DEVELOPMENT OF LIGHTBRIDGE'S ADVANCED METALLIC FUEL FOR WATER-COOLED REACTORS

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ABSTRACT

Lightbridge Fuel™ is an advanced metallic nuclear fuel designed for use in water-cooled reactors, including existing and new build water-cooled nuclear power plants, and small modular reactor designs. Lightbridge's metallic fuel simultaneously offers step-change improvements in safety, economics, operational flexibility, and proliferation resistance.

Lightbridge Fuel consists of a uranium-zirconium (U-Zr) alloy fuel core, zirconium-alloy cladding, and central zirconium displacer, which are co-extruded to form monolithic, multi-lobed, and helically twisted fuel rods. The design features of Lightbridge Fuel improve safety margins through lower fuel operating temperatures, enhanced coolability, and a robust mechanical design. The design potentially enables power uprates, cycle-length extensions, and burnup extensions to very high burnups.

Preliminary studies including simulations, out-of-pile experiments, fabrication demonstrations, and proof-of concept test reactor irradiations confirmed the expected performance of the Lightbridge Fuel design and provided the basis for continued development. Currently, Lightbridge is funding fuel development activities at Idaho National Laboratory, comprising fabrication process development, and production of samples for irradiation testing in the ATR and TREAT reactors. The US Department of Energy is currently funding two, three-year projects through the Nuclear Energy University Programs framework – one led by Massachusetts Institute of Technology, and one led by Texas A&M University – to evaluate the performance of Lightbridge Fuel in water-cooled SMRs. In addition to these activities, a feasibility study evaluating the use of Lightbridge Fuel in CANDU reactors is being conducted by the Romanian Institute for Nuclear Research (RATEN ICN).

This paper presents a selection of qualitative results from previous and ongoing studies of Lightbridge Fuel, gives an overview of the status of ongoing development activities, and summarizes plans for future work.

1. Introduction

Lightbridge Fuel™ is an advanced nuclear fuel for use in small as well as giga-watt scale water-cooled reactors. The design consists of metallic fuel rods that are multi-lobed and helically twisted. The design and materials give Lightbridge Fuel inherently better performance than conventional ceramic, pellet-in-tube fuel designs. The Lightbridge Fuel rod design uses a similar uranium-zirconium alloy composition as fuel that was previously used for approximately two decades in nuclear-powered icebreaker ships, and which has had specific modifications implemented by Lightbridge for use in modern water-cooled reactors. The fuel performance experience of the icebreaker fuel up to very high burnups (~300 MWd/kgHM) provides confidence that Lightbridge Fuel will enable reaching burnup levels that are only limited by the fissile content of the fuel.

2. Overview of Lightbridge Fuel Design

Lightbridge Fuel rods consist of three components; 1) a fuel core, 2) cladding, and 3) a displacer (See Fig. 1). Fuel rods are produced by co-extruding these components, where the co-extrusion process enables metallurgical bonds between the displacer, the fuel core, and cladding, resulting in a monolithic fuel rod with no gas gaps between the components, and with no gas plenum. The extrusion process also imparts the multi-lobed geometry, and the helical twist.

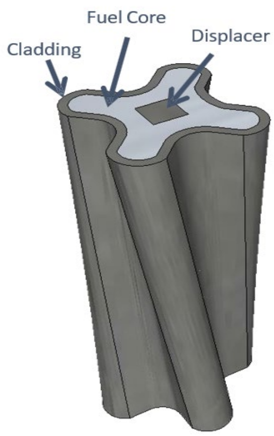


Fig. 1, Cross-section cut-away illustration of a four-lobed Lightbridge Fuel rod, showing the fuel core, cladding, and central displacer.

The fuel core material is a δ-phase uranium and zirconium alloy consisting of approximately 50 weight percent of each of these materials. This corresponds to approximately 25 volume % uranium and 75 volume % zirconium. The uranium component of the U-Zr fuel alloy can be enriched up to 19.75% in U-235. The cladding material has a typical nuclear fuel rod cladding alloy composition which can be adjusted as necessary for use in different reactor types and water chemistry regimes. The central displacer consists of zirconium which may be alloyed with burnable poisons, as necessary for the neutronic design of the fuel.

The helically twisted and multi-lobed geometry of Lightbridge Fuel allows for self-spacing of the rods within a fuel assembly, similar to wire-wrapped geometries used in sodium fast reactor fuel. This feature eliminates the need for spacer grids and mixing vanes in fuel assemblies consisting of Lightbridge Fuel rods.

3. Advantages of Lightbridge Fuel

The materials, construction, and geometry of Lightbridge Fuel rods lead to several inherent advantageous fuel performance characteristics that can result in improved safety margins, reduced waste volume, and enhanced proliferation resistance, while at the same time, enabling power uprates, cycle-length extensions, and burnup extensions to very high burnups.

Low Operating temperature: Lightbridge's metallic fuel has a high thermal conductivity, enabling low operating temperatures within the fuel. The central displacer, which does not contain fissile material, also contributes to maintaining low fuel centreline temperature since no fission heat is generated in the displacer.

Enhanced Coolability: The metallurgical bond between the central displacer, fuel core, and cladding, and the lack of gas gaps between these components, ensures improved heat transfer from the fuel to the coolant. The multi-lobed cross-sectional geometry results in a large surface area for heat transfer to the coolant, where Lightbridge Fuel rods have approximately 30%, or more, higher surface area than comparable cylindrical fuel rods. The helically twisted geometry further enhances coolability by inducing coolant mixing along the entire length of the fuel rods, as opposed to conventional fuel where coolant mixing is largely induced by spacer grid mixing vanes at only a few axial locations within the fuel assembly.

Robust Mechanical Design: The fabrication of Lightbridge Fuel rods using the co-extrusion process produces mechanically robust monolithic rods. In Lightbridge Fuel rods, the cladding is not the primary structural component as in conventional pellet-in-tube fuel rod designs. Eventual degradation of the cladding material via mechanisms such as oxidation, hydriding, and fretting have less severe consequences in Lightbridge Fuel as compared to the effect of the same mechanisms in conventional fuel rod designs. The monolithic design with metallurgically bonded components is not susceptible to pellet-clad-interaction, and can enable relatively rapid power adjustments, including for load-follow operation.

Fuel Composition: The U-Zr Lightbridge Fuel can use enrichments up to 19.75 weight percent U-235, i.e. High Assay Low Enriched Uranium (HALEU), which has sufficient fissile material to support reaching high burnups and to enable power-uprates and cycle-length extensions. Since the fuel alloy consists of approximately 50 % by weight of uranium and zirconium, the Lightbridge Fuel alloy contains only about 35 % of the mass of U-238 that is contained in conventional UO_2 fuel, resulting in decreased production of Pu-239, contributing to better proliferation resistance of spent Lightbridge Fuel [1]. By enabling reaching higher burnups, the use of HALEU in Lightbridge Fuel results in reduced waste volume since the fuel can operate longer.

Its low operating temperatures, enhanced coolability, and robust mechanical structure result in Lightbridge Fuel potentially having improved safety margins and less severe consequences from damage or adverse operating conditions. Simultaneously, the robust design and use of HALEU enable Lightbridge Fuel to support power uprates and cycle-length extensions. Due to the materials and geometry of Lightbridge Fuel, operating margins, safety limits, and performance phenomena that are relevant for UO_2-based fuels in normal as well as off-normal conditions, may not be relevant for Lightbridge Fuel (and vice versa), so caution should be used when evaluating Lightbridge Fuel according to UO_2 fuel-based limits and phenomena.

4. Overview of Previous and Ongoing Studies

A series of studies, including simulations, out-of-pile experiments, fabrication demonstrations, and proof-of concept irradiations have been performed to confirm fabrication processes, determine preliminary fuel designs for different applications, and to investigate performance and economic benefits of Lightbridge Fuel. These studies encompass neutronics calculations, thermal hydraulics calculations and lab tests, fabrication process development and demonstrations, and proof-of-concept irradiations – all of which have thus far confirmed the expected performance of the Lightbridge Fuel design.

4.1 Neutronics

Detailed neutronics calculations were performed to determine an equivalent representation of the Lightbridge 4-lobed geometry as cylinders to facilitate modelling of Lightbridge Fuel in lattice physics codes that do not accommodate the multi-lobed geometries [2]. A 2D model of the 4-lobed fuel rod geometry was built using MCNP-6, and the lattice-cell code DRAGON was used to model the Lightbridge fuel rod as concentric cylinders. An equivalent concentric cylinder pin-cell model was found that correctly reproduces the MCNP reference K_{inf} values at the pin level, while preserving the mass of the various materials. See Fig. 2 for the modelled MCNP and equivalent concentric-cylinder DRAGON geometries.

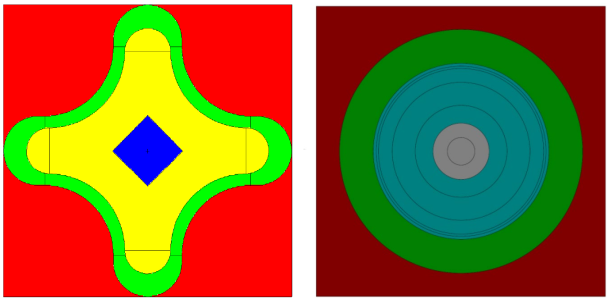


Fig. 2. 2D rod geometry in MCNP (left), and equivalent cylinder geometry in DRAGON (right).

A 17x17 PWR fuel assembly was modelled in MCNP, using the 4-lobe rod geometry, and in DRAGON, using the equivalent cylinder geometry [2]. An optimized equivalent cylinder design was determined via parametric studies on the concentric cylinder properties, comparing K_{inf} vs. burnup for the MCNP fuel assembly model and the DRAGON assembly model. The results of this study indicate that Lightbridge 4-lobed fuel rods can be accurately modelled using equivalent concentric cylinder models, while areas for improving the reactivity agreement of these models in specific conditions, such as at high burnups, were identified.

Further neutronics calculations have been conducted to evaluate the use of Lightbridge Fuel in various 17x17 configurations in a Westinghouse AP-1000, an AREVA EPR, and in a reference PWR (Seabrook). These studies evaluated reactivity control and burnable poison design, power uprates, equilibrium core designs, burnup calculations, reactivity coefficients, control rod worth, discharge isotopics, initial enrichment, cycle lengths, and the associated fuel cycle costs. These studies concluded that using Lightbridge Fuel can provide more power and/or longer fuel cycles than is possible with conventional UO_2 fuels [3]. A series of neutronics studies were also performed to evaluate previous seed-and-blanket Lightbridge fuel design (comprising multi-lobed helically twisted uranium-zirconium alloy rods in the central seed region and uranium-thorium-dioxide fuel rods based on conventional fuel rod design in the surrounding blanket region), including configuration and design of burnable poisons [4].

4.2 Thermal-Hydraulics

4.2.1 Analytical Studies

Several analyses and calculations have been performed to determine thermal-hydraulics characteristics of Lightbridge multi-lobed fuel rods. In [5], calculations were performed to determine preliminary quantifications of surface heat flux around the perimeter of the 4-lobed fuel rods and coolant flow rates vs. burnup, through a 17x17 PWR seed and blanket fuel assembly design.

An analytical study was performed to determine procedures for the heat transfer coefficient in swirling coolant flows and provide recommendations for methods to calculate and experimentally verify coolant velocity profiles around the perimeter of the multilobed helically twisted rods [6]. This study concluded that the value of the average coefficient of heat transfer from twisted rods is of the same order as the heat transfer coefficient value for cylindrical rods, and additionally that the coefficient of heat transfer from twisted rods differs around the perimeter of a rod, where it is higher on the lobes and lower in the valleys between the lobes. Experimental studies were recommended to determine the coolant velocity profile around the perimeter of the helically-twisted rods.

Another analytical study was performed that examined the preliminary thermal-hydraulic characteristics of a Lightbridge VVER-1000 seed-and-blanket fuel assembly design, where the results showed technical feasibility (i.e. no violations of thermal safety limits) for the use of such a fuel assembly design to support a power uprate and extended cycle length.

Subchannel calculations were performed using the SC-1 code, an analogue to COBRA-4, on the multi-lobed helically twisted metallic fuel rods in the seed and blanket fuel assembly. These simulations were used, together with experimental data described in the following section, to develop a correlation to calculate Departure from Nucleate Boiling Ratios.

4.2.2 Thermal-Hydraulics Experiments

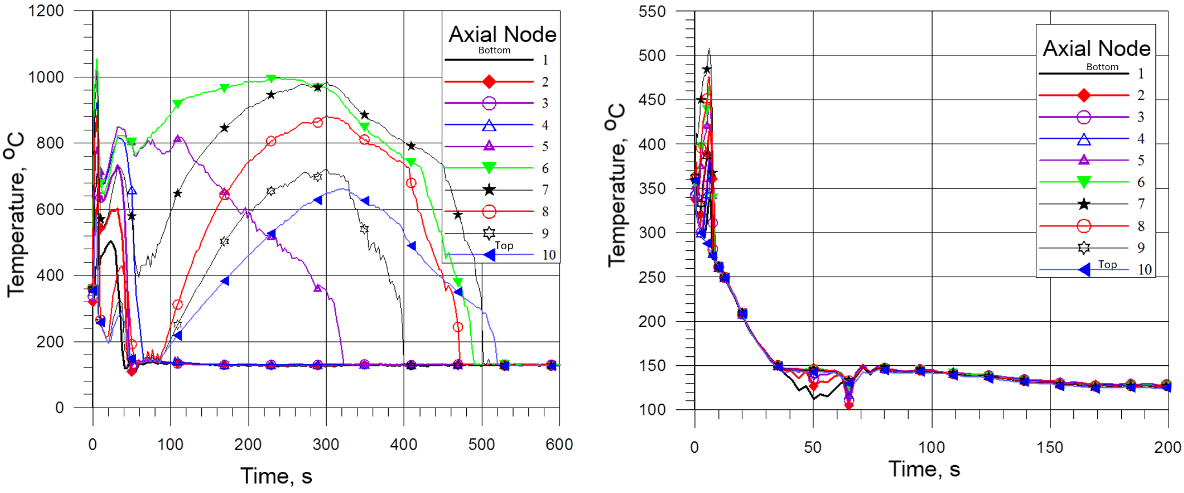
A 19-rod fuel bundle, comprised of 3-lobed helically twisted dummy fuel rods, was tested in low-pressure and high-pressure thermal hydraulic test loops at the Kurchatov Institute to verify and improve calculation techniques and codes used in thermal physical analysis for metallic helically twisted rods. The experiments determined the hydraulic resistance for a variety of coolant inlet temperatures and determined steady-state critical power for different flow rates and temperatures.

Another thermal-hydraulic experiment was performed on a Lightbridge VVER-1000 seed and blanket fuel assembly design with a seed assembly consisting of 108 3-lobed, metallic, helically twisted Lightbridge dummy fuel rods [7] - [12]. These tests determined pressure gradients and hydraulic and vibration characteristics for flow rates varying from 200 to 400 cubic meters per hour for water temperatures from 50°C to 60°C. Fig. 3 shows the mock-up assembly used for testing.

Fig. 3. Photo of the 108-rod seed-assembly consisting of 3-lobed, metallic, helically twisted Lightbridge Fuel rods used for thermal-hydraulic and vibration testing.

4.3 Safety Analyses

Safety analysis calculations were performed for the seed and blanket Lightbridge VVER-1000 fuel assembly design using the codes KANAL, RELAP5, RECOL, and TIGR-1 [13]. Inputs to these analyses included the results from the analyses and experiments described in section 4.2. Several Anticipated Operational Occurrences and Design Basis Accidents were analysed, including: loss of power to the four coolant pumps; loss of power to one coolant pump; control rod ejection; run-down of one coolant pump; and Loss of Coolant Accident. Plots showing peak cladding temperature at different axial nodes for the standard VVER-1000 fuel and the Lightbridge 3-lobed, metallic, helically twisted fuel are shown in Fig. 4.



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

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

Fig. 4. Peak cladding temperature at different nodes during LOCA event in a VVER-1000. The left plot shows standard VVER-1000 fuel, and the right plot shows Lightbridge 3-lobed, metallic, helically twisted fuel. Note the temperature and time scales of these plot are different to aid in visibility.

Note that the Lightbridge metallic fuel rods were calculated to have lower temperatures and quicker cool-down time as compared to the standard VVER-1000 UO_2 fuel. For all conditions analysed, it was shown that all acceptance criteria were fulfilled, and design requirements were satisfied for the Lightbridge metallic fuel. These results show that the Lightbridge Fuel and the UO_2 fuel both have large margins to their fuel melting temperatures: ~1000ºC and ~1500ºC margins, respectively. The lower temperature of the Lightbridge Fuel is further advantageous with regard to temperature-driven and temperature-dependent phenomena, such as steam-zirconium interaction (beginning at ~800ºC and with a parabolic reaction rate from ~1000ºC to ~1500ºC [14]). It should be noted that due to the materials, geometry, and construction of Lightbridge Fuel, performance in accident conditions may differ significantly from UO_2 fuel, including which critical phenomena affect fuel performance, and including different consequences of materials degradation.

4.4 Fuel Performance

Lightbridge has access to a significant database of performance information on the icebreaker fuel, which used similar uranium-zirconium alloy composition as for the Lightbridge Fuel design. This database includes performance data and post irradiation examination (PIE) information on more than 1,500 fuel rods of various cross-sectional geometries, irradiated in different conditions in research reactors and icebreaker ships to different burnups, up to approximately 300 MWd/kgU.

Fuel performance models were developed using ANSYS to determine temperatures, displacements, strain and stress over a selection of fuel geometries in the icebreaker fuel database [14]. The models capture properties and phenomena such as thermal conductivity, swelling, thermal creep, and irradiation creep and were utilized to evaluate variations in geometry and materials to determine sensitivities to these parameters and to select optimized parameters for the Lightbridge Fuel design. Comprehensive calculations were performed [16] for the Lightbridge 4-lobed metallic fuel rod design to determine: thermal and elastic strains, plastic strains, creep strains, irradiation induced strains, aggregate strains, swelling, and temperature distributions. Fig. 5 shows an example temperature distribution and an example of aggregate thermomechanical strains determined using the developed models for a 1/8 section of a Lightbridge 4-lobed metallic fuel rod.

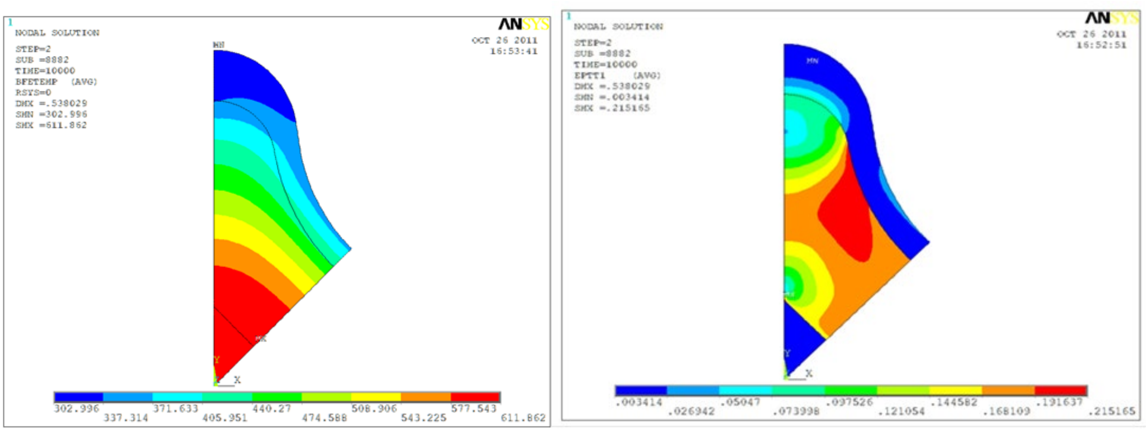


Fig. 5. Temperature distribution (left) and aggregate thermomechanical strains (right) in a 1/8 section of a Lightbridge 4-lobed metallic fuel rod.

4.5 Irradiations

In addition to the over twenty years of irradiation experience of thousands of metallic icebreaker fuel rods, and the extensive database of icebreaker fuel performance, Lightbridge sponsored a proof-of-concept irradiation test of the Lightbridge Fuel concept in the IR-8 research reactor at the Kurchatov Institute. In this test, three Lightbridge 3-lobed metallic and helically twisted fuel rodlets, and three icebreaker-type rodlets, were placed in circulating water capsules, and subjected to irradiation. Three capsules were irradiated, where each capsule contained one Lightbridge 3-lobed rodlet and one icebreaker-type square-cross section fuel rodlet, positioned along the same vertical axis. The primary aim with this irradiation test was to determine the presence or absence of fabrication-related faults in tri-lobe fuel rods for different fabrication parameters. Two of the three capsules operated as planned and were irradiated for more than 200 days, where the Lightbridge 3-lobed fuel rods exhibited good performance.

Due to technical issues with the third test capsule, which resulted in flow blockage, the two rodlets in that capsule experienced flow starvation and operated in dryout conditions for approximately 24 hours, until radiation detection monitors identified a problem, and the test was stopped. The square cross section rodlet and 3-lobed rodlets each experienced loss of cladding and some loss of fuel material, but both rodlets maintained their coolable geometry. As shown in Fig. 6, damage to the Lightbridge 3-lobed rodlet was minimal and primarily affected the valleys between the lobes.

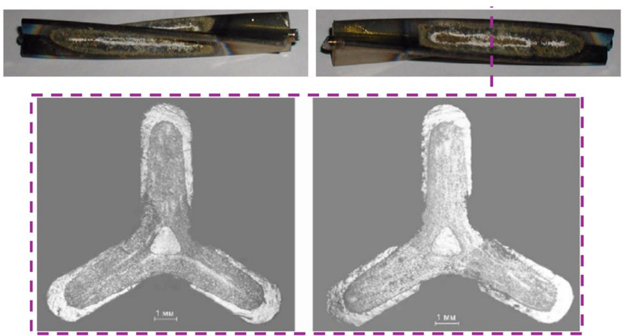


Fig. 6. Cross section of a 3-lobed Lightbridge rodlet after ~24 hours under dryout conditions during irradiation showing minimal damage in the valleys between the lobes.

4.6 Fabrication Development

Lightbridge's fabrication process consists of casting ingots of the fuel alloy, and assembling billets where the central displacer material is inserted into the centre of the fuel alloy ingot, which is placed into an outer shell of cladding material. This billet assembly is then co-extruded through a special die, to produce the monolithic, multi-lobed, and helically twisted Lightbridge Fuel rods. In recent years, fabrication development activities have involved co-extrusion of 6-foot-long, three-lobed fuel rods consisting of surrogate materials [17], investigation of ingot casting techniques at Pacific Northwest National Laboratory under a US DOE Gateway for Accelerated Innovation voucher [18], as well as work sponsored by Lightbridge at Idaho National Laboratory (INL) to perform additional castings and extrusions [19].

5. Conclusions and Outlook

Currently Lightbridge conducts fuel development activities internally and sponsors or participates in several ongoing projects with external partners, focused on continued development of Lightbridge Fuel and evaluations of Lightbridge Fuel performance for various applications. Lightbridge sponsors a fuel development program at INL that encompasses fabrication development, test sample fabrication, irradiation experiments, and associated PIE. Lightbridge also sponsors a study, conducted by the Romanian Institute for Nuclear Research (RATEN ICN) to evaluate feasibility of using Lightbridge Fuel rods in CANDU reactors.

In addition to these activities, Lightbridge also supports two ongoing US DOE Nuclear Energy University Program (NEUP) projects led by Massachusetts Institute of Technology, and Texas A&M University (TAMU). The MIT NEUP project is focused on evaluating Accident Tolerant Fuels in Small Modular Reactors (SMRs), and specifically includes evaluating the use of Lightbridge Fuel in the NuScale VOYGR, encompassing studies of neutronics, thermal-hydraulics, fuel performance and accident performance. The TAMU NEUP project focuses on use of Lightbridge Fuel in NuScale's VOYGR SMR, encompassing thermal-hydraulics simulations studies and laboratory experiments.

Many analyses, simulation studies, out-of-pile experiments, fabrication development activities, and some proof-of-concept irradiations have been performed, and more are currently being conducted, to support development and qualification of Lightbridge Fuel. The results of these activities thus far have demonstrated the expected enhanced performance capabilities of Lightbridge's metallic fuel design. Future results for BWR, PWR, CANDU, and selected SMR cases will form the basis for regulatory licensing of Lightbridge Fuel for use in a variety of applications to bring the advantages of superior metallic fuel performance to existing and future water-cooled reactors.

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