INL/CON-15-35597
PREPRINT

Preliminary Physics Analysis of the Accident Tolerant Fuels Loop Experiment

2015 ANS Winter Meeting and Nuclear Technology Expo

Wilson M. Cowherd

October 2015

Preliminary Physics Analysis of the Accident Tolerant Fuels Loop Experiment

Wilson M. Cowherd

Idaho National Laboratory, 1795 N. Yellowstone Hwy. P.O. Box 1625, Idaho Falls, ID 83415, wilson.cowherd@inl.gov

INTRODUCTION

After the Fukushima Daiichi power plant disaster in 2011, the United States Congress ordered the Department of Energy (DOE) to investigate new fuel and cladding types that would be more tolerant in an accident similar to the accident at Fukushima. The resulting program was dubbed the Accident Tolerant Fuels (ATF) program. The ATF program is a subset of the Fuel Cycle Research and Development (FCRD) Advanced Fuels campaign. The ATF program partnered private industry, universities, and national laboratories in order to develop these new fuels and claddings. The end goal of the ATF program is a lead test assembly or a lead test rod inserted into a commercial reactor by 2022.

The first phase of the ATF program, called ATF-1, was the insertion of drop-in capsules with new fuel and clad concepts into the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). The purpose of these drop-in experiments is to test the feasibility of these concepts and to help down-select concepts for insertion into later experiments and, ultimately, choose a concept for insertion into a commercial reactor. So far, Oak Ridge National Laboratory (ORNL), Westinghouse Electric Company, Areva, and General Electric (GE) have inserted capsules for ATF-1 [1], although there are more concepts that are planned for insertion [2].

The second phase of the ATF program (ATF-2) is the selection and insertion of possible fuel and cladding concepts into the center loop-2A. This phase is the focus of this paper. The third phase of the ATF program (ATF-3) is insertion of concepts from ATF-2 into the Transient Reactor Test Facility (TREAT) at INL to test accident characteristics of the concepts after some irradiation time in a transient setting. After each step, post-irradiation examination (PIE) is done in order to learn more about the fuel and/or cladding and to help the down-selection process for future experiments. The goal is to complete these phases and perform PIE in order to meet the 2022 goal of insertion into a commercial reactor.

The ATF-2 experiment is to test these cladding and fuel concepts in prototypical pressurized water reactor (PWR) conditions. One of the advantages of irradiating experiments at the ATR is the ability to set irradiation conditions separate from the ATR primary coolant by way of in-pile tubes (IPTs) or loops. Pressure, temperature, and water chemistry can be manipulated in the IPTs and loops to the conditions desired by the customer. For the ATF program, prototypic PWR conditions are desired, so those will be present in the loop. In support of insertion, several safety analyses must be done, including thermal, structural, and physics. This paper will focus on the safety analysis of the physics aspect of the ATF-2 loop experiment and how this affects the design of the experiment, the selection of concepts for the test train, and the different analyses that must be done for experiment insertion into the loop-2A.

DESCRIPTION OF THE ACTUAL WORK

The ATF-2 experiment is split into two tests: the sensor qualification test and the fueled test. ATF-2 will have sensors in order to measure characteristics of the fuel and cladding, such as cladding elongation, temperature of the fuel and clad, and fuel swelling. Some of these measurements will be made in real time while others will be available after PIE. These two tests will go in separately; first the sensor qualification in fiscal year 2016 and the fueled test in fiscal year 2017. The sensor qualification test has two objectives: to test the loop and test train with the water chemistry and to test the sensors under irradiation conditions. This test will have no fuel, but will have a resemblance to the fueled test train. The fueled test will have both fuel and sensors in the test train.

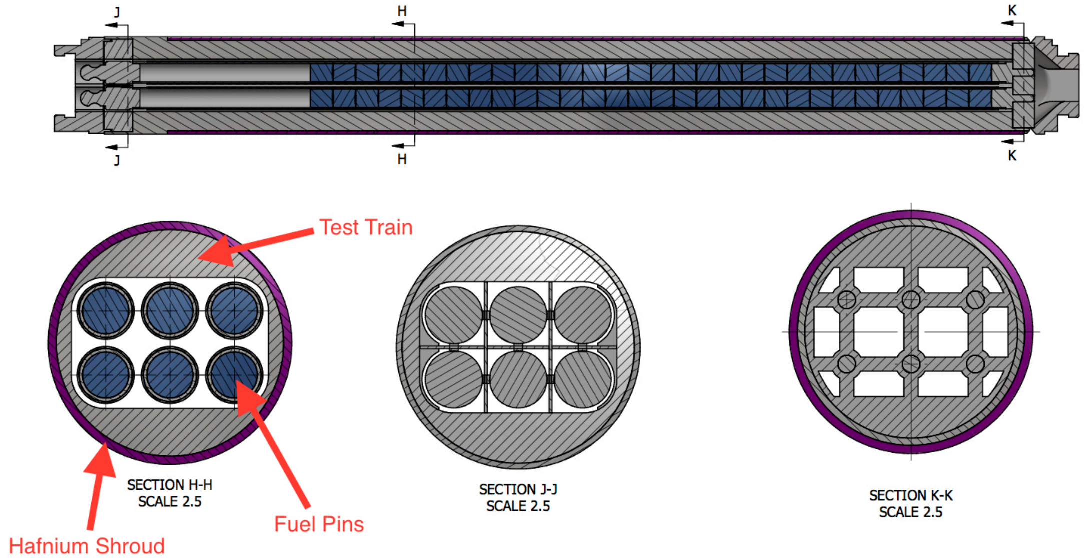

Figure 1: Test Train Design

The design of both the sensor qualification and the fueled test trains have undergone several revisions, and are still not yet fully decided upon. As of now, the sensor qualification test train is based on the fueled test train design. The fueled test train cross-sectional view and cutaway of one rack of fuel is shown in Figure 1. The fueled test train has three racks to hold pins. Each rack has a 2x3 pitch. The top two racks hold 40.64 cm (16 inch) pins with 30.48 cm of fuel (12 inch). The bottom rack holds 15.24 cm (6 inch) pins with 10.16 cm (4 inch) of fuel. Between the racks are dovetails for flow, and a dovetail above and below the racks for flow and instrumentation out of the core. The test train is surrounded by a hafnium shroud, which holds down the fission heating in the test train.

In order for any experiment to be inserted into the ATR, certain safety analyses must be performed, including a physics analysis. Monte Carlo N-Particle Transport Code (MCNP) [3] and ORIGEN2.2 depletion code [4] were used in the support of the safety analysis for ATF-2. There are standard physics analyses that are done for all experiments inserted into the ATR: fission heating for fueled specimens and gamma heating for non-fueled materials, the effect of the experiment on the axial fission profile on the ATR driver core, the moderator temperature coefficient, the experiment reactivity worth compared to a water-filled test position, and the backup experiment reactivity worth compared to the experiment. However, for experiments being inserted into a loop, other safety criteria must be met. This paper will focus on the unique safety analysis that must be done for the loop rather than the normal analysis that are done for all experiments.

Chapter 10 of the ATR Safety Analysis Report (SAR) gives guidance for the safety parameters for experiments in the 2A loop [5].

Table I: Loop 2A Physics Safety Parameters

Loop 2A Physics Safety Parameters	
Maximum Loop Void Worth	0.80$
Maximum Reactivity Insertion due to Hardware Failure	0.10$
Maximum Test Fission Power	200 kW

Therefore, in addition to the standard experiment physics analyses, the void worth of the experiment, the reactivity insertion due to hardware failure, and the test fission power must be calculated. The void worth is found by voiding out the water from inside the loop and the water between the loop and the envelope tube and comparing the k_{eff} to the k_{eff} of the experiment by equation 1:

$$\Delta\rho(\$) = \frac{k_2 - k_1}{k_1 k_2 \beta} \tag{1}$$

Where β is the delayed neutron fraction of 0.0072. There are two scenarios for the hardware failure: the hanger rod that holds the test train fails and the test train shears in half and falls to the test stop. The test fission power is simply the total fission heating in the fuel.

Because ATF-1 has just begun and concepts have not been available for PIE, no down-selection has been made for specimen insertion into ATF-2.

However, safety analysis still must be done in order to show that the test can feasibly be done and to give the industry partners some idea of what can and cannot go into the test train. Therefore, a conservative loading that in order to give the industry partners some idea as to the limits of the fuel type that could be inserted, yet the loading had to be realistic enough that the analysis done had some real merit. 4.95% UO_2 fuel and zirconium cladding was assumed to be the loading in 16 of the 18 possible positions, with steel dummy pins in the other 2 positions.

RESULTS

The unique analyses that are done for experiments going into the loop-2A IPT are the void worth calculations, the limit on test fission power, and hardware failure of the experiment. These analyses were done for both the sensor qualification test and the fueled test and are presented here. In addition to the test train loading, the water in the loop is pressurized to 15.17 megapascals (2200 psi), heated to 300° C, and 1500 parts per million boron via boric acid (H_3BO_3).

For the sensor qualification test, only the void worth and the test train failure reactivity insertion analyses were done because of the lack of fuel in the test train. As a baseline case, the dovetail below the rack of sensors was assume to be a solid cylinder with a diameter that as wide as the inner diameter of the loop. This caused the smallest reactivity insertion because this design pushed the most water out of the loop. This case resulted in a reactivity insertion of 0.33$.

Because there must be flow through the dovetail and loop, this baseline case cannot be the actual design. The dovetail design has a 0.0645 cm gap between the diameter of the dovetail and the inner diameter of the flow tube and a 1.588 cm hole through the center for flow. The void worth for this design was 0.42$.

The hardware failure of the sensor qualification test resulted in a reactivity drop. For the hanger rod failure, the reactivity drop was 0.01$ and for the shearing of the test train, the reactivity drop was 0.04$.

The fueled test had the added complexity of the fission power limit of 200 kW. For the 200 kW limit, the test must be below that limit at the maximum lobe power and it must include instrumentation uncertainty. Equation 2 is the equation used to determine total fission power:

$$FP = \frac{kW}{ft} \times ft(Fuel) \times IU \times \frac{MW\,(\max)}{MW\,(nominal)} \qquad (2)$$

Where IU is the instrumentation uncertainty (conservatively 10%). The feedback we had gotten from industry said they would like to their fuel to have a heating rate of 10-15 kW/ft nominally. Using Equation 2, the test train can run at 12 kW/ft and pass safety analysis. With 16 pins with fuel and 2 dummy pins, the MCNP-calculated total fission power equals 123 kW nominally and 170 kW at maximum lobe power and instrumentation uncertainty. With 3.66 meters (12 feet) of fuel, nominal the heat rate is 10.3 kW/ft and, at maximum, 14.2 kW/ft. So, this design meets industry partner objectives and meets the safety requirement for fission power.

Because the fueled test has fuel in the test train, it has a lower void reactivity worth than the sensor qualification. Because of the decrease in the moderation of the neutrons before they reach the fuel in the test, the uranium-235 is not able to fission as much as the water-moderated center loop. There is a 22% decrease in the thermal neutron flux and a 17% decrease in the fission heating between the water-filled loop and the voided loop. The void reactivity insertion for the fueled case is 0.34$.

For the hardware failure of the fueled test train, only the sheared test train changed the k_{eff}. The sheared test train caused a reactivity drop of 0.03$. Both are obviously less than 0.10$, so there is reasonable confidence that a test train failure will not result in a reactivity insertion, much less a reactivity insertion of 0.10$.

One of the tensions in for the fueled test is the tension between the fission power limit and the void worth limit. This can be seen by replacing the fuel in the fueled test with steel dummy pellets in place of the fuel, which results in a 0.076$ decrease in reactivity worth to 0.42$. So, the more fuel that can go into the test decreases the void worth. However, that must be balanced with the 200 kW fission power limit. This tension is also present in the sensor qualification test because of its lack of fuel. Therefore, the sensor qualification design must push out as much water of the loop as possible in order to minimize the water that is voided when the void worth is analyzed.

While a 0.42$ and 0.34$ void worth's are significantly less than the 0.80$ void worth limit, there is a difference between the void worth that the physics analyst calculates and ATR Reactor Engineering calculates the void limit. ATR Reactor Engineering calculates an absolute worst-case void worth using a different code than MCNP, and in some cases the void worth can be significantly higher. For example, in the EPRI-3 (a test in the same position as the ATF-2 experiment will be in), the void worth calculated by the physics analyst was

0.57$ [6]. However, the void worth as calculated by ATR Reactor Engineering was 0.78$. Therefore, the lower the void worth, the more confident the industry partners can be that the experiment will be able to pass the worth limit.

CONCLUSION

The ATF-2 sensor qualification test and the fueled test are unique tests compared to many of the tests analyzed by the physics analysts at INL. There are very few tests that go into a loop and even fewer have fuel in the test train. Also complicating the test is the lack of down-selection at the point in time when we must do safety analysis and provide feedback to the industry, university, and national laboratory partners in order to give confidence that this test can be done and meet their objectives. Undoubtedly a separate safety analysis will have to be done when the test matrix is finalized, but this work builds a foundation that the test can be based on.

The initial void worth, hardware failure, and test fission power calculations were presented in the previous section. For the sensor qualification test, the void worth was 0.42$ and the hardware failure for a hanger rod failure and test train shear was -0.01 $ and -0.04$, respectively. There was no test fission power because there is no fuel in the sensor qualification test.

For the fueled test, the void worth was 0.34$, the hanger rod failure was 0$, the shearing of the test train was -0.03$, the nominal test train power was 123 kW nominally and the maximum test train power was 170 kW. Also discussed was the tension between the fission power limit and the void worth limit and the necessity of having as low a void worth as possible.

Future work must include the final test matrix safety analysis for physics, thermal, and structural design. Final enrichments and fuel specimens must also be defined, and special consideration must be made if the enrichment goes about 4.95% or if the fuel differs from UO_2. This test not only presents an interesting problem that is unique in analysis, but presents the opportunity for meaningful and impactful work that could make a real difference in fuels that commercial power plants use in operation.

REFERENCES

1. C. R. Glass, "Beginning of Life Loading and Best Estimate Heat Generation Rates for the Accident Tolerant Fuels (ATF) Experiment," ECAR-2538 Rev. 0, Idaho National Laboratory, Aug. 2014.
2. S. L. Hayes and K. E. Barrett, "Irradiation Testing of Accident Tolerant Fuels in the ATR," PLN-4444 Rev. 3, Idaho National Laboratory, June 2015.
3. X-5 Monte Carlo Team, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5," Vol 1: Overview and Theory, LA-UR-03-1987, Los Alamos National Laboratory, Apr. 2003.
4. A. G. Croff, "A User's Manual for the ORIGEN2 Computer Code," ORNL/TM-7175, Oak Ridge National Laboratory, July 1980.
5. ATR Reactor Engineering, "Safety Analysis Report Chapter 10: Irradiation and Experiment Facilities," SAR-153-10 Rev. 22, Idaho National Laboratory, June 2015.
6. J. W. Nielsen, "ATR Physics Analysis of the EPRI-1, -2, and -3 Experiment in Loop 2A," ECAR-1844 Rev. 3, Idaho National Laboratory, July 2014.