A Testing Facility for Advanced Reactor Development and Demonstration

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INTRODUCTION

Recently, the Generation IV International Forum (Gen-IV) has established a set of nuclear reactors, with main objectives to improve overall reactor safety, efficiency, sustainability, proliferation resistance, and cost [1]. However, the financial cost and time required to license and build an advanced reactor is so great that only the Sodium-cooled Fast Reactor (SFR), High-Temperature Gas-cooled Reactor (HTGR), and Molten Salt Reactor (MSR) have proceeded beyond early design stages. All Gen-IV systems are designed to operate at normal and off-normal temperatures that are beyond existing nuclear industry experience and necessitate high-burnup capability for fuels and long lifetimes for cladding and structural materials. In addition, five of the six Gen-IV reactors operate in a fast-spectrum, which have increased materials performance requirements in terms of radiation damage resistance and corrosion resistance. Candidate fuels proposed for these advanced reactors are mainly uranium, plutonium, or TRU bearing fuels in the form of oxide, nitride, carbide, or metal. Candidate cladding and structural material are ferritic/martensitic steels (such as HT-9), oxide dispersion-strengthened steel, ceramics, Ni-based alloys, or refractory alloys [1]. The lack of data for most of these advanced materials calls for renewed testing efforts. However, the financial cost and time required to test advanced fuels and materials overseas prohibits many promising concepts from proceeding.

To overcome this problem, Niowave in collaboration with Los Alamos National Laboratory and the University of Michigan, is currently developing a hybrid fast/thermal spectrum subcritical testbed coupled to a superconducting electron linac through a lead-bismuth eutectic (LBE) neutron converter. Fast neutron fluxes greater than 10^{14} n/cm^{2}s are required for in-situ radiation damage studies, whereas, fluxes greater than 10^{15} n/cm^{2}s are required for radiation damage studies with significant displacements per atom. The proposed system will create a peak fast-spectrum neutron flux in excess of 10^{15} n/cm^{2}s in a liquid metal environment for testing and demonstrating novel fuels and materials used in Generation-IV designs, where fast-spectrum reactors are prominent. In addition, Niowave is developing a corrosion test station using liquid LBE (or lead) for improved characterization and examination of advanced nuclear reactor fuels and materials during normal reactor operation and accident scenarios.

An initial proof-of-concept fast neutron source, driven by a superconducting linac and LBE neutron converter already exists at Niowave. Additionally, Niowave is operating a subcritical low enriched uranium (LEU) target assembly, licensed by the NRC, to provide the US with critical radioisotopes and nuclear energy R&D capability such as experimental measurements for reactor physics code and nuclear data evaluation. Also, a stagnant LBE-based corrosion station was developed and operated at temperatures up to 700 °C. This paper presents Niowave's development process and current status on the LEU subcritical assembly, small-scale hybrid testbed, and linac-based photoneutron source.

FACILITY DESCRIPTION

The Niowave Electron Research and Development (NERD) facility is a 14,000 ft^2 building equipped with high-tech manufacturing, testing, and processing capabilities (Fig. 1). The facility has 3 MW of electrical power available, three below-grade trenches, and two shielded tunnels for linac operations up to 40 MeV and 100 kW.

Fig. 1. View of the NERD test facility shielded tunnels.

The facility also includes a spectroscopy laboratory where low-power physics experiments with the subcritical assembly is performed for experimental data evaluation, active interrogation demonstration, and radioisotope production. In addition, the facility includes a radiochemistry laboratory where irradiated uranium fuel undergoes chemical processes such as the LEU Modified Cintichem and UREX to extract specific radioisotopes and recycle uranium fuel, respectively.

Also, the NERD facility includes a high-temperature stagnant LBE corrosion test station to characterize and examine advanced reactor materials. Advanced steels, ceramics, refractory metals, and coated metals have been tested in LBE at temperatures up to 700 ºC.

To support the nuclear energy community's advanced reactor developer and the fuels and materials qualification program, Niowave is developing a hybrid fast/thermal-spectrum subcritical testbed that will provide a fast neutron flux in excess of 10^{15} n/cm^{2}s in significantly large volume (>100 cm^3), shown in Fig. 2. In this system, a superconducting electron linac will be used to produce an intense source of neutrons via photonuclear reactions in a converter comprised of liquid LBE. The intense neutron source will be coupled to a hybrid fast/thermal-spectrum subcritical core to create a fast neutron flux that mimics a fast reactor spectrum in an LBE medium. Optionally, the testing materials can be encapsulated in a sodium environment that is submerged in the irradiation region.

This system will reproduce the corrosive effects of liquid metal chemistry and fast neutron bombardment, making it uniquely valuable for fast reactor community. The proposed subcritical testbed facility is not a reactor, hence it is cheaper and faster to license than a reactor. Niowave has embarked on developing key components of this system and testing them independently prior integration. The main components are focused on demonstrating the uranium core, testing the accelerator-based neutron source, and examining the LBE long-term corrosion impact on structural materials.

Uranium Target Assembly

The Uranium Target Assembly (UTA-1) is a pool-type low enriched uranium subcritical assembly designed and built at Niowave and licensed by the NRC. UTA-1 is driven by an external neutron source, for example Cf-252, DD neutron generator, or superconducting electron linac equipped with a photoneutron converter. Uranium pellets are filled into aluminum cladding rods, which are loaded into a stainless steel tank filled with light water, which serves as a coolant, moderator, reflector, and shielding. UTA-1 has the versatility to vary the core configuration and moderating materials to operate as a thermal or fast core. UTA-1 has 1.8 kg of LEU and 4.6 kg of natural uranium loading. UTA-1 filled with light water has an effective multiplication factor of k_{eff}=0.43. The core layout is shown in Fig. 3 with a Cf-252 port (also used for electron beam) and DD neutron generator port.

Windowless Photoneutron Converter

The accelerator-based neutron source drives the subcritical assembly. The external neutron source is created from a superconducting electron linac that accelerates the high-power electron beam and delivers it to the liquid LBE target to convert the electron kinetic energy into x-rays that subsequently knock off neutrons via photonuclear reactions. Fig. 4 shows the photoneutron energy spectrum compared to ^{235}U thermal fission. Similar spectrum is shown where the average neutron energy is about 2 MeV. This photoneutron spectrum was computed using the general Monte Carlo based neutral particle transport code MCNP6 [2].

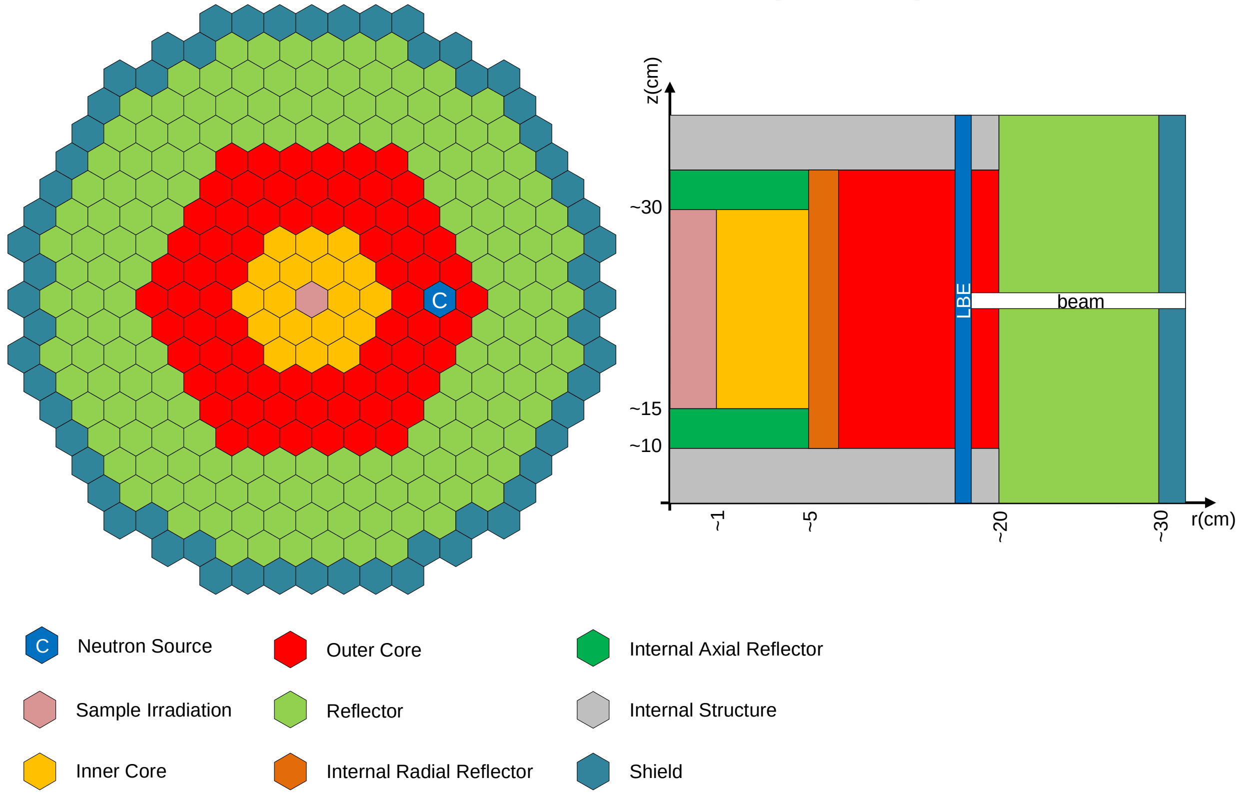

Fig. 2. Schematic of proposed hybrid subcritical testbed.

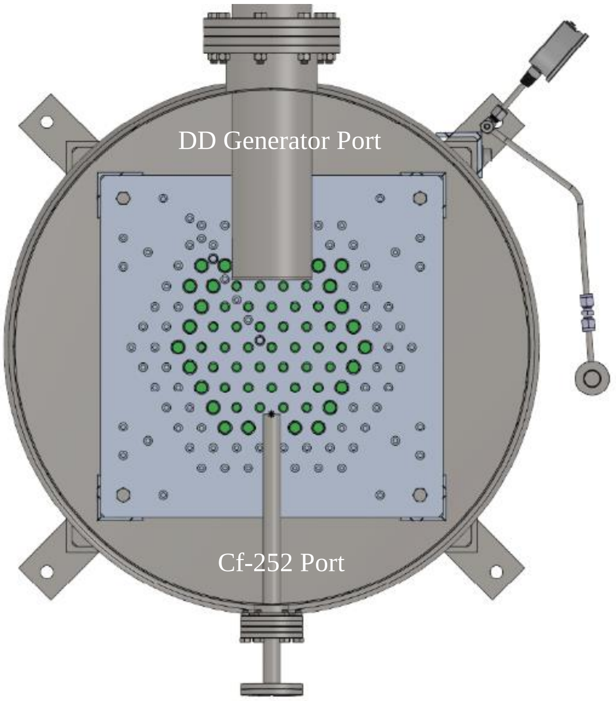

Fig. 3. CAD drawing of UTA-1 radial configuration.

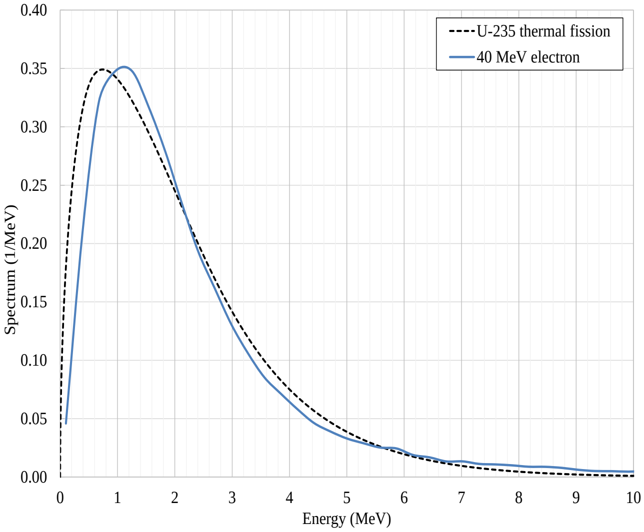

Fig. 4. Neutron energy spectrum from a 40 MeV electron.

Due to the power limitation incurred by a conventional window-based design, a windowless design approach was considered for high power application. The ultimate goal is to achieve a high intensity neutron source $>10^{15}$ n/s from a 40 MeV, >100 kW superconducting electron linac for driving a subcritical assembly and material irradiation studies. A prototype windowless converter was designed and tested with LBE, shown in Fig. 5. This design uses a “waterfall” feature where LBE is pumped from the lower tube and exits through the upper tube.

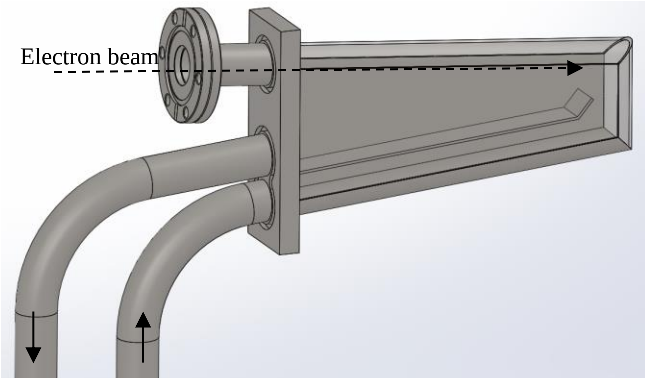

Fig. 5. CAD drawing of LBE windowless converter.

DEMONSTRATION AND TESTING

UTA-1 Operation and Testing

UTA-1 allows us to perform a zero-power physics experiment to extract data for reactor physics code and nuclear data evaluation. A picture of the test setup is shown in Fig. 6. The versatility of UTA-1 allows us to use this system as a starting point for the small-scale hybrid assembly demonstration by introducing a fast region in the system.

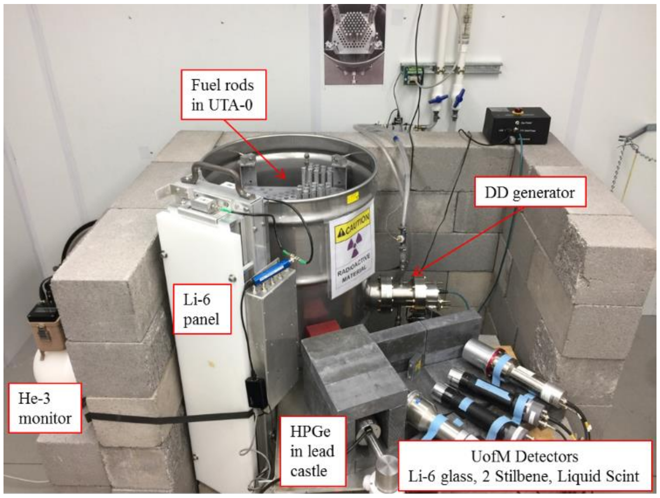

Fig. 6. DD driven UTA-0 with neutron and gamma detectors. UTA-0 has less fuel loading than UTA-1.

Neutron transient testing was performed using a DD neutron generator. This provides a technique for assembly subcriticality measurement as well as demonstrating active interrogation detection methods. The DD neutron source was operated at steady-state for ~3 minutes before shutting down the source. The beta-delayed neutron transient behavior was recorded using a sensitive lithium-6 proportional counter. Fig. 7 shows the delayed neutron emission signal recorded as a function of time. It can be seen that the delayed neutron signal was evident in the first 10 seconds (red line), indicating a fissionable material is present. Knowing the delayed neutron fraction beta and the neutron generation lifetime lambda of the system, the expected/calculated signal was shown using well-established six-group delayed neutron parametrization (blue curve).

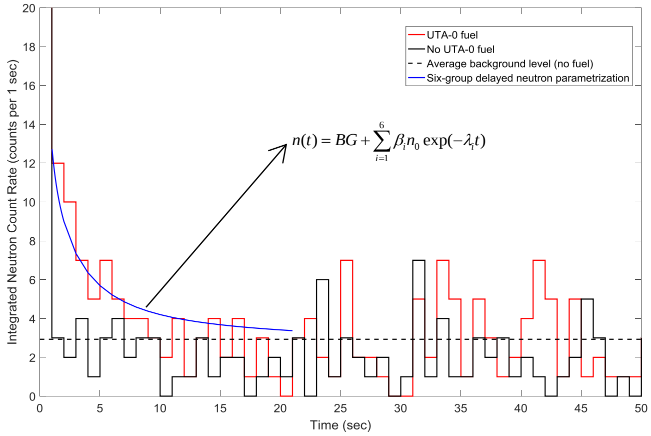

Fig. 7. Beta-delayed neutron temporal profile in lithium-6 panel detector after the DD neutron source was turned off at time=1 s.

Small-Scale Hybrid Subcritical Testbed

To evaluate the proposed hybrid fast/thermal core design, MCNP6 scoping studies was performed to develop a small-scale hybrid subcritical testbed for low-power demonstration. Unlike Robert Avery's coupled-fast-thermal power breeder [3] where the starting point is a fast reactor core and then a thermal spectrum is enforced in the outer region via a moderator, the proposed testbed starting point is a compact, high power density, thermal-spectrum core (commonly found in research reactors). Then an inner fast core region is developed and coupled to the thermal-spectrum core (outer annular region). Hence, the testbed system consists of inner fast core region surrounded by an outer annular thermal core. High-density uranium metal fuel with low-irradiation swelling stainless steel cladding, such as HT-9 alloy, cooled with liquid lead-bismuth eutectic will be used in the inner fast core region to mimic a fast reactor environment. Uranium silicide or uranium oxide fuel with aluminum cladding, cooled and moderated with light water will be used in the outer thermal core region. Uranium fuel enrichment was limited to 20 wt% of ^{235}U. Outside the outer core is a beryllium metal reflector.

Results from the scoping study shows that a peak fast neutron flux of 10^{15} n/cm^{2}s can be achieved with 7.21 MW of total fission power. The total heavy metal loading in the small-scale hybrid assembly is 6.2 kgU. The inner fast core has a 4 cm radius (H/D=1).

Detailed simulations will be performed next to design and build this small-scale hybrid assembly. This is a pivotal step and a major opportunity because it will demonstrate that limited operation and testing of a subcritical core can proceed without first obtaining a reactor license. However, planning for the NRC license application is vital to take this low-power demonstration system to higher fission power, larger fissile inventory, and higher subcriticality while maintaining sufficient margin to criticality. This effort will advance and promote the establishment of the yearning need for a versatile testing reactor.

Windowless Photoneutron Converter

A test station was setup as shown in Fig. 8, with a pump and purge set-up, which consists of a roughing pump and argon cylinder, connected to the upper chamber at the tee. A pressure difference of 0.75 atm was created using a roughing pump to raise the LBE level up to the "waterfall" edge. Then forced flow of LBE was attained using a mechanical pump, where the electric motor is controlled using a variable frequency drive. A glass viewport was used to monitor the flow. Steady LBE flow was maintained up to 2 gpm. Higher flow rate induced flow instability where the LBE overshoots from the "waterfall" edge. The results from this test will assist in designing an improved system for even higher flow rates.

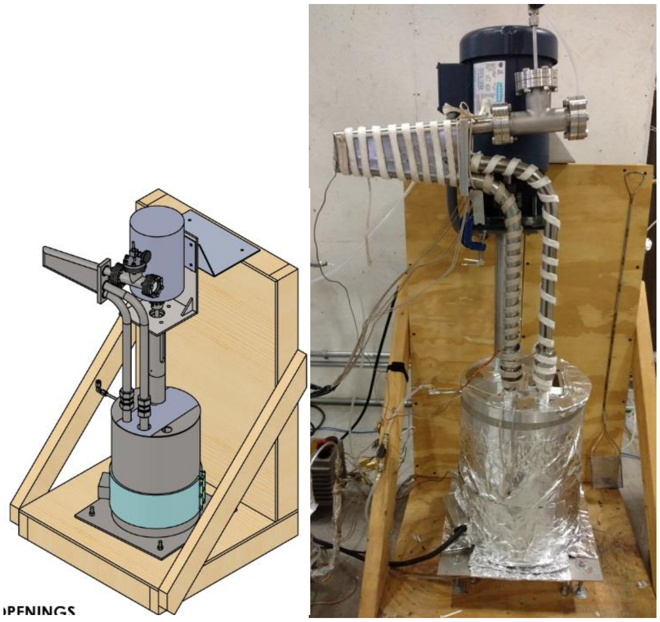

Fig. 8. Windowless photoneutron converter operation with flowing LBE.

ACKNOWLEDGEMENT

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