous, being uninhibited by typical pellet-clad interfacial contact or gaps.

The fuel cladding and central displacer are made from a Zr-1Nb alloy with high corrosion resistance in LWR environments. The central displacer may also include burnable absorber materials such that excess reactivity control is integral to the fuel rod.

The geometry of the fuel rod is also quite different than conventional fuel with a multi-lobed and helically-twisted shape. Figure 1 shows a schematic of a section of the fuel rod with the helical twist and a cross-section view of 4-lobed variant of the fuel rod. This unique shape serves several purposes including increased surface area for heat transfer, increased coolant mixing, and self-spacing of the fuel rod array. Compared to an equivalent cylindrical fuel rod, the cruciform (4-lobed) fuel rod has ~35-40% more surface area for heat transfer to the coolant which drastically increases the margins to fuel thermal failure due to critical heat flux or departure from nucleate boiling.

SELF-SPACING FUEL ROD ARRAY

When aligned in a fuel assembly, the array of the helically-twisted fuel rods is self-spacing and requires no spacer-grids. Fuel rod positioning within the assembly is maintained via support plates at the top and bottom of the assembly and a shroud around the periphery of the assembly. The circumscribed diameter of the fuel rod is equal to the pin-to-pin pitch of the conventional UO_2 fuel rods it replaces, for example, 12.6 mm in a typical 17x17 PWR assembly. As a result,

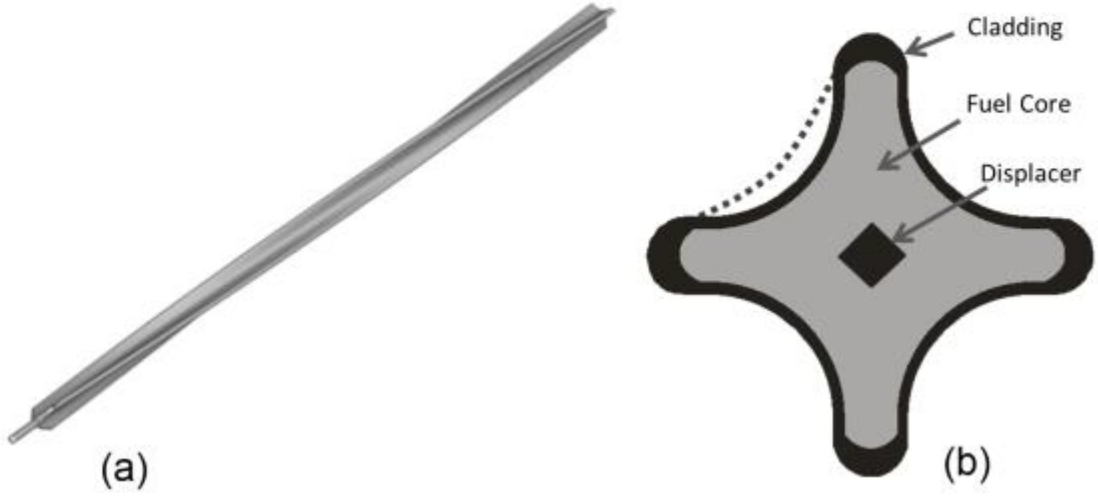


Figure 1. Schematic of Lightbridge's metallic fuel rod for PWRs. (a) Segment of rod showing helical twist; (b) cross-section showing the fuel core, central displacer and cladding of a 4-lobed fuel variant for square lattice assemblies. The dashed line identifies the primary location of swelling deformation. [Not to scale].

each fuel rod contacts adjacent rods at multiple planes along the length of the assembly. Figure 2 provides a schematic representation of the fuel rod configuration at the self-spacing plane (where rod-to-rod contact occurs) and half-way between self-spacing planes. Currently, fuel assemblies of the metallic fuel incorporate twice as many self-spacing planes as there are spacer grids in conventional fuel assemblies. The cladding has extra thickness at the lobe tips to provide additional protection from cladding breach due to rod-to-rod fretting wear. Preliminary coolant flow testing has shown that such fretting wear is negligible and further testing will be performed on the final fuel assembly design.

The twisted rod geometry also provides for increased coolant mixing in the core as the entire fuel column performs the functions of the intermittent mixing vanes utilized in conventional fuel assemblies. This reduces the likelihood of the development of hot spots within the fuel assembly.

The absence of spacer grids in the fuel assembly reduces the potential for cladding breach due to debris-trapping and greatly reduces the coolant pressure drop across the fuel assembly. Preliminary thermal hydraulic experiments show that the pressure drop in a bundle of the metallic fuel may be as ~~much~~ little as one half that of a conventional fuel assembly. This reduction in core pressure drop could result in increased safety margin during accident scenarios for advanced reactors that utilize natural circulation as a passive safety feature.

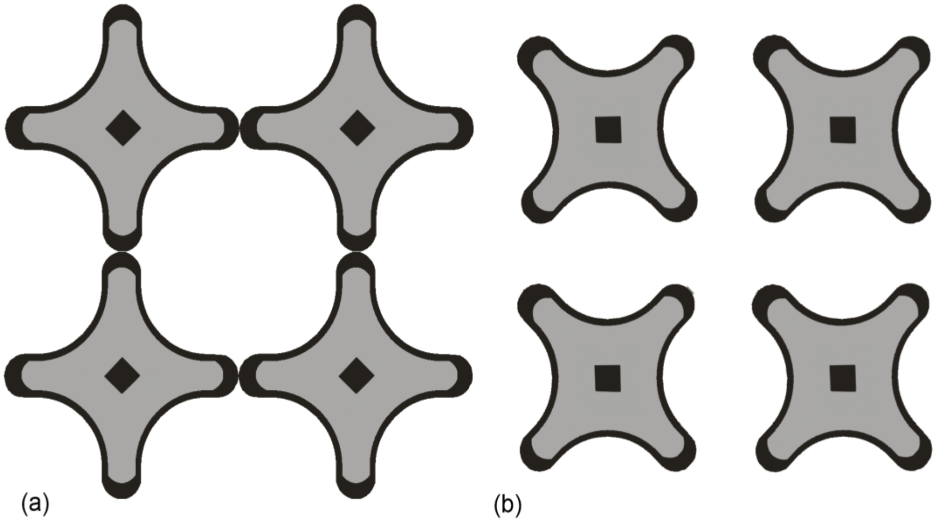


Figure 2. Schematic cross-section of the metallic fuel rod aligned in a square lattice array. (a) Showing the self-spacing plane wherein rod-to-rod contact eliminates the need for spacer grids; (b) axially half-way between self-spacing planes

UNIQUE CHARACTERISTICS OF THE METALLIC FUEL

Lightbridge’s fuel development program includes planned irradiations of fuel samples in a test reactor prior to lead test assembly (LTA) demonstration in a commercial power reactor. A quantitative discussion follows, based on Lightbridge’s preliminary experiments and modeling of the metal fuel as well as knowledge of the performance of similar metal fuels.

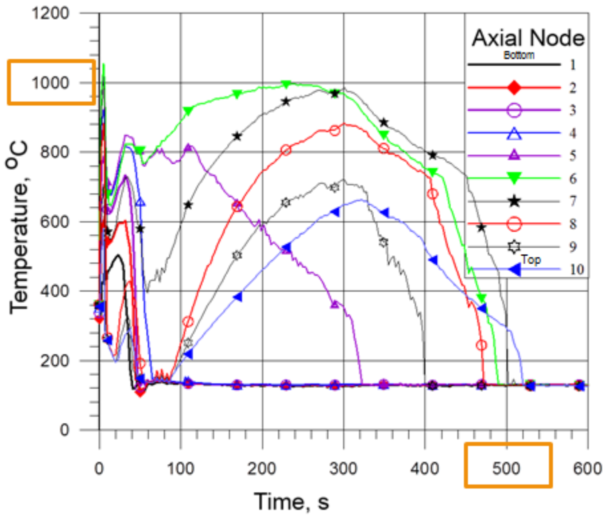
Lightbridge is designing the metal fuel to operate to a target burnup of 21 a/o (i.e., atomic percent of initial U atoms). The commonly used metric of MWd/kgHM for oxide fuels is not appropriate for comparing oxide fuels to metallic fuels due to the difference in heavy metal loading. Uranium oxide fuel at a burnup of 60,000 MWd/MTU burnup is equivalent to ~ 6.5 a/o. In terms of core residence time, the metallic fuel is capable of operating in a 17x17 PWR configuration with 24 month fuel cycles while providing a power uprate of up to 10%. Higher power uprates are achievable with the fuel; however, constraints on initial excess reactivity limit the cycle length of the fuel above 10% power increase.

The improved heat transfer capabilities of the metallic fuel result in drastically lower fuel operating temperatures compared to uranium dioxide fuels. For example, a UO_2 fuel rod operating at a power density of 427 W/cm (13.0 kW/ft) in a 17x17 PWR is predicted to have peak fuel temperatures in the range of ~ 1600 ^oC [2]; while the Lightbridge metallic fuel operating at a power density of 580 W/cm (17.7 kW/ft) would have a peak fuel temperature of 560 ^oC. The lower stored thermal energy within the fuel impacts fuel and cladding temperature response during accident scenarios as well. Figure 3 shows a comparison of peak cladding temperature of oxide fuel and the metallic fuel during a design basis large-break loss of coolant accident (LOCA) in a VVER-1000. The peak cladding temperature of the metallic fuel is ~ 500 ^oC during the initial spike and cladding temperatures decrease to ~ 150 ^oC in less than 60 seconds where they remain throughout the progression of the accident. Uranium dioxide fuel on the other hand experiences a peak cladding temperature of ~ 1000 ^oC and, during blowdown and refill, several axial segments of the fuel cladding remain above 800 ^oC until reflood is complete after 500 seconds. This simulation demonstrates the effectiveness of the increased heat transfer capabilities of the metallic fuel and suggests that the fuel may be able to effectively transfer heat axially to the coolant even as it is uncovered during the accident.

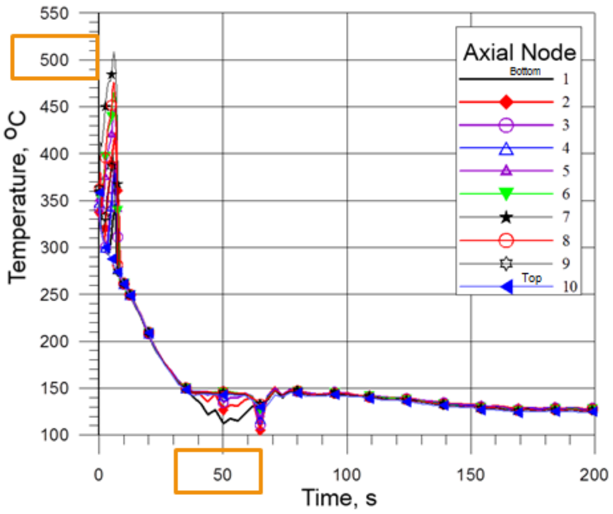
Radiation-induced swelling occurs primarily in the interior region of the fuel lobes, resulting in an expansion of the central region and lobe thickness of the fuel rod (depicted by the dashed line in Figure 1). This method of expansion allows the fuel to swell without significantly increasing the circumscribed diameter of the rod and imparting detrimental stress between adjacent rods. The low fuel operating temperature inhibits diffusion-controlled mechanisms such as fission gas atom mobility resulting in fission gases behaving similarly to solid fission products and remaining near where they are created. Thus, the formation of fission gas bubbles in the fuel, and their associated swelling is limited and the swelling rate of fuel is nearly linear with burnup, on the order of 1% per atom percent burnup.

As the fission products are nearly immobile at the operating temperatures of the fuel, the fuel core itself takes on part of the role of the first barrier to radionuclide release. In the event of a cladding breach in the metal fuel, only those fission products located at the breach site will be immediately available for release and all other radionuclides will have to diffuse to the breach location. This behavior is quite different from pellet-in-tube fuels wherein the fuel-clad gap and plenum becomes filled with an inventory of radioactive fission product gases that are released nearly instantaneously after cladding breach. A preliminary estimate of fission gas diffusion in the alloy can be made via comparison to the diffusion of Xe in pure Zr as the composition of Lightbridge's metallic fuel is ~ 70 atom percent Zr. At a temperature of 400 ^oC, the diffusion coefficient for Xe in Zr is ~ 3×10^{-20} cm^2/s [3]. Investigation of fission gas release in unclad U-Zr alloys shows a comparably small fractional release for the alloy composition used in Lightbridge's metallic fuel of 0.02% at 1.2 atom percent burnup at temperatures above 600 ^oC [4]. The retention of radionuclides within the metallic fuel in the event of a cladding breach suggests the fuel has significant advantages toward lowering the radiation dose exposure to nuclear plant workers.

Figure 3. Peak cladding temperature comparison during large-break LOCA in a VVER-1000 between conventional UO_2 fuel (a); and a variant of Lightbridge's metallic fuel (b). The time scale shown for (b) is reduced to provide increased visibility of the region of interest, the peak cladding temperature did not rise during the time period from 200-500 seconds during the simulation.



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



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

CONCLUSION

As the global energy market continues to move towards carbon-free generation sources, nuclear power remains the most reliable source of baseload generation. The metallic LWR fuel being developed by Lightbridge Corporation provides highly desirable benefits for the commercial nuclear power industry including increased safety, longer fuel cycles, and higher power output. The current development plan for the metallic fuel envisions lead test assembly demonstration in a PWR in the 2021 time frame with commercial deployment to follow. Existing reactor designs operating with the Lightbridge's metallic fuel could realize the benefits discussed above though the ability to increase reactor power output of existing plants is limited by the size of the nuclear steam supply system and containment volume. It is likely not economically feasible to uprate an existing PWR by 30%, allowing it to take full advantage of the power capabilities of the metallic fuel. However, the many other benefits of the fuel make it an attractive option for existing LWR designs. It is easy to envision new LWR designs with increased steam flow capacity that could fully utilize the power density capabilities of the metallic fuel.

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