DESIGN OF AN IN-PILE EXPERIMENTAL LOOP FOR FAST TEST REACTOR CONDITIONS

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INTRODUCTION

Liquid metal fast reactors have gained recent attention as a potential reactor type suitable for next-generation power and research capabilities. However, the United States has not operated any liquid metal fast reactors for a number of years. Due to this, it is imperative to have a test facility to examine irradiation damage, accident tolerant fuel, and fuel performance with plutonium. These tests would require a facility to have high fast neutron flux levels to allow for multiple experiments to be run simultaneously. However, most research facilities in the United States operate on a thermal spectrum, which provides little to no information for fast reactor research. In order to adequately test fast reactor components, a full fast reactor test facility will be required; or some type of test loop for an already existing research reactor which replicates the flux in a fast reactor will be necessary. Given that the time it takes to design and build a reactor is on the order of tens of years, a test loop provides a better alternative for initial research efforts.

There is presently an effort for a new fast test reactor – termed the Versatile Test Reactor (VTR) – to be designed, constructed, and operated in the United States. The deployment of this new infrastructure would result in a significant growth in the expansion and impact of the U.S. capabilities to perform both fundamental and applied research. Through all phases of executing research and development to support the deployment of this new VTR requires the experimental assessment of systems, subsystems, components, and materials under acceptably representative conditions to those which would be experienced within the new reactor. These experimental campaigns include both ‘out-of-pile’ and ‘in-pile’ tests which explicitly or implicitly demonstrate the robustness of the concept and facilitate the design of said reactor. While new infrastructure may be built and assembled for out-of-pile experimental testing efforts, it is not economically feasible to build a new reactor specifically for performing in-pile testing of VTR development effort. Therefore, it is necessary to explore the ability to ‘boot-strap’ existing nuclear test reactor infrastructure which could perform ‘in-pile’ testing under acceptable VTR-like conditions.

BACKGROUND

The Advanced Test Reactor (ATR), located at Idaho National Laboratory (INL), is the largest thermal-power nuclear test reactor in the United States with a core-configuration suitable for handling many in-pile experiments during a single operating cycle, as seen in Figure 1 [1].

![Figure 1: Detail of Advanced Test Reactor flux trap positions [1]](image)

Furthermore, in-pile loops have been developed and utilized for long periods of time within the ATR, such as the pressurized water flow loop. A cross-sectional sketch of the pressurized water flow loop in-pile vehicle is shown in Figure 2 [2]. Unlike the proposed VTR, the ATR operates on a predominantly thermal neutron spectrum.
This fact presents a unique challenge for designing a test loop that is subjected to a more prominent fast spectrum than is available at research reactors in the United States. The implementation of a sodium-cooled loop within a water-cooled reactor is not an unexplored concept; an in-pile experimental sodium loop was utilized at the French research reactor CABRI [3]. In the United States, several design concepts have been explored for developing in-pile experimental loops that maximize the use of, or boost the production of, a fast neutron spectrum.

A previous campaign developed a Flux Enhanced Large-I (FELI) Position experiment [4], which leveraged the local placement of partial ATR-like fuel elements around the outer circumference of the location. An experimental vehicle that was placed within its central region was exposed to actively irradiated fuel elements directly adjacent to it.

Similar to the FELI project, this project explores the feasibility of the use of the Large-I position for irradiation experiments. Located in the outermost region of the reactor vessel (beyond the control drums), this section does not presently have as much use as other irradiation positions located closer to the core. Additionally, the large relative diameter at this position enables the flexible design envelope for an in-pile loop to be implemented.

Regardless of the potential benefits that are characteristic of the Large-I position, the ATR’s core spectrum is thermally dominant. This irradiation position is also located far from the core, resulting in additional thermalization of the neutron spectrum. As a result, it is necessary to develop a design feature within the Large-I position that hardens the spectrum to a level suitable for fast spectrum testing capabilities.

An experimental campaign was conducted with the design of the Gas Test Loop (GTL) [5] (later dubbed the Boosted Fast Flux Loop [6]) located within the ATR core region; a cross-sectional sketch of this loop design is shown in Figure 3. A set of concentric “rings” of fuel are arranged using curved plates of previously irradiated ATR fuel, and are distributed on the outermost regions of the core position. The neutron flux interacts with the fuel plates, creating an additional source of neutrons - including fast spectrum neutrons - that then interact with the materials placed within the circular region inside of the fuel rings. In addition, a thermal neutron filter (hafnium) is placed inside of the fuel plate structure (but outside of the test section) to further improve the fast-to-thermal neutron ratio.

Figure 3: Cross section of the in-core position within the gas test loop in ATR [5]

DESCRIPTION OF THE PROJECT

Researchers at Oregon State University (OSU), along with collaborators from INL, began a project to develop the experimental design for this fast spectrum test loop concept. This project is still underway; the work performed to date and preliminary conclusions are presented herein.

The desire of this work is to provide a conceptual design of an in-pile loop experiment to be located in the Large-I position at the ATR. The unique design leverages previous experimental loop designs such as the PWR flow loop within the FELI position [4] and the GTL [5, 6]. The purpose of this experiment is to produce acceptably representative conditions that would be experienced within a fast test reactor, such as the VTR. With this goal in mind, a unique coolant fluid – sodium – will be required within this loop concept.

This project focuses on three aspects relative to the experimental concept of the fast spectrum test loop: mechanical design, neutronic assessment, and...
thermal hydraulic assessment. The goal is the development of a concept that includes relative predicted comparisons between the operating conditions in the VTR and those within the Large-I position of the ATR. This comparison is vital in demonstrating the basis for the relative configuration of hardware for an in-pile test loop, and the selection of materials within the core-region.

MECHANICAL DESIGN

The in-pile test loop is currently being built in multiple formats for initial inquiry. For mechanical, neutronic and thermal hydraulic considerations, detailed designs of each component were built in SolidWorks® (Figure 5). The end goal is to provide a common model that will propagate through the codes to be used for the neutronic and thermal hydraulic assessment tasks.

Figure 5. SolidWorks models of the booster flux trap and booster fuel plate assembly

The task of computational assessment of the in-pile vehicle mechanical design and comparison with the VTR reactor physics assessment is currently underway. This process will provide feedback from the reactor physics assessment on the in-pile vehicle mechanical design, allowing an iterative design process to refine the parameters for the intended flux spectrum and choices of materials for design.

NEUTRONIC ASSESSMENT

The SolidWorks model developed in the mechanical design portion of the project is input into the radiation transport code Attila® and used as a model for deterministic neutron transport calculations. Attila also has the ability to create MCNP [7] input files with appropriate weight windows for variance reduction; MCNP tallies flux and energy spectra.

An initial investigation into neutronic properties was required for additional input into refining the initial SolidWorks models. This assessment provided a basis for the desired neutron spectrum that an in-pile experimental loop would require, and establish a baseline comparison against the in-pile vehicle neutron spectrum. A simplified in-pile test loop was created in MCNP to produce these initial results (Figure 6).

Figure 6. Cross-sectional view of the initial sodium-cooled fast spectrum test loop model (MCNP)

For the initial MCNP model, two neutron sources were defined. The first source was the prominently thermal flux from ATR that penetrates the experimental port. To model the ATR flux, a source was placed on the outer surface of the aluminum baffle (Figure 6). The incident flux is split into fast (1 MeV) and thermal (0.5 eV) categories. The flux level in the Large-I position of ATR is known to have a roughly 13:1 thermal-to-fast ratio, which is represented in the source [2]. Additional information is being gathered to create a more robust source that accurately represents the ATR flux with respect to energy.

The second source is the neutron generation rate from the uranium silicide fuel plates. This rate is dependent on the known flux from ATR at the Large-I position. The flux from ATR was used to gain an initial fission rate from the fuel plates, which was then transformed into a neutron source. The source was created to produce an isotropic neutron distribution using a Watt fission spectrum. With both neutron sources, a more accurate representation of the flux
levels in the experimental section can be predicted, as seen in Figure 7.

For the sake of comparison to the spectrum of a typical sodium cooled fast reactor (SFR), a single SFR assembly was created in MCNP. The assembly was fueled with 217 uranium-zirconium fuel rods with an enrichment of 27-wt% U-235. The remainder of the assembly consisted of a lower reflector, plenum and upper reflector. Reflecting boundaries were placed on all radial sides of the assembly to simulate adjacent fuel assemblies.

![Figure 7. Neutron spectrum profile for fast neutrons in a SFR (blue), from a source generated using only ATR flux (orange), and from a source generated using both ATR flux and fuel plates (green)](image)

Without the adding the source of fast neutrons from the uranium plates, there is nearly over a 50% reduction in the fast flux. It is important to note that the in-pile test loop provides nearly an identical shape for the fast and epithermal flux. However, some of these features may be normalized when a more resolved ATR flux profile is utilized. This may also help remove the large spike in thermal flux that is due to the thermal source only having a singular energy value.

**THERMAL HYDRAULIC ASSESSMENT**

The industry-standard thermal-hydraulic code RELAP5-3D [8] will be used to assess the thermal and hydraulic balances within the in-pile test loop. Given the information developed from the reactor physics and thermal hydraulic assessments of the vehicle, along with the relative arrangement of the ATR existing infrastructure, develop a relative mechanical layout of supporting balance-of-loop hardware necessary to enable an integrated fast test loop concept within the FELI position in ATR. This portion of the project has just begun as of this writing, and will implement the design model described above.

**CONCLUSIONS**

The goal of this project is to provide a detailed conceptual loop for the ATR within the Large-I position which has been designed based on benchmarking against predicted in-reactor conditions that the VTR will produce, including a mechanical detailed design of the in-pile vehicle as well as material delineation of primary components. It will include a general physical arrangement of the balance of loop hardware necessary to compliment the in-pile vehicle to provide a sodium-cooled environment within the ATR passing through the Large-I position.

**ACKNOWLEDGMENTS**

This project is funded by Idaho National Laboratory under Contract Number 145660, Release 22.

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