# LIGHTBRIDGE FUEL – MONOLITHIC, METALLIC, MULTI-LOBED, AND HELICALLY TWISTED FUEL RODS FOR USE IN WATER-COOLED REACTORS

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*Abstract*

Lightbridge Fuel™ is an advanced metallic nuclear fuel for use in water-cooled reactors that has inherently superior properties compared to conventional $UO_2$-based nuclear fuel, and simultaneously offers step-change improvements in safety, economics, operational flexibility, and proliferation resistance. Lightbridge Fuel can be used in existing and future nuclear power plants and future water-cooled small modular reactors. This paper presents an overview of Lightbridge Fuel, a selection of results from previous studies conducted to confirm the performance of Lightbridge Fuel, an overview of selected ongoing and planned future studies, as well as an overview of selected preliminary results of a study to evaluate suitability of Lightbridge Fuel for use in CANDU reactors.

***Keywords:*** *Nuclear Fuel, CANDU, Fuel Performance, Metallic Fuel*

## Introduction

Lightbridge Fuel™ rods are designed for use in water-cooled reactors and have an advanced design that simultaneously offers significant improvements in safety, fuel cycle economics, operational capabilities, and proliferation resistance. The Lightbridge Fuel rod design is comprised of advanced geometry and materials, consisting of metallic, monolithic, multi-lobed, and helically twisted fuel rods. A similar delta-phase uranium-zirconium alloy fuel composition with helically twisted rods was previously used successfully for decades in nuclear icebreaker ships.

A host of analyses, laboratory tests, and proof-of-concept irradiations have been performed by Lightbridge in cooperation with other partners, including universities, research laboratories, and other industry partners. These studies have supported optimization of the Lightbridge Fuel rod design for various applications and confirmed the expected excellent performance. Previous studies have primarily focused on various Light-Water Reactor (LWR) applications, and a study is currently being conducted by the Romanian Institute for Nuclear Research (RATEN ICN), to perform an initial evaluation of the use of Lightbridge Fuel rods in CANDU reactors.

## Lightbridge Fuel Rods

Lightbridge metallic fuel rods consist of three components: 1) the fuel core, 2) the fuel rod cladding, and 3) the central displacer (see Fig.1), which are co-extruded to form monolithic, multi-lobed, and helically twisted fuel rods [1]. Ingot materials for the three components are assembled into a billet, which is then co-extruded. The co-extrusion process imparts the multi-lobed cross-section and helical twist, and forms metallurgical bonds between the components. The fuel core consists of a metallic, δ-phase, $UZr_2$ with approximately 50 wt% uranium and 50 wt% zirconium. The uranium in the fuel alloy can be enriched up to 19.75 wt% $U^{235}$ (i.e. High Assay Low Enrichment or HALEU), as necessary for the application. The cladding is a nuclear-grade zirconium alloy typical for nuclear fuel rod cladding, and the central displacer consists of zirconium which may be alloyed with a burnable poison. The helical twist provides self-spacing, allowing for the elimination of spacer grids in LWR fuel assemblies.




Fig.1. Cutaway view of Lightbridge Fuel rod, showing the three components: the *$UZr_2$ Fuel Core*, the *fuel rod Cladding*, and the *central Displacer*

**Inherent Advantages of the Lightbridge Fuel Design**

Advantages of Lightbridge Fuel that lead to superior performance include operating at low temperatures, features that enhance coolability, the robust mechanical design, and the ability to accommodate higher enrichments [2]. These characteristics improve safety margins, enhance operational flexibility, and improve proliferation resistance – supporting power uprates, cycle length extensions, and burnup extensions – all of which lead to improved fuel cycle economics.

Lightbridge Fuel operates at low temperatures. The metallic fuel alloy used in Lightbridge Fuel has a high thermal conductivity, and the metallurgical bond between the fuel rod components, and subsequent absence of gas gaps, leads to excellent heat transfer from the fuel to the cladding to the coolant. The central displacer does not contain fissile material, and thus does not produce power, further contributing to low fuel centerline temperatures.

The geometry of the Lightbridge Fuel rod design results in enhanced coolability. In addition to the high thermal conductivity and metallurgical bonds between the fuel rod components, the multi-lobed design has a large surface area to volume ratio, with approximately 30%, or more, higher surface area than conventional cylindrical fuel rods. The surface heat flux in a Lightbridge rod will thus be significantly decreased compared to conventional cylindrical rods operating at the same Linear Heat Rate (LHR). In addition to the increased surface area, the helical twist and self-spacing of Lightbridge Fuel rods induce coolant mixing along the entire length of the fuel rods, in contrast to conventional LWR fuels where coolant mixing is imparted by spacer grids at discrete axial positions in each fuel assembly.

Lightbridge's monolithic, and metallic fuel rod design constitutes a very robust mechanical design. In fact, in this fuel rod design, the cladding is not the primary structural component of the fuel as is the case in conventional cylindrical pellet-in-tube fuel rod designs. This means that Lightbridge Fuel is relatively insensitive to damage to, or degradation of, the cladding via oxidation, hydriding, mechanical stresses, or fretting wear, and Lightbridge Fuel rods are not susceptible to pellet-clad-interaction. Lightbridge Fuel tolerates rapid power adjustments thus offering enhanced operational flexibility and enabling load follow operation. The robustness of the fuel rod mechanical design is evidenced by decades-long successful use of similar type of fuel in nuclear-powered icebreaker ships.

The metallic fuel alloy enables reaching high burnups. Since the uranium component of the uranium-zirconium fuel alloy can utilize HALEU (i.e. up to 19.75 wt% enrichments in $U^{235}$), the fuel can contain sufficient fissile inventory to support reaching high burnups. The increased fissile inventory (as compared to conventional fuel) can be leveraged to increase cycle lengths, increase discharge burnups, and to implement power uprates, while reducing waste volumes at the same time. The metallic δ-phase fuel has also been shown to exhibit low swelling and excellent fission product retention. The icebreaker fuel, using high enriched uranium, reached burnups of nearly 300 MWd/kgU. While reaching this level of burnup is not possible using HALEU, it demonstrates the successful performance of the materials to the extended burnups that can be reached using HALEU.

**Overview of Previous Lightbridge Fuel Development Activities**

Lightbridge has conducted many analyses, calculations, and tests to evaluate, optimize, and confirm the fuel rod design.

In the area of neutronics, calculations have been performed to determine an accurate cylinderized model of Lightbridge multi-lobed fuel rods to enable modelling in e.g. lattice codes that only accommodate cylindrical geometries [3]. Additionally, a series of neutronics calculations have been performed to evaluate the use of Lightbridge Fuel in EPRs, AP-1000s, and VVER-1000 reactors for a variety of conditions, including power uprates, and cycle length extensions in these reactor types [4]. These studies confirmed the feasibility and economic advantages of using Lightbridge Fuel.

Thermal-hydraulics studies have consisted of both simulations and laboratory experiments [5 – 12]. Calculations have been performed to determine preliminary heat fluxes around the perimeter of the multi-lobed fuel rods, and coolant flow rates through the fuel assemblies. Procedures were specified to determine heat transfer coefficients in swirling coolant flows and to calculate and experimentally verify coolant velocity profiles around the perimeter of the multi-lobed helically twisted rods. Subsequent experiments were conducted on a mock-up fuel assembly, where several thermal hydraulics parameters were experimentally determined, including hydraulic resistance and steady-state critical power for different flow rates and temperatures.

Several transient analyses have been performed for Lightbridge multi-lobed fuel rods in VVER-1000 reactors, including various scenarios where power is lost in recirculation circuits and for a Loss of Coolant Accident (LOCA) [13]. These analyses indicated that Lightbridge Fuel met acceptance criteria and fulfilled design requirements for all conditions analyzed. Cladding temperatures and coolability of Lightbridge Fuel in the LOCA event was significantly improved over standard $UO_2$ fuel.

Fuel performance models have been developed for the Lightbridge multi-lobed fuel rod design, based on experimental data from an extensive database of the icebreaker fuel performance [14, 15]. These models have been confirmed to reproduce the known behaviour of the icebreaker fuel and were subsequently used to predict the performance of the Lightbridge four-lobed fuel rods, including calculations of thermal and elastic strains, plastic strains, creep strains, irradiation induced strains, aggregate strains, swelling, and temperature distributions.

A proof-of-concept irradiation test was conducted at the Kurchatov Institutes IR-8 reactor where three Lightbridge 3-lobed fuel rodlets were tested together with three reference rodlets of the icebreaker fuel design.

The aim of these tests was primarily to verify the fabrication processes for the Lightbridge 3-lobed, helically twisted, metallic fuel rods. Two of the rods were successfully irradiated for more than 200 days; however, due to technical issues with the irradiation capsule, one of the Lightbridge rodlets and one icebreaker-type rodlet were operated in dryout conditions for ~24 hours. This inadvertent dryout test showed that there was minimal damage to the Lightbridge fuel rod and that the coolable geometry was maintained.

Fabrication processes for Lightbridge Fuel have been internally developed, and several fabrication studies have been conducted with partner organizations. Recently, a US Department of Energy (DOE) Gateway for Innovation in Nuclear (GAIN) award funded research at the US DOE's Pacific Northwest National Laboratory (PNNL) which investigated the casting process for Lightbridge's uranium-zirconium fuel alloy [16].

Together with another industrial partner, Lightbridge extruded fuel rods using a surrogate fuel alloy material with the aim of investigating the as-extruded cladding properties. Fabrication work has also been conducted at Idaho National Laboratory (INL), where castings of the fuel alloy have been produced and subsequently extruded [17].

**Overview of Ongoing Lightbridge Fuel Development Activities**

In addition to Lightbridge's own internal engineering efforts to further optimize and qualify the Lightbridge Fuel design, and in addition to the activities described in the previous section, there are several ongoing fuel development activities Lightbridge conducts together with external partners.

In late 2022, Lightbridge signed two framework agreements with INL to support the development of Lightbridge Fuel. These agreements [18] encompass fuel fabrication studies, fabrication of test samples, and irradiation experiments in INL's research reactors and associated Post Irradiation Examinations of the irradiated samples. Fuel fabrication activities include casting fuel alloy ingots, examination of the as-cast chemistry and microstructure, and extrusion of the ingots in order to verify the fabrication process. This process will be used to extrude samples which will then be placed in irradiation experiments. The first irradiation experiment will be performed to confirm basic thermo-physical properties of the Lightbridge Fuel, primarily to confirm thermal-conductivity and swelling behavior as a function of burnup. The framework agreements with INL include provisions for conducting additional irradiation experiments, for example on Lightbridge Fuel rodlets in steady-state and transient conditions.

Lightbridge is an un-funded partner in two US DOE Nuclear Energy University Program (NEUP) projects that examine the use of Lightbridge Fuel in water-cooled Small Modular Reactors (SMRs). One of these is led by Massachusetts Institute of Technology (MIT) [19], and the other is led by Texas A&M University (TAMU) [20].

The MIT NEUP project is aimed at evaluating the use of Accident Tolerant Fuels in water-cooled SMRs, and specifically includes evaluation of Lightbridge Fuel for use in the NuScale VOYGR SMR. These evaluations include simulation studies of neutronics, thermal-hydraulics, fuel thermo-mechanical performance, and accident performance. The TAMU-led NEUP project also focuses on the use of Lightbridge Fuel in the NuScale VOYGR SMR, where the TAMU team will evaluate the thermal-hydraulic performance of Lightbridge Fuel via detailed simulation studies and experimental studies in flow loops.

Lightbridge also sponsors an initial engineering study conducted by the Romanian Institute for Nuclear Research (RATEN ICN) to evaluate Lightbridge Fuel for use in CANDU reactors. This study comprises evaluation of a preliminary mechanical design, preliminary neutronics, and preliminary thermal-hydraulics. The outcome of this study will be used to guide the next steps in further evaluation or optimizing the Lightbridge Fuel design for use in CANDU reactors.

**Preliminary Evaluation of Lightbridge Fuel for CANDU Reactors**

For the preliminary evaluation of Lightbridge Fuel in CANDU reactors, a preliminary bundle configuration was selected with 37 Lightbridge 4-lobed rods, where this configuration closely matches the bundle design currently used in the Cernavodă Nuclear Power Plant in Romania [22]. An end view of the Lightbridge 37-rod fuel bundle is shown in Fig. 2.

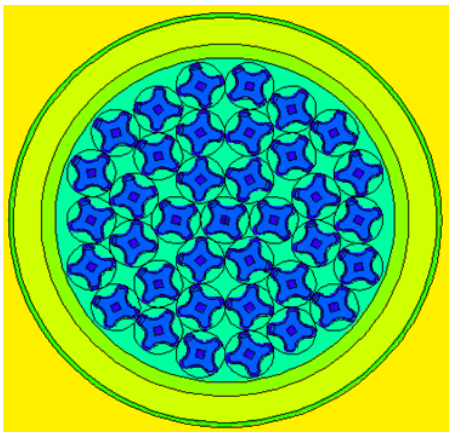


Fig.2. End view of a preliminary Lightbridge CANDU bundle with 37 4-lobed Lightbridge Fuel rods

Initial neutronics calculations have been performed on this mechanical design using MCNPX to evaluate enrichments and burnable poison configurations for the Lightbridge CANDU bundle [23]. This includes a sensitivity study that was conducted to evaluate the reactivity vs. burnup evolution of the Lightbridge CANDU bundle for enrichments varying from 1 to 3 wt% $U^{235}$ without the presence of burnable poisons.

Fig. 3 shows the typical CANDU reactivity vs. burnup evolution (left) and the reactivity vs. burnup evolution for several Lightbridge Fuel enrichments (right). The enrichment required in this 37-rod Lightbridge bundle configuration to match the reactivity of standard 37-rod CANDU bundles with natural enriched $UO_2$ fuel was determined to be 1.138 wt % $U^{235}$. At this enrichment, the 37-rod Lightbridge CANDU bundle would achieve the same discharge burnup as a standard 37-rod CANDU bundle, i.e. approximately 7 MWd/kgU.

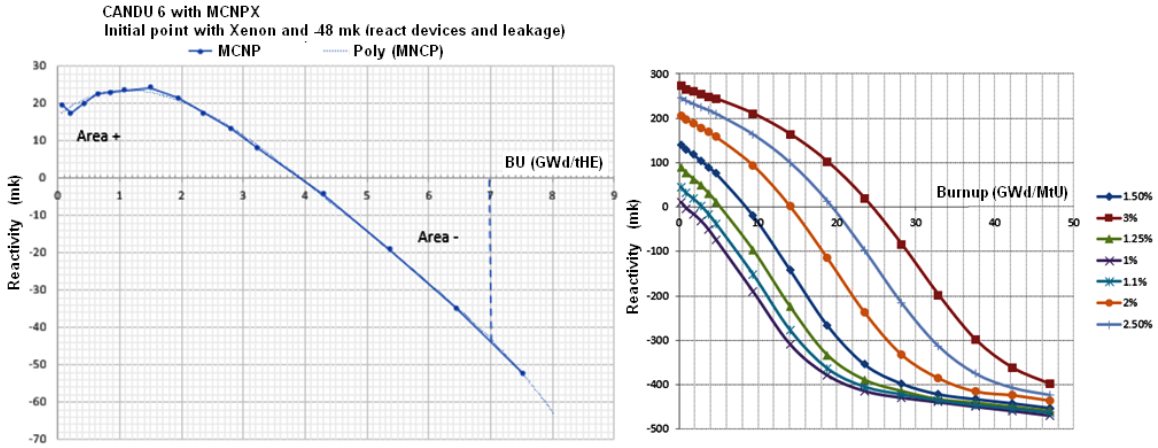



Fig. 3. Reactivity evolution vs. burnup for a standard 37-rod CANDU bundle (left) and for a 37-rod Lightbridge CANDU bundle for several enrichments varying from 1 to 3 wt % $U^{235}$

Calculations were performed to evaluate various combinations of enrichment, burnable poison content, and burnable poison configuration. The aim was to maximize the discharge burnup and reduce the initial reactivity of the Lightbridge CANDU design to be similar to that of the initial reactivity of the CANDU bundle reference design.

Conventional CANDU bundles achieve a discharge burnup of approximately 7 MWd/kgU. Preliminary results indicate that discharge burnups for the Lightbridge CANDU bundle can be increased to ~9 to ~15MWd/kgU depending on the combination of enrichment, burnable poison content and burnable poison configuration.

Future neutronics studies in this work include depletion analysis, evaluation of radial and axial power distributions within the fuel bundle, evaluation of the void reactivity coefficient. Thermal-hydraulics CFD analyses will also be performed, including determination of pressure drop across the Lightbridge CANDU bundle, temperature distribution within the bundle, and radial and axial flow distributions in the bundle.

## Conclusions and Outlook

Lightbridge Fuel offers significant advancements compared to conventional $UO_2$-based fuels, including improved safety, fuel performance, fuel cycle economics, waste reduction, and proliferation resistance. Simulation studies, laboratory tests, and limited irradiation testing have thus far confirmed these advantages in large and small LWRs.

Similar advantages are expected with the use of Lightbridge Fuel in CANDU reactors. The outcomes of the ongoing CANDU study will be used to identify any challenges associated with the use of Lightbridge Fuel in CANDU reactors, and will inform future work to further optimize the Lightbridge CANDU fuel design.

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