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Feasibility of Power Ramp Testing in the Advanced Test Reactor (2023 ANS Winter Meeting)

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Feasibility of Power Ramp Testing in the Advanced Test Reactor

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INTRODUCTION

For decades, the Halden Boiling Water Reactor (HBWR) in Norway was an international resource for assessing nuclear fuels and materials behavior, and its unexpected shutdown in 2018 represented a significant loss in experimental capability for prototypical irradiation testing. In the aftermath of the closure, a study was performed to assess capability gaps related to the Accident Tolerant Fuels (ATF) program [1]. It was concluded that the primary capability gaps left by the closure of the HBWR were the loss of prototypic in-pile light water reactor (LWR) loops that provide operational transient testing and in-pile loss-of-coolant accident (LOCA) testing capabilities. The study also concluded that the Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT) likely have the necessary key capabilities to absorb the breadth of the HBWR mission gaps related to the ATF program, but additional investments in experimental infrastructure were needed. One such investment is the design and installation of additional pressurized water loops in the medium-I positions of the ATR, hereafter referred to as I-Loops, to support power ramp testing and testing in boiling water reactor (BWR) conditions. This paper gives an overview of the planned ATR I-Loops and assesses the feasibility of performing power ramp testing inside such a loop.

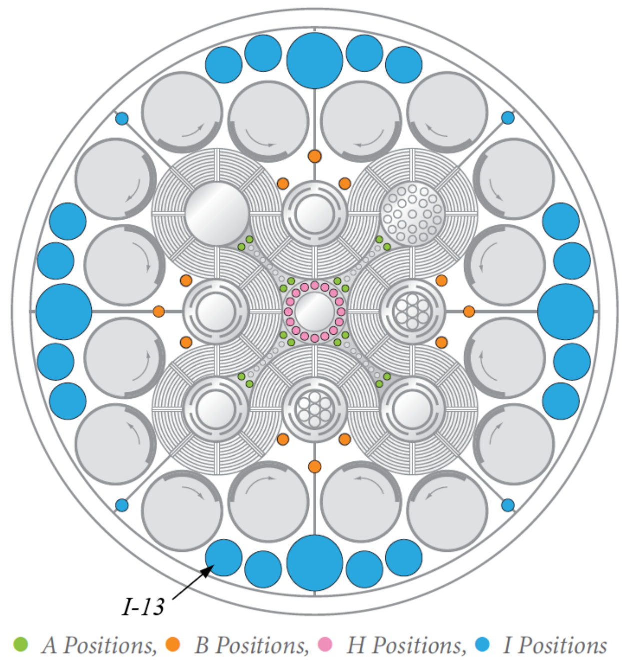

Fig. 1. ATR experiment position map [3].

DISCUSSION

ATR I-Loop Description and Status

According to current plans, the ATR I-Loops will be installed in at least one of the medium-I positions in the ATR (see Figure 1) to support LWR testing. The medium-I positions are ideal for LWR loop systems because they (1) have relatively high availability for experiments relative to other positions in the ATR, (2) have a weak reactivity interaction with the main core, thus enabling coolant voiding and actively controlled specimen flux manipulations, and (3) have a neutron flux that is similar to the HBWR and is well thermalized for fuel testing. If additional neutron flux is needed, booster elements in the form of standard ATR fuel elements can optionally be placed in large-I positions to boost the thermal neutron flux in the I-Loops by approximately 10% [2].

A new reactor head closure plate was installed during the latest ATR core internals changeout (CIC) that includes additional penetrations that support the installation of the I-Loops. The design of the actual I-Loops is ongoing, but they are expected to be operational by 2026.

Power Ramp Testing

The ATR has a rich history of transient testing in its pressurized water loops using the powered axial locator mechanism (PALM) device which mechanically drives fuel specimens in and out of the ATR core during high-power operation. During a PALM cycle, the southern lobes of the ATR are operated at a much higher power than in a standard irradiation cycle (i.e., 45–50 MW lobe power vs. 20–25 MW lobe power) to maximize the power transient seen by the experiment.

At the HBWR, power ramp testing was performed via pressure control of He-3 gas (a strong neutron absorber) that surrounded the test specimen. The use of a PALM device and pressure control of He-3 gas are both valid methods for creating rapidly changing flux environments in a test specimen, but the location of the I-Loops precludes the use of PALM devices due to interferences with structural components. Thus, power ramp testing in the ATR I-Loops will be accomplished via pressure control of He-3 gas, similar to the HBWR.

A cross-section of a conceptual I-Loop power ramp experiment holder is shown in Figure 2. In this concept, a fuel pin clad in zircaloy is placed inside an experiment holder that contains an annulus of He-3 gas. The holder and I-Loop tubes are made of zircaloy-2.5Nb, which has a higher yield strength than standard zircaloy. Structural supports in the He-3 regions are necessary to prevent buckling. The He-3 pressure is controlled via an external system that can add/remove helium from the annulus as necessary.

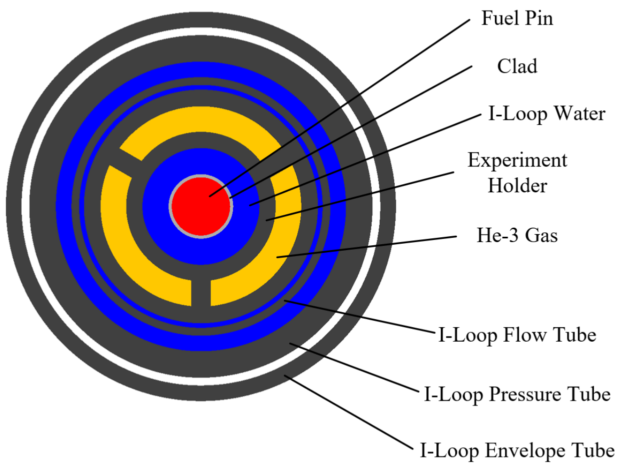

Fig. 2. Radial cross section of conceptual ATR I-Loop ramp test holder.

Model Description

An MC21 model of the conceptual I-Loop ramp test holder is constructed to assess the feasibility of using only He-3 gas to control the heating rate in an experiment fuel pin. The modeled fuel pin is 10 inches long and made of solid 4% enriched uranium dioxide (UO2). The fuel pin is clad in a 0.020-inch thick zircaloy-4 tube that is 13 inches long. He-4 gas is modeled in the plenum above the fuel pin. The ramp test holder is also modeled as 13 inches long. Above and below the holder are homogenized stainless steel and water (75% SS316, 25% water) to approximate the test train structure. An axial cross section of the model can be seen in Figure 3.

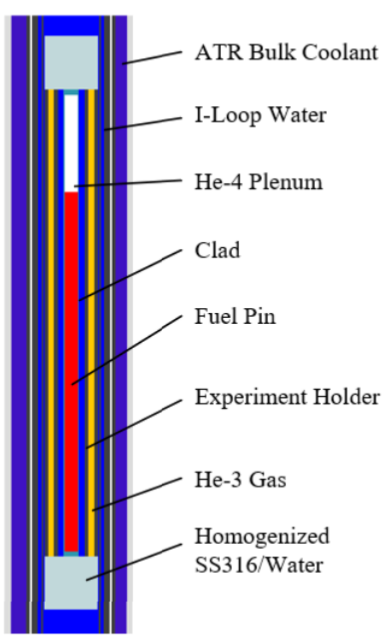

Fig. 3. Axial cross section of conceptual ATR I-Loop ramp test holder.

The ramp test holder is placed in the I-Loop tube, which is modeled in the I-13 position of the ATR (noted in Figure 1). To maximize the flux in the experiment, the fuel pin is centered on the ATR core midplane (24 inches above the bottom of the ATR fuel). The I-Loop tube water is modeled at 600°F and 2,250 psig, which is the expected I-Loop nominal operating conditions.

The I-Loop tube model is placed in a larger ATR core model with the other experiment positions having contents reflective of ATR Cycle 167A, which was the most recent PALM cycle at the ATR. ATR outer shim control cylinder (OSCC) and neck shim positions were fixed at their average positions for Cycle 167A. Although not included in this paper, sensitivity studies showed that OSCC positions in the range used in a typical PALM cycle did not drastically affect the results. Thus, the average positions are judged to be adequate for this study.

RESULTS AND ANALYSIS

In order to determine the feasibility of power ramp testing in the I-Loops, the He-3 pressure in the experiment holder is varied from 0 atm (i.e., no He-3) to 160 atm (2,351 psia) and the linear heat generation rate (W/cm) (LHGR) in the fuel pin is calculated for each case. Figure 4 shows the calculated LHGR scaled to a constant 55 MW southwest (SW) lobe power. The SW lobe is used to scale the results because it is the nearest lobe to the I-13 position and therefore has the largest impact on the heating rate.

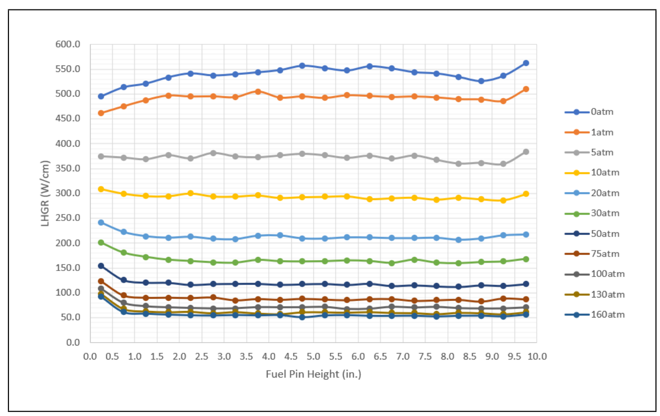

Fig. 4. Ramp test fuel pin LHGR for various He-3 pressures (55 MW SW lobe power).

As can be seen in Figure 4, there is a large difference between the maximum (562.1 W/cm) and minimum (51.1 W/cm) calculated LHGR across the range of helium pressures examined. This indicates that using He-3 as a means of controlling experiment power in the I-Loops is potentially valid. The other thing to note from this data is that the LHGR is relatively constant across the fuel pin. This is as expected with the experiment centered on the ATR core midplane, but if axial gradients in the LHGR profile are desired in an actual experiment, the capsule can be translated up or down until the desired profile is reached. However, moving the capsule away from core midplane will reduce the maximum achievable LHGR.

The preceding discussion demonstrates that varying the He-3 pressure is an effective way of controlling the LHGR in an experiment, but it does not yet fully indicate the feasibility of power ramp testing in the I-Loops. To do that, it must be shown that the He-3 addition/removal rate necessary to achieve the desired ramp rate is reasonable. Figure 5 shows the average LHGR across the fuel pin, per MW of SW lobe power. The data is fit to an exponential curve with an R-value of 0.99, which is shown in Equation 1. The fit is also shown in Figure 5.

$$LHGR = 9.653 P_{SW} * e^{-0.192\sqrt{p}} \quad (1)$$

where P_{SW} is the SW lobe power in MW, and p is the He-3 pressure in atm. Using this equation, a parametric study of LHGR for various He-3 pressures and SW lobe powers can be performed.

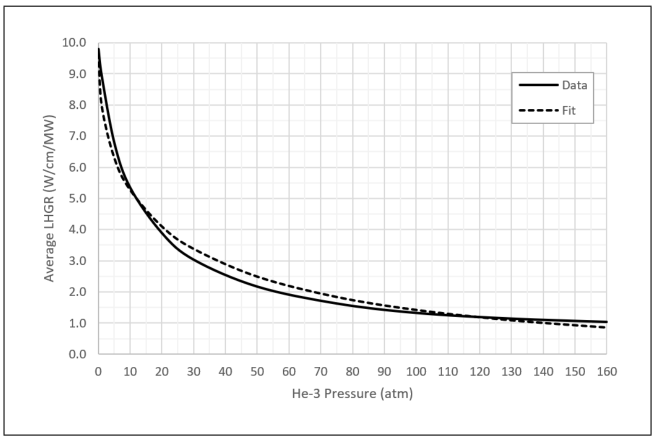

Fig. 5. Average fuel pin LHGR per MW of SW lobe power as a function of He-3 pressure.

The result is shown Table I. For each selected SW lobe power, the He-3 pressure bounds are set at 0 and 100 atm since there are diminishing returns to the minimum LHGR at pressures greater than 100 atm (see Figure 5).

Assuming a peak experiment LHGR of >450 W/cm and a target ramp rate of 100 W/cm-min, which were typical power ramp conditions for the HBWR [4], several conclusions can be made. First is that in order to reach the desired peak LHGRs for power ramp testing, SW lobe powers greater than 40 MW will likely be necessary. This is not a problem for PALM cycles in the ATR, but standard ATR cycles would not be suitable for power ramp testing because SW lobe powers are typically limited to around 25 MW. It is noted that increasing the enrichment of the fuel could increase the peak LHGR in the fuel pin, but that evaluation is beyond the scope of this paper. The I-Loop booster elements described previously could also be a valid option for increasing the maximum achievable heating rate.

The other conclusion that can be drawn is that even with acceptably high SW lobe powers, achieving a constant power ramp rate of 100 W/cm-min is going to be challenging considering the exponential relationship of LHGR to He-3 pressure. For example, going from 100 W/cm to 200 W/cm at a 55 MW SW lobe power would require a decrease in helium pressure from 75.6 atm (1,111 psia) to 25.9 atm (381 psia) over the course of a minute, or 49.7 atm/min (730 psia/min). This a fairly rapid pressure gradient for a relatively modest change in LHGR. Conversely, going from 400 W/cm to 500 W/cm at a 55 MW SW lobe power would only require a He-3 pressure transient of 2.1 atm/min (31 psia/min), which is much more reasonable. In a real power ramp test, the desired LHGR range from minimum power to maximum power would likely span hundreds of W/cm, which means that the He-3 control system will have to handle a large range of He-3 addition/removal rates in order to maintain a constant power ramp rate.

In addition to the non-linear behavior of the heating rate with respect to He-3 pressure, experiment designers will also need to contend with the fact that the ATR power will not be entirely constant during a cycle. In a typical PALM cycle, southern lobe powers are held at low power for several days to allow for experiments to reach thermal equilibrium before increasing to the maximum lobe power and beginning the transient testing with the PALM device. This transition from low lobe power to high lobe power is usually performed over the course of several hours so the I-Loop He-3 control system will have to continually adjust for changing ATR lobe power if a constant experiment power is to be maintained.

TABLE I. He-3 Pressures at Various SW Lobe Powers and LHGRs

SW Lobe Power (MW)	LHGR (W/cm)	He-3 Pressure (atm)
70	99	100
70	100	99.0
70	200	40.2
70	300	17.9
70	400	7.5
70	500	2.5
70	676	0.0
55	78	100
55	100	75.6
55	200	25.9
55	300	8.8
55	400	2.2
55	500	0.1
55	531	0.0
40	57	100
40	100	49.5
40	200	11.7
40	300	1.7
40	386	0.0
25	35	100
25	100	21.1
25	200	1.0
25	241	0.0

CONCLUSIONS

In summary, additional pressurized water loops are currently being designed for the ATR that are aimed at replacing some of the irradiation capability lost due to the closure of the HBWR. These new loops, known as I-Loops, will be placed in the medium-I positions of the ATR to support power ramp testing and testing in BWR conditions. This paper assessed the feasibility of power ramp testing in the I-Loops using He-3 to control the power ramp rate. A model of a hypothetical power ramp experiment was constructed, and heating rates were calculated for a fuel pin at various He-3 pressures. It was concluded that using He-3 to control experiment heating rates is a valid strategy if ATR lobe powers are sufficiently high, but that controlling the He-3 addition/removal rate to achieve a constant power ramp rate is going to be challenging. Future studies will be needed to further address these challenges.

ACKNOWLEDGMENTS

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Calculations in this report are made using the Common Monte Carlo Design Tool (CMCDT) consisting of the Monte Carlo code MC21 and the Physics Unified Modeling and Analysis (PUMA) system. The CMCDT suite is developed and maintained by the Naval Nuclear Laboratory.

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