FUEL CYCLE FOR ARC-100 COMMERCIAL DEMONSTRATION AT THE POINT LEPREAU NUCLEAR SITE IN NEW BRUNSWICK

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Abstract

ARC Clean Technology's 100 MWe sodium-cooled fast reactor is a Generation IV advanced Small Modular Reactor leveraging the proven prototype experience of Experimental Breeder Reactor II (EBR-II) with modern design improvements to meet industry and public expectations for nuclear power generation in a net-zero economy. The ARC-100 core assemblies are comprised of sodium-bonded U-10Zr metallic fuel pins which provide the foundation of its inherent, walk-away safety. Metallic fuel is a mature technology with no further need for in-reactor or R&D activities prior to a commercial demonstration unit based on the extensive operations at EBR-II and the Fast Flux Test Facility (FFTF). The ARC-100 can confidently employ proven fuel technology to operate with a 20-year fuel cycle, reducing complexity and operational costs. New Brunswick Power has chosen to partner with ARC Clean Technology to deploy an ARC-100 commercial demonstration reactor which plans to be in operation by 2030 at the existing Point Lepreau Nuclear Generating site.

1. Introduction to Metallic Fuel History

ARC Clean Technology's ARC-100 is a fast spectrum, sodium-cooled reactor with a 286 MWt, 100 MWe capacity. The reactor is fuelled by sodium-bonded, binary metallic uranium fuel alloy at a nominal enrichment of 13.1%. Core inlet and outlet coolant temperatures are 355°C and 510°C, respectively. Further technical details on the ARC-100 are available in the 2022 IAEA small modular reactor technology developments update [1].

The choice of ARC's metallic fuel is based on the prototypical operations at EBR-II at Idaho National Laboratory (then Argonne National Laboratory). EBR-II began operation in 1964 and successfully ran until 1994 when the Integral Fast Reactor Program was terminated. The core was relatively small, outputting 62.5 MWt and 20 MWe. Consequently, the active fuel length was 34.3 cm. While the nuclear industry largely moved to adopt oxide fuel due to early issues in achieving high burnups with metal fuel, further testing and developments proved that increased burnup was indeed possible by understanding the irradiation-induced swelling phenomena. A key discovery during the 1960's and 1970's that came out of EBR-II's metallic fuels research was that high burnups could be achieved by allowing room for the fuel to swell within the cladding instead of constraining the swelling. The sodium bonding maintains thermal conductivity between the fuel and cladding, while partially compensating for the porosity induced while fission gas bubbles are produced during irradiation. At approximately 30% volumetric swelling, enough fission gas bubbles are produced to interconnect and provide a pathway to the fission gas plenum [2]. This discovery led to predicable fuel swelling behavior and determination that a smear density of 75% allowed the fuel to swell out to the cladding without breaching. The smear density is defined as the areal density of the fuel inside the inner wall of the cladding and is typically expressed as a percentage. The equation for calculation of smear density is shown in Equation 1.

$$Smear\ Density = 100\ \times (\%\ of\ theoretical\ density)\frac{\sqrt{fuel\ outer\ diameter}}{\sqrt{cladding\ inner\ diameter}}$$

Equation 1 Calculation of smear density for metallic fuel

Figure 1 below illustrates the chemical and mechanical phenomena involved in the irradiation performance of typical metallic fuels, such as the U-10Zr (uranium with 10 weight% zirconium) fuel for the ARC-100. By incorporating a large fission gas plenum, running at lower linear heat rates, and maintaining lower peak cladding temperatures to minimize cladding wastage due to fuel-cladding chemical and mechanical interactions, the ARC-100 fuel design mitigates the effects of these phenomena.

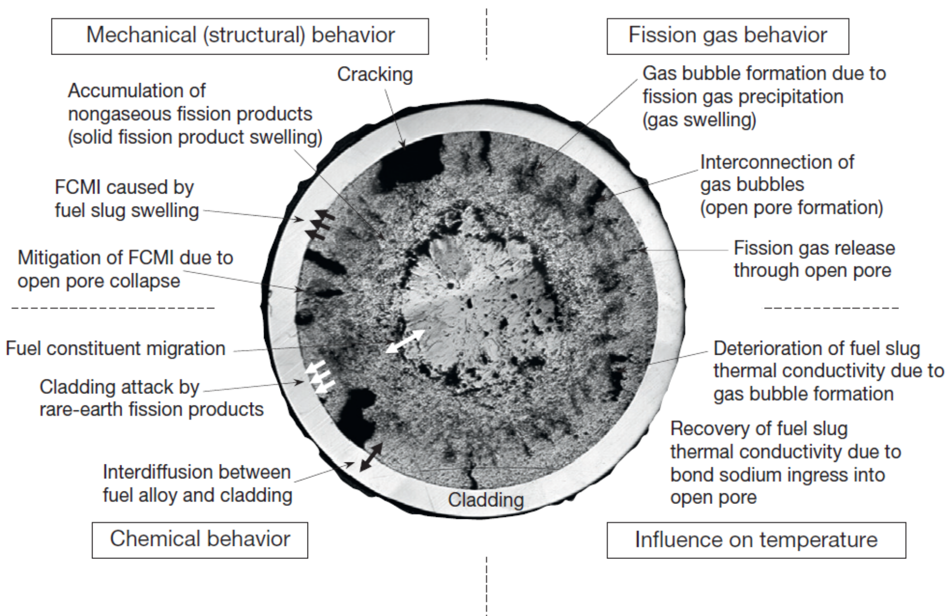

Figure 1 Metallic fuel irradiation phenomena [3]

A major benefit of using metallic fuel in sodium-cooled fast reactors is the chemical compatibility of uranium metal with sodium and the HT-9 steel used in the cladding and ducts. In the unlikely event of a cladding breach during reactor operation, there is no energetic reaction between the fuel and coolant. The reactor can continue to operate with a small number of fuel defects as the sodium coolant purity can be maintained by sodium and cover gas purification systems.

Given that larger, commercial reactors would require longer fuel, there were concerns that approximately one-meter-long metallic fuel pins might not behave the same as shorter lengths or potentially slump under their own weight. The FFTF reactor, built at the Hanford Site in Washington, was a larger sodium-cooled fast reactor (SFR) than EBR-II with a 400 MWt capacity.

Operations at FFTF began in 1978 where the core employed longer fuel at 91.4 cm. FFTF experience showed that the longer fuel performed as successfully as the shorter EBR-II fuels under the same operating conditions [4].

Further rapid transient over-power testing was performed at the Transient Reactor Test (TREAT) facility where the metallic fuel pins were purposely breached to study the effects of failed fuel. As few metallic fuel pins actually failed during regular operation, these tests were designed to force failure using pre-irradiated pins modified with intentional cladding defects and exposed to four-times overpower conditions. The U-10Zr fuel clad with HT-9 (heat-treated martensitic steel), was not successfully breached even under these extreme testing conditions that caused fuel melting [5].

Over 130 000 metallic fuel pins were irradiated in EBR-II and more than 1000 in FFTF [6]. Figure 2 shows an illustration of a typical metallic fuel pin which includes the metallic uranium alloy in the fuel slugs (labelled "fuel rod" below), sodium bond which provides thermal conductivity between the fuel and cladding, and a generous gas plenum to collect fission gases and limit internal fuel pin pressure. Metallic fuel units are referred to as "slugs" which are longer than oxide fuel pellets, like those employed in CANDU fuel assemblies. The entire fuel pin is clad with ferritic/martensitic alloy steel, HT-9. This alloy contains 12% chromium, 1% molybdenum and is known for its high thermal conductivity, high creep rupture strength, and low void swelling rates under neutron irradiations [7].

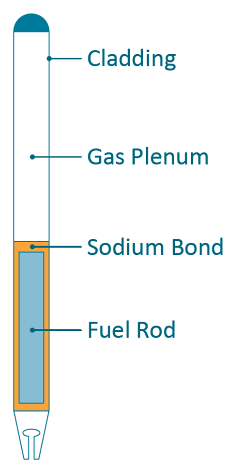

Figure 2 Typical Metallic Fuel Pin

Metallic fuel provides the basis for the inherent safety of the ARC-100 reactor with its high thermal conductivity and lower peak centerline temperature in comparison to oxide fuel. In a loss-of-power event where the coolant flow is interrupted, there is an initial increase in reactivity and the core will increase in temperature. As the core heats up, the core expands outward causing increased neutron leakage which in turn leads to a decrease in reactivity. Power will drop and the core will then begin to decrease in temperature without operator intervention.

2. ARC-100 Core and Fuel Design

The ARC-100 core consists of 99 fuel assemblies with three levels of enrichment categorized in Table 1 below. The average enrichment is maintained at 13.1%, which is classified as High-Assay Low-Enriched Uranium (HALEU).

Table 1 ARC-100 Core Assemblies

Core Position	Enrichment Level (%)	Number of Assemblies at Position
Inner	10.9	30
Middle	12.4	33
Outer	15.5	36

The fuel pins are ~1 cm in diameter, wider than the largest fuel pins tested at EBR-II (5.84 mm) and the 6.86 cm pins fabricated for FFTF. ARC-100 fuel is similar to the diameter of the U-2Zr fuel used in EBR-I, which had a fuel slug diameter of 9.8 mm, and the blanket fuel used in EBR-II [8, 9]. The total active fuel length in the ARC-100 is 150 cm, which is longer than the fuel used in EBR-II. Testing performed in FFTF demonstrated that the length of the fuel did not adversely affect its performance under similar operating conditions as EBR-II. Graphical representations of a typical sodium-bonded fuel pin and SFR fuel assembly, similar to the FFTF designs, are shown in Figure 3 and Figure 4 below. In Figure 3, the “fuel slug stack” is the same as the fuel rod and represents the total active fuel length.

The ARC-100 core contains six control rods and three shut-off rods inside the active fuel array. A layer of reflector assemblies and shielding assemblies are located around the outside of the core. Non-fuel assembly details are provided in Table 2. A schematic of the core illustrating the positions of all assemblies is shown in Figure 5.

Table 2 Non-fuel ARC-100 Core Assemblies

Type of Assembly	Material	Number of Assemblies
Control Rods	HT-9/B_4C	6
Shut-off Rods	HT-9/B_4C	3
Reflector	HT-9	42
Shielding	HT-9/B_4C	48

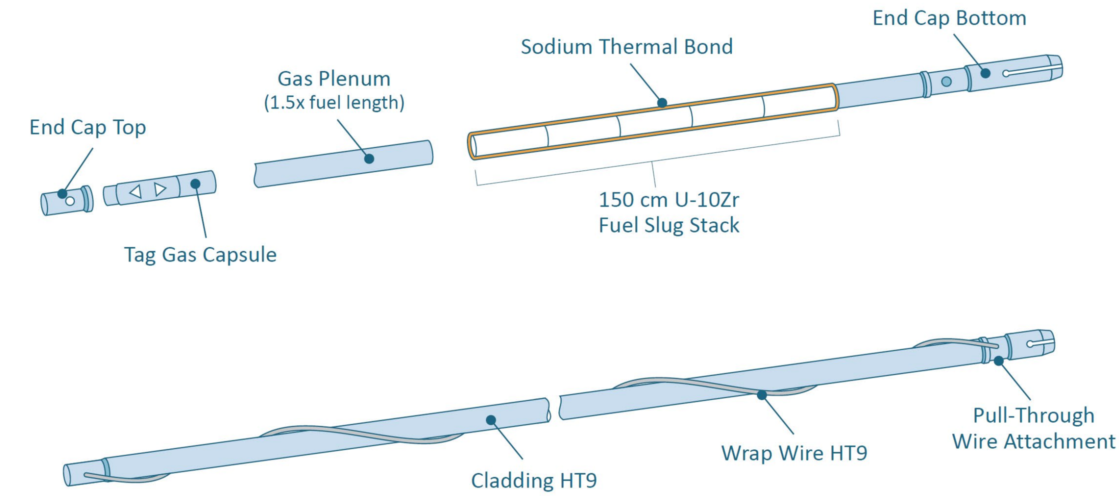

Figure 3 Graphic of sodium-bonded metallic fuel pin

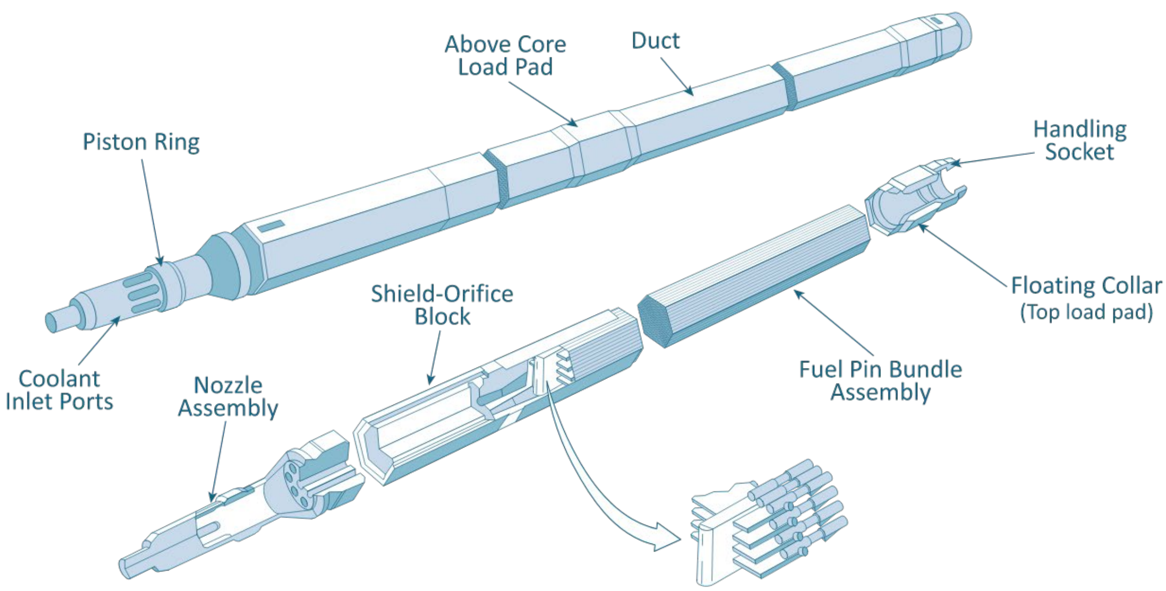

Figure 4 Graphic of metallic fuel assembly

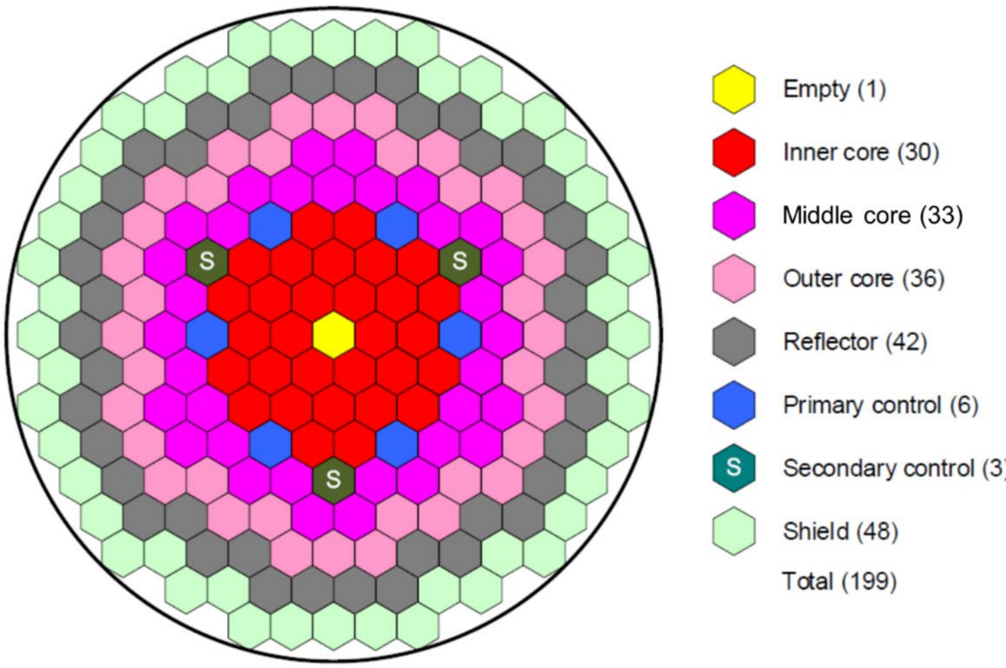

Figure 5 Core arrangement for the ARC-100 reactor [from reference 10]

3. Operational Readiness of ARC-100 Fuel

The ARC-100 fuel design is based on the driver fuel used in EBR-II and the metallic fuel pins successfully tested in FFTF and TREAT. Based on the extensive operational experience, the Canadian Nuclear Laboratories (CNL) reviewed ARC's fuel design against the Canadian Nuclear Safety Commission (CNSC) and United States Nuclear Regulatory Commission (USNRC) requirements, along with International Atomic Energy Agency (IAEA) recommendations. In total 126 regulatory requirements and recommendations related to fuel design and qualification were identified. Of those requirements applicable to metallic fuel for SFR's, CNL determined that ARC's fuel adequately met 84% of the requirements during the pre-licensing stage of design development. The project was initiated in November 2021 and a report was issued in June 2022 highlighting CNL's conclusion that the ARC-100 fuel for the commercial demonstration unit does not require any further in-reactor testing [11]. A quote from the conclusions of this report is shown below:

"*CNL believes that ARC has sufficiently demonstrated a conservative approach in their estimation of fuel performance and behaviour to allow the operation of the ARC-100 reactor to its design operating envelope.*"

As part of an initiative to transfer sodium-bonded fuel fabrication technology to Canada, ARC continues to work with the nuclear fuel experts at CNL. In July 2022, ARC once again engaged CNL to execute a sodium-bonded fuel pin technology demonstration under a Canadian Nuclear

Research Initiative (CNRI) project. The project is estimated to be two years of work and is currently in it's first phase.

As further assurance toward deploying advanced nuclear technology without further in-reactor testing of metallic fuel, Argonne National Laboratory sought to apply a quality standard to the EBR-II legacy fuel pin data organized into the Fuels Irradiation and Physic Database (FIPD) and Out-of-Pile Transient Database (OPTD). The Quality Assurance Program Plan (QAPP) for FIPD and OPTD will follow ASME NQA-1 2008/2009 standards. Included in the databases are all the test pin data and associated documentation from EBR-II along with further hot-cell testing performed on previously irradiated EBR-II test pins [12].

It is expected that a comprehensive fuel surveillance program will confirm the current fuel design will operate safely until reactivity deficit requires refuelling after 20 full power years of operation. The long refuelling cycle reduces complexity related to fuel handling and allows the fuel to reach a peak burnup of 14at%. The ARC core operates with large safety margins and much lower average linear heat rate than EBR-II and FFTF, at an average of ~8 kW/m. By comparison, FFTF ran fuel up to ~59 kW/m.

4. Metallic Fuel Fabrication Process

For the ARC-100 commercial demonstration unit, ARC intends to source Canadian-mined natural uranium and convert to uranium hexafluoride (UF_6) in Canada. The enrichment of the UF_6 will likely progress in a staged approach. More information will be available on the fuel supply for advanced reactors as the various commercial entities develop their processes. The first stage of enrichment goes from natural (0.7%) to low-enriched uranium (LEU, up to 5%), and then to LEU+ up to as high as 9.95%. Further enrichment to high-assay low-enriched uranium (HALEU), defined as enrichment between 10% and 19.75% will be the key step for many advanced reactor designs, including the ARC-100. The supply chain for HALEU fuel is in development as commercial enrichers work with governments and technology developers to support the global energy demand.

HALEU fuel in the UF_6 form needs to be deconverted to metallic form and alloyed with zirconium to make the fuel slugs prior to the production of ARC-100 sodium-bonded fuel pins. Along with the HALEU supply chain, the establishment of deconversion and reduction capability is being explored in North America and Europe to support advanced nuclear reactor deployment.

There are several types of fabrication processes for cylindrical, metallic fuel slugs including vacuum-injection casting, continuous casting, extrusion, and additive manufacturing. The vacuum-injection casting process has the most extensive operational experience as it was used to manufacture over 200 000 fuel rods at EBR-II. It was also the metallic fuel manufacturing choice for the United States proposed Versatile Test Reactor (VTR), a 300 MWt sodium-cooled fast test reactor [13]. Injection casting begins with an induction heating furnace under vacuum used to heat the metal alloy fuel in a graphite crucible until molten. Long, glass quartz tubes mounted in a cylindrical array are lowered into the molten fuel. The casting furnace is then rapidly pressurized with inert gas, quickly filling the molds with fuel to create fuel slugs. Processing to ensure proper length and quality is performed after breaking the glass mold to release the fuel slugs.

Other manufacturing technologies are expected to be developed to ensure efficient production of commercial metallic fuel assemblies with minimized waste, but injection casting technology has the most experience in the production of metallic fuel supplied to the EBR-II and FFTF reactors.

5. Spent Fuel Management Plan

ARC's long-term goal is to close the fuel cycle by recycling the spent fuel when the reprocessing method has regulatory approval, public acceptance, and is economically viable. The Integral Fast Reactor (IFR) concept demonstrated the ability to close the fuel cycle during EBR-II operations between 1964-1969. During this time, 35 000 metallic fuel pins were fabricated, irradiated, recycled using pyrometallurgy, remotely refabricated, and returned to the core to continue generating electricity for the grid. This program ultimately demonstrated the capability of closing the fuel cycle using metallic fuel in an SFR [8].

Over the planned 60-year life of the ARC-100, only ~300 spent fuel assemblies will be produced from the three core loads. At the end of 20 years, the first core load of fuel will be moved to in-vessel storage around the outside of the core to cool. After a minimum ~six month decay period, the fuel can be moved to on-site dry interim storage.

For the commercial demonstration unit, ARC will generate a plan for direct disposal in a proposed Deep Geological Repository. An initial draft of the ARC-100 Spent Fuel Management plan, including the methodology for spent sodium-bonded metallic fuel assemblies to potentially be integrated with the DGR planning, is under review. Discussions with the Nuclear Waste Management Organization (NWMO) are ongoing.

6. Collaborative Relationship with New Brunswick Power

Beginning in 2017, as part of the overall energy supply planning and to address the emerging requirements for GHG emission reductions, NB Power reviewed various nuclear supply options. Recognizing the potential benefits of the emerging SMR market, NB Power assessed over 90 SMR technologies for on-grid application. Based on several criteria such as nuclear safety, safeguards, reliability, environmental and waste, fuel supply, cost competitiveness, technological readiness, public acceptance and potential for economic benefits, NB Power focused in on advanced fast neutron spectrum reactors. In 2018, in consultation with the Provincial Government, two advanced Generation IV SMRs technologies were selected, and Memorandums of Understanding were signed with ARC Clean Energy Canada's for an ARC-100 reactor and with Moltex Energy Canada's SSR-W and its associated WATSS fuel conversion facility.

Since 2018, ARC Clean Energy, now ARC Clean Technology Canada, has been working closely with NB Power to progress the design of the ARC reactor [14, 15]. In December 2020, the Government of New Brunswick, and New Brunswick Power (NB Power) signed a new

Memorandum of Understanding with ARC Clean Technology Canada to deploy a commercial demonstration of the ARC-100, a 100MWe sodium-cooled advanced Small Modular Reactor (aSMR) by the end of the decade at the Point Lepreau Nuclear Generating Station (PLNGS) site. NB Power has been safety operating PLNGS since it went into service in early 1983 and is an experienced nuclear operator.

ARC is collaborating with senior leadership and the Advanced Reactor Development (ARD) team at NB Power to achieve the ambitious timeline to deploy the ARC reactor at the Point Lepreau site by 2030 as the need to reach Net-Zero by 2050 quickly approaches. Since the signing of the MOU, both the utility and technology developer have been growing their teams and resources while meeting the regulatory timelines throughout the pre-licensing Vendor Design Review phases and licensing processes with the CNSC.

The ARC-NB Power relationship extends past the commercial demonstration at the PLNGS site to explore industrial applications for the ARC-100 in the province of New Brunswick. The ARC-100 produces high-quality, super-heated steam from the higher coolant temperatures achievable using sodium, which has a boiling point of 883°C. The size and output of the reactor makes it ideally suited to support industry and clean fuel production. In November 2022, the Port of Belledune authority announced its intention to work with Cross River Infrastructure Partners for the development of a Green Energy Hub employing ARC's advanced SMR technology [16].

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