LIGHTBRIDGE CORPORATION'S ADVANCED METALLIC FUEL FOR LIGHT WATER REACTORS

MATERIALS FOR NUCLEAR SYSTEMS

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Lightbridge Corporation is developing an advanced metallic nuclear fuel capable of increasing the power output and extending the cycle length of current-generation light water reactors (LWRs). This paper provides a review of the unique geometry and composition of the metallic fuel and its application to power uprates in LWRs.

I. INTRODUCTION

Nuclear power is expanding on multiple levels depending on local market factors. In mature markets, with a large base of existing reactors, economic considerations have led to expansion in the form of power uprates and plant life extensions. Emerging markets—with few existing reactors but with aggressive growth plans—are progressing quickly and are anticipated to add significantly to the global nuclear generation capacity in the coming decades.

The driving force for nuclear expansion is a cleaner, healthier environment and improved economics of electricity generation—with a financial goal of achieving the lowest generation costs in terms of dollars per megawatt hour. In mature nuclear markets, capital expenditures per kilowatt(electric) for new-build[a] far outweigh the incremental capital cost of power uprates and license extensions. This is evident by the multitude of power uprates and plant life extensions that have occurred in the United States—more than 130 uprates and 60 life extensions have been approved by the U.S. Nuclear Regulatory Commission. However, in emerging markets, or those with substantial anticipated growth, the capital expenditure for new-build cannot be avoided, yet these markets are also seeking the most efficient use of capital. Here, too, new fuel designs that allow greater power output without increasing plant size can be used to reduce generation costs. As an example, if 10 new reactors were constructed—each uprated by 10% without a significant incremental capital cost—the generating capacity of 11 units could be achieved with reduced cost. This scenario could be demonstrated in countries with aggressive growth plans such as China and the United Arab Emirates.

Reactor power output is primarily limited by the capacity of the components [e.g., reactor pressure vessel (RPV) and coolant and safety systems] and the performance limits of the fuel. Some components can be, and are regularly, replaced at least once in a plant's lifetime, possibly with higher-capacity units (e.g., steam generators). Installation of higher-capacity components is limited by several factors including the size of the containment, which, along with the RPV, is impractical to replace. The performance limits of the fuel can be increased by modifying the fuel and cladding design. Uranium oxide fuels have seen continued improvements in performance (e.g., burnup and reliability) over the years. Many efforts to further modify existing fuels (via alloying additions to both the fuel and cladding) have been, and are being, investigated with varying degrees of success. However, the limits of UO_2 fuel are likely being approached as fission gas release and fuel

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[a] "New-build" refers to new reactor construction.

swelling appear to be exacerbated at higher burnup.[1,2] Significant further improvements in fuel performance will require new fuel technologies.

Lightbridge Corporation (Lightbridge) is developing a high power density metallic nuclear fuel that will allow current and future light water reactors (LWRs) to increase power output and fuel cycle length without changing the reactor footprint and is expected to meet or exceed the performance and safety of uranium dioxide fuel. This paper presents a general description of Lightbridge's metallic fuel and its application to LWRs.

II. BRIEF REVIEW OF METAL FUEL DEVELOPMENT

Metal alloy fuels have a long history in nuclear reactors. Their high fissile atom density (which allows for smaller core size) and superior heat transfer properties make them excellent candidates for certain applications. During the 1950s the United States developed a variety of uranium fuel materials including metallic alloys, carbides, nitrides, and cermets, among others. The U.S. program included a large metallic fuel development effort for fast reactor applications.[3] One of the major issues with some metal fuel alloys is that they may undergo a large amount of swelling at very low burnup. Alloying additions were investigated to reduce the rate of swelling and increase the melting temperature of the these fuels, and zirconium was ultimately selected as it addressed these concerns to an extent and offered additional benefits in terms of cladding compatibility.[4] The metal fuels investigated for the Experimental Breeder Reactor and Integral Fast Reactor programs had a relatively low concentration of alloying constituents (e.g., U with 5 wt% to 10 wt% Zr additions).

The high degree of swelling observed in these low alloy metal fuels is primarily due to the presence of α-phase U and high operating temperatures. Cavitational swelling results from anisotropic grain growth during irradiation of polycrystalline α-phase uranium wherein the growth of individual grains causes mismatched strain at grain boundaries resulting in plastic deformation. Reducing the amount of α-phase uranium has been shown to reduce this effect.[4] Swelling due to fission gases is difficult to mitigate without significantly reducing the fuel temperature as gas atom mobility is diffusion controlled. Reliable performance to high burnup was achieved with these low alloy fuels only when the fuel rod design incorporated a large fuel-clad gap to accommodate swelling.

Another class of metallic uranium fuel alloy, with a lower uranium fraction (δ-phase alloy), was investigated, and its unirradiated properties were documented.[5,6] With the ascendance of oxide-fueled LWRs and reduced federal research funding, development of metallic nuclear fuels was discontinued in the United States. The metallic fuel being developed by Lightbridge utilizes this δ-phase composition to overcome the issues associated with metallic fuels developed for fast reactors.

III. DESCRIPTION OF LIGHTBRIDGE'S METALLIC FUEL TECHNOLOGY

Lightbridge's metallic fuel technology utilizes a unique alloy composition and fuel rod geometry to safely operate at a higher power density than current oxide fuels. The fuel core is a Zr-U alloy with zirconium content near 50 wt%. The alloy is a mixture of δ-phase (UZr_2) and α-Zr. The high Zr content reduces the uranium loading per unit volume to about one-half that of UO_2. Therefore, the metallic fuel requires increased enrichment to compensate for reductions in both the initial fissile loading and the fissile plutonium generated during reactor operation. Lightbridge is currently developing the metallic fuel with ^{235}U enrichment of up to 19.7 wt%. Although the commercial nuclear power industry has little experience with such enrichments, research reactors around the world have been converted to use near 20 wt% enriched fuel to reduce proliferation concerns under the Reduced Enrichment in Research and Test Reactors program. This higher ^{235}U enrichment is within the internationally accepted limits for non-weapons-useable uranium and does not pose a significant proliferation risk compared to current fuels.[7] Use of material enriched to this level will require some infrastructure changes to existing enrichment and fuel fabrication facilities, amendments to plant licenses, and reevaluation of transportation and storage procedures.

IV. FUEL ROD GEOMETRY

The metallic fuel rod incorporates a unique multilobed, helical geometry. Each fuel rod consists of a central displacer, fuel core, and cladding metallurgically bonded to one another during fabrication. Figure 1 shows a schematic of the fuel rod including the helical twist and a cross-section view for fuel rods used in square lattice fuel assemblies (cruciform shape); a trilobed rod is utilized in hexagonal lattice fuel assemblies. The shape of the rod provides increased surface area for heat transfer and accommodates fuel rod swelling during irradiation. The central displacer, comprising a zirconium alloy, lowers the centerline fuel temperature and increases the thermal conductivity in the center of the rod. There is no fuel-clad gap as the cladding and fuel core are metallurgically bonded. The metallic fuel rod is very robust and has higher mechanical strength and flexural rigidity than current pelletized fuel rods.

The circumscribed diameter of the fuel rod is equal to the pitch of conventional UO_2 fuel rods. As a result, each fuel rod contacts adjacent rods at multiple planes

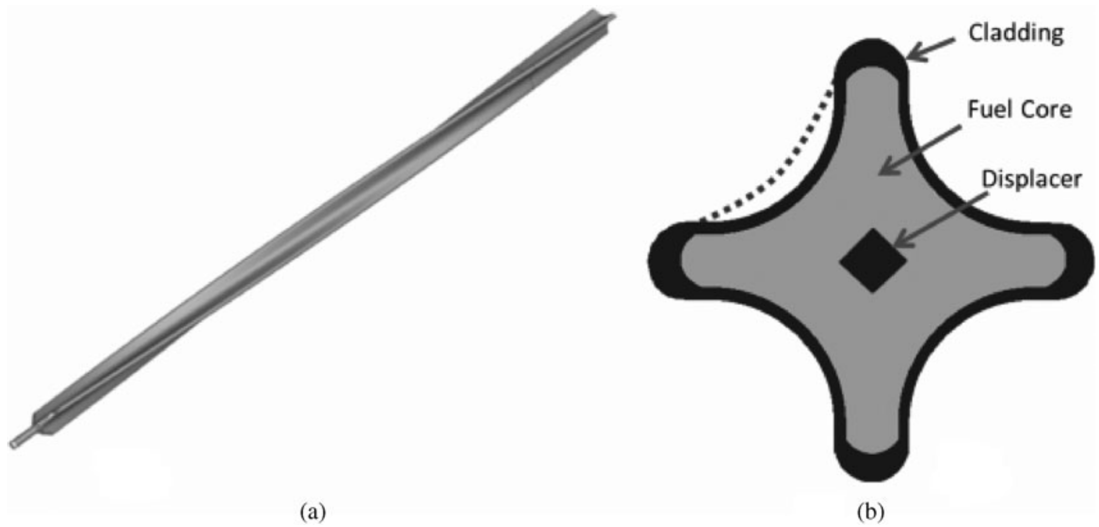

Fig. 1. Schematic of Lightbridge's metallic fuel rod for PWRs: (a) segment of rod showing helical twist and (b) cross section showing the fuel core, central displacer, and cladding. The dashed line identifies the typical change in fuel rod profile at end of life due to swelling deformation. (Not to scale.)

along the assembly length, eliminating the need for spacer grids as the rods are self-spacing. Figure 2 shows a schematic of the fuel rod configuration at both the self-spacing plane (rod-to-rod contact) and halfway between self-spacing planes. The number of self-spacing planes depends on the helical twist pitch of the rod and is about twice the number of spacer grids in a standard UO_2 assembly. The helical twist essentially turns the entire fuel column into a mixing vane and reduces the likelihood of hot spots developing in the fuel. The cladding is thicker at the outer edge of the lobes to provide additional protection against fuel damage due to cladding wear at the contact points. Vibration measurements during fluid flow experiments show that fretting wear at the cladding contact points will not result in fuel failure. Further, the potential for fretting from debris is greatly reduced since there are no spacer grids to trap debris within the active fuel region, and debris trapping at fuel rod contact points is not expected to occur. Removing the spacer grids leads to a significant reduction in the coolant pressure drop

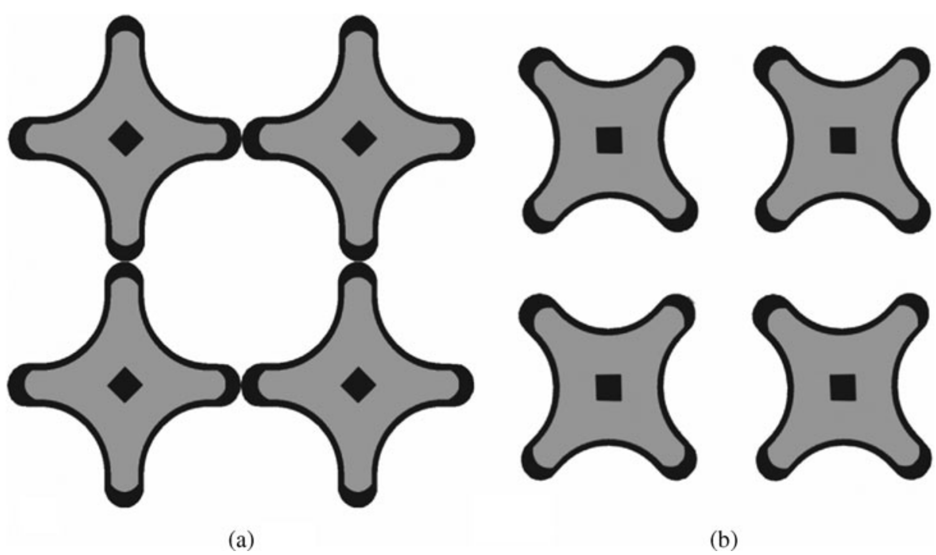

Fig. 2. Schematic cross section of the metallic fuel rod aligned in a square lattice array (a) showing the self-spacing plane wherein rod-to-rod contact eliminates the need for spacer grids and (b) axially halfway between self-spacing planes.

across the fuel assembly. Preliminary thermal-hydraulic experiments suggest that the pressure drop in a bundle of the metallic fuel may be as much as one-half that of a conventional UO_2 fuel assembly. The results and analysis of these experiments and an explanation for the difference in pressure drops in the metal fuel and UO_2 bundles will be reported at a later date. Fuel rod positioning is maintained via support plates at the top and bottom of the assembly and a shroud around the periphery of the assembly.

V. APPLICATION OF THE METALLIC FUEL IN PWRs

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

Lightbridge is designing the metal fuel to operate to a target burnup of 21 at. % (i.e., atomic percent of initial U atoms). The common metric of MWd/kg HM used with oxide fuels is not appropriate for comparing oxide fuels to metallic fuels because of the difference in heavy metal loading. Uranium oxide fuel at a burnup of 60 000 MWd/tonne U burnup is equivalent to ~6.5 at. %. The metal fuel is capable of providing up to a 17% power uprate in existing pressurized water reactors (PWRs) and up to, and potentially beyond, 30% in new-build PWRs. Most existing four-loop PWRs are limited in power uprate to ~17%, depending on the specific reactor design, but these limitations could be overcome with design changes in new-build units. Specifically, increasing the size of the containment building in new-build units could allow for higher-capacity nuclear steam supply systems (NSSSs) and accommodate the increased thermal power. Preliminary analysis suggests fuel cycle lengths of up to 24 months for existing PWRs and 18 to 24 months for new-build units with a 30% uprate. Various burnable absorber configurations are being evaluated to allow fuel cycle length extensions. The metal fuel is suitable for use in all LWRs including boiling water reactors and small modular reactors.

The majority of swelling occurs 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 Fig. 1). This method of expansion allows the fuel to swell without significantly increasing the circumscribed diameter of the rod and imparting detrimental strains in the cladding. The swelling rate of this metal fuel is nearly linear with burnup, on the order of 1% per atomic percent burnup. This level of swelling very nearly corresponds to solid fission product swelling. That is, all the fission products, including the gaseous fission products Xe and Kr, behave like solid fission products. For comparison, solid fission product swelling in oxide fuel has been variously calculated from 0.2% to 0.4% per atomic percent burnup. When the gaseous fission products are included and treated as solid fission products, the "inexorable" swelling in UO_2 has been reported as between 0.8% and 1% per atomic percent burnup.[8] Swelling in the metallic fuel will lead to a reduction in the available coolant flow area; however, the accompanying reduction in power density and increase in flow velocity will provide adequate cooling capability throughout the fuel's lifetime.

The average fuel operating temperature of the metal fuel in an AREVA-designed EPR with a 30% power uprate is ~370°C. Fuel temperatures for a Westinghouse-type four-loop PWR with a 17% power uprate are expected to be lower and will be reported at a later date. The peak operating fuel rod centerline temperature is limited, by design, to 560°C. The thermal conductivity of the alloy, in its unirradiated state, is ~15 W/m·K, compared to ~3 W/m·K for uranium oxide fuel. The cruciform geometry provides ~40% more surface area than equivalent cylindrical fuel rods, providing increased margin to departure from nucleate boiling.

The melting point of the metal alloy is ~1600°C, and the average operating temperature–to–melting temperature ratio, i.e., homologous temperature, is ~0.35 (for comparison, UO_2 fuel is ~0.56). At this low operating temperature, temperature-driven phenomena are significantly reduced in the metal fuel (e.g., diffusion and growth of fission gas bubbles). While quantitative analysis of fission product diffusion in the Zr-U alloy is yet to be completed, a preliminary estimate can be made based on the diffusion of Xe in Zr as the alloy comprises ~70 at. % Zr. At a temperature of 400°C, the diffusion coefficient for Xe is $\sim 3 \times 10^{-20}$ cm^2/s (Ref. 9), confirming that there is little to no tendency for migration of gaseous fission products. As a result, fission products are primarily concentrated where they are generated.

This inhibits the formation of large (several-micron-diameter) fission gas bubbles in the fuel as fission product gas atoms exist as single atoms or form very small bubbles depending on the fuel operating temperature.[10] Investigation of fission gas release in various unclad U-Zr alloys shows a very small fractional release for the alloy composition used in Lightbridge's metallic fuel: 0.02% at 1.2 at. % burnup at temperatures above 600°C (Ref. 11). In pelletized UO_2 fuel rods the fuel-clad gap becomes filled with radioactive fission gases. Upon cladding breach, these fission products are expelled to the coolant, increasing the radioactivity of the primary coolant system. In the Lightbridge-designed fuel, these fission products essentially behave like solid fission products and occupy the lattice in the fuel matrix, near where they are created. This results in a major reduction in the radioactive source term for cladding breach events. In the event of a cladding breach, reaction between the water and UZr_2 could be expected. However, the net change in density is not as large as in the reaction between pure uranium and water where the density changes from 19.1 g/cm^3 for pure uranium to 10.96 g/cm^3 for uranium dioxide. The theoretical density of UZr_2 is 10.2 g/cm^3, and therefore, the change in density with water reaction is not as high.[6] Further, experiments conducted in the 1950s on Zircaloy-bonded uranium fuels indicate that when the fuel-cladding bond integrity is maintained, the exposed area for reaction is limited even in the case where the fuel is nearly pure uranium.[12]

VI. LIGHTBRIDGE'S ADVANCED PWR FUEL DESIGNS

As mentioned, the metal fuel is suitable for use in water-cooled reactors. Lightbridge is currently developing three families of fuel products that incorporate the metal fuel for PWRs. These include two variants for power uprate and enhanced fuel cycle length and a thorium-based fuel assembly that provides a reduction in used fuel inventory. A brief description of the power uprate fuel for existing reactors follows.

The two power uprate fuels are designed for existing and new-build power plants. For existing PWRs the fuel assembly utilizes a seed-and-blanket configuration with the metallic fuel comprising the bulk of the assembly and the outer row incorporating conventional UO_2 pelletized fuel rods. Figure 3 shows a schematic of the cross section of this fuel assembly. The metallic fuel rods are enclosed in a shroud to separate coolant flow channels. The fuel assembly is designed as a one-to-one replacement for existing 17 × 17 PWR fuel assemblies, and the peripheral row of UO_2 rods ensures that the assembly envelope is compliant with existing core internals.

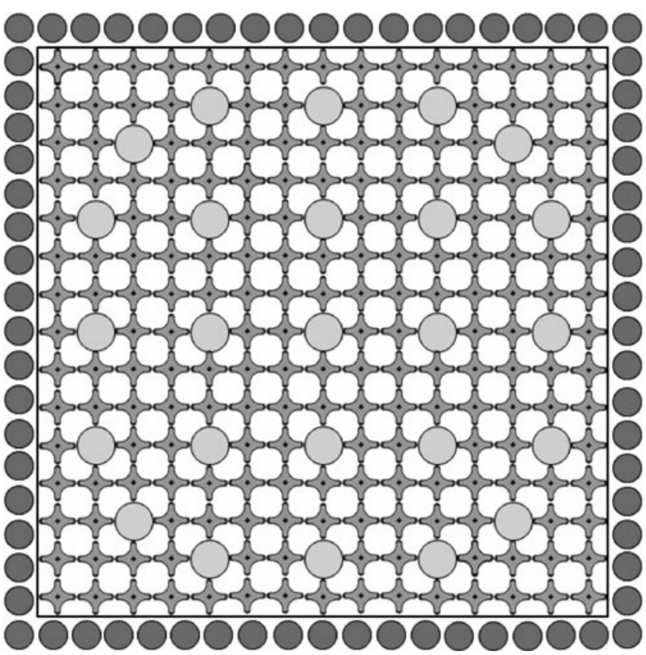

Fig. 3. Lightbridge's all-uranium seed-and-blanket fuel assembly for power uprate in existing 17 × 17 PWRs. Central region contains helical-cruciform metallic fuel rods and control rod guide tubes. Peripheral row comprises pelletized UO_2 fuel rods.

This fuel assembly is capable of increasing the power output of an existing Westinghouse-type four-loop PWR by up to 17% compared to the original design power with a planned 24-month operating cycle. Preliminary evaluation of this fuel in a PWR shows that the fuel behaves similarly to existing oxide fuels. Figure 4 shows the hot-full-power (HFP) moderator temperature coefficient (MTC) and Doppler temperature coefficient (DTC) of reactivity as a function of full-power days. Both values are negative and decrease with burnup as expected. From a reactor operations standpoint, utilizing the metallic fuel will not present any changes to the inherent stability of the reactor.

The lower operating temperature and increased heat transfer of the metallic fuel are expected to contribute to increased safety margins during normal reactor operation and off-normal events such as anticipated operational occurrences and design-basis accidents. Lightbridge is conducting a comprehensive fuel qualification program that includes computer modeling and various in-reactor and out-of-reactor experiments that will confirm the performance of the metallic fuel. Lightbridge is confident that the metallic fuel will perform as well as, if not better than, conventional fuel during design-basis-accident scenarios.

VII. CONCLUSION

Lightbridge is developing an advanced fuel technology that will allow current-generation LWRs to safely increase reactor core power density by up to 30%. Clearly, a power increase of this level may not be attainable in existing units as the capacity of NSSS equipment and containment building volume may not allow such an extensive power uprate. However, initial technical and economic evaluation suggests that new-build units could be designed to incorporate the necessary capacity increases for relatively low incremental capital cost, resulting in significant cost savings on a per-kilowatt basis. At the same time, existing four-loop Westinghouse-type PWRs should be able to accommodate power uprates on the order of 17% within their existing containment buildings. Such power uprates can be an attractive option to nuclear utilities as they can expand the generating capacity of existing units at a much lower overnight cost and shorter time than constructing new reactors.

The development program for the metallic fuel is currently focused on demonstrating the fuel in LTAs in a commercial PWR. Several preliminary irradiations and experiments to confirm fuel behavior will be performed

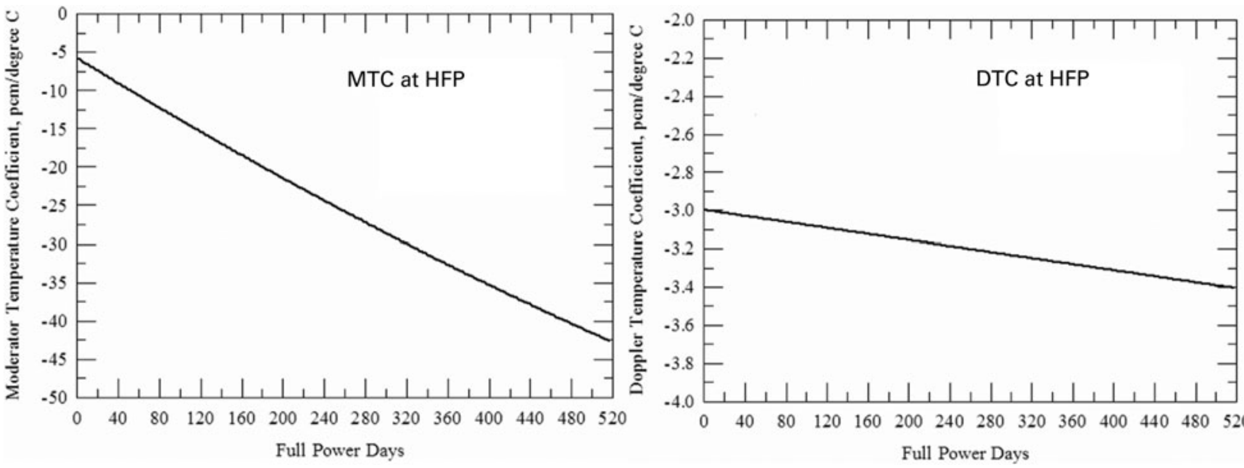

Fig. 4. MTC and DTC of reactivity for a typical PWR utilizing Lightbridge's all-uranium seed-and-blanket fuel assembly.

leading up to the LTA demonstration. Lightbridge is currently part of a university, industry, and U.S. Department of Energy national laboratory team that is working to demonstrate the metallic fuel in the Advanced Test Reactor National Scientific User Facility at Idaho National Laboratory; this effort is being led by the Fuel Cycle and Materials Laboratory at Texas A&M University. Concurrently, other demonstrations and measurement experiments are being planned and organized to fully demonstrate the metallic fuel's behavior during normal operation and accident scenarios and to provide data to confirm that the fuel meets or exceeds all regulatory requirements. Lightbridge anticipates that its metallic fuel will allow the nuclear industry to continue to realize the fuel performance improvements it has grown accustomed to, beyond what can be achieved with conventional oxide fuels.

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