INL/RPT-23-74493

ACCIDENT TOLERANT FUEL TEST 2C (ATF-2C) IRRADIATION TEST REPORT

August 2023

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Changing the World's Energy Future

Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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SUMMARY

A new fully prototypic testing platform for testing new accident tolerant fuel (ATF) designs for light water reactors has been established in the center flux trap of Idaho National Laboratory's advanced test reactor (ATR). The irradiation experiment named ATF-2C has completed its first cycle of prototypic steady state irradiation. Irradiation conditions have been maintained via the loop 2a pressurized water coolant loop and have been monitored through in-situ instrumentation during each cycle. Power and fast neutron flux histories of each of the 24 test pins has been calculated.

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ACCIDENT TOLERANT FUEL TEST 2C (ATF-2C) IRRADIATION TEST REPORT

1. INTRODUCTION / BACKGROUND

Following the core damage events that occurred at the Fukushima Daiichi nuclear power plants in Japan following the 2011 Tohoku earthquake and tsunami, the U.S. Department of Energy (DOE) began the development of light water reactor fuel materials that can better withstand severe accident conditions. To support the development of ATF, the Idaho National Laboratory (INL) developed a fully prototypic irradiation testing environment in the center flux trap of the advanced test reactor. This fully prototypic irradiation test would be required to test integral fuel and cladding pins with radial dimensions fully representative of commercial designs, albeit at reduced lengths. It also required the use of fuel with densities and enrichments typical of commercial products. The operating conditions of the test would involve test pin linear heat rates that are typical of operating fuel rods (~250 w/cm) up to the limiting condition of operation (~420 w/cm). Target burnups for the test pins would vary with peak burnups of 62 MWd/kgU required for some test pins. The prototypic testing environment needed to be pressured water coolant at ~15 MPa between 250 C and 350C with a sufficient flow rate to keep the test pins in a subcooled boiling condition during irradiation.

2. EXPERIMENT DESIGN

This fully prototypic irradiation test has been given the designation ATF-2 at INL. The test was designed to make use of the newest pressurized water loop which had recently been installed in the center flux trap of the Advanced Test Reactor (ATR) designated as Loop 2A. A core map of ATR showing the location of Loop 2A and the fuel elements that make up the center lobe power is shown below in Figure 1. Loop-2A supplies the pressurized water coolant to the ATF-2 test train via an annular in-pile tube coming in from the bottom of the ATR pressure vessel. Fresh coolant flows up the annulus of the in-pile tube and then reverses direction in an upper plenum at the top of the in-pile tube and then flows down through the test section and back out of the core through the bottom of the ATR pressure vessel. Loop-2A controls coolant in the ATR-2 test completely independently from the ATR primary coolant. The system is complete with a pressurizer, heat exchangers, line heaters, pumps as well as a chemical make-up secondary coolant circuit for chemistry control. Gas bottles can be attached to the loop to control the concentrations of non-condensable gasses such as hydrogen, oxygen, and nitrogen. Boric acid and lithium hydroxide are also added to simulate pressurized water reactor (PWR) chemistry conditions inside the loop. Figure 2 below shows a simplified PID of Loop-2A. Real time measurements of coolant flow, coolant pressure, inlet and outlet coolant temperature, are all documented and stored in an NQA-1 compliant database. Periodic water samples are taken during the irradiation cycle and sent for chemical analysis of oxygen, nitrogen, hydrogen boron, lithium hydroxide (LiOH), pH, and visual crud concentration (VCC).

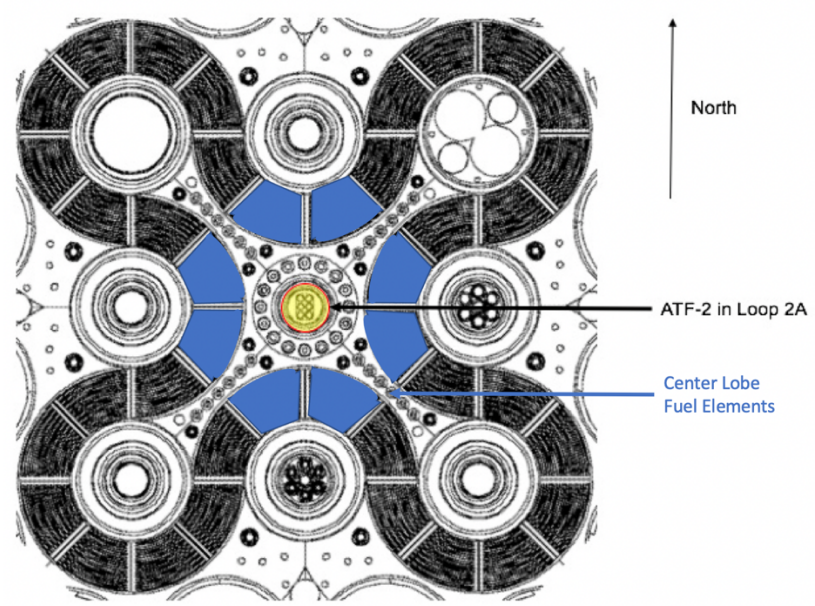


Figure 1. Core Map of ATR showing Center Lobe Fuel Elements and Loop 2A installed in the Center Flux Trap

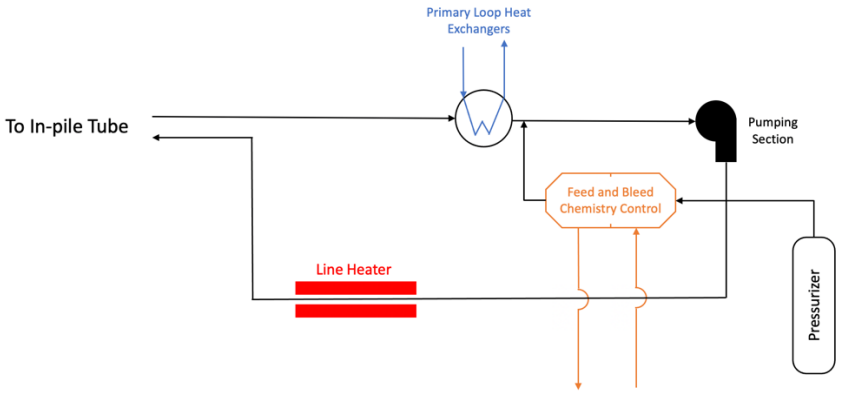


Figure 2) Simplified PID of Loop 2A

The ATF-2C test train consists of 4 tiers which are arranged axially in the core each of which contains a 2x3 array of test pins. The flow area in the tiers when configured with standard 17 × 17 PWR-sized fuel pins is ~2.677 cm^2. In the ATF-2C configuration, the top half of the test train consists of a single tier to allow for the irradiation of the longer test pins with in-situ instrumentation. The bottom three tiers (i.e., Tiers 1, 2, and 3) will be joined to each other and the upper tier with dovetail joints and held in place by spring clamps. These lower tiers will continue the irradiation of test pins from earlier phases of ATF-2, as well as novel SiC-SiC clad test pins. Figure 3 and Figure 4 show the modified ATF-2C test train tier 4/5/6 (combined tier 4).

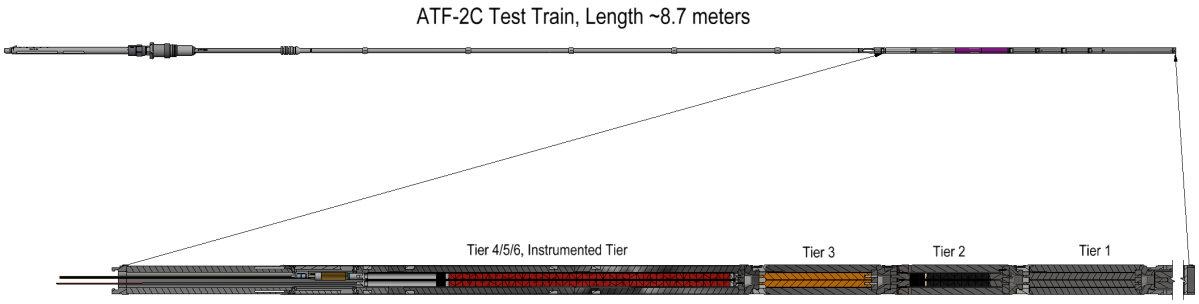


Figure 3 ATF-2C test train with consolidated Tiers 4/5/6 (Tier 4).

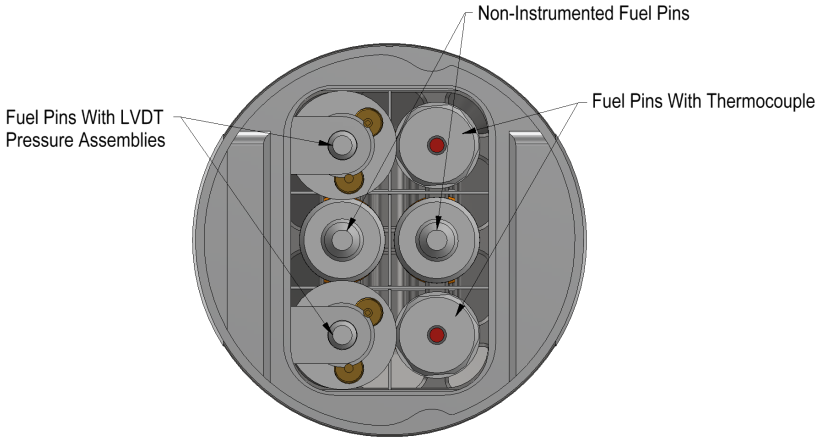


Figure 4) Loading arrangement of Tier 4 with instrumented and un-instrumented pins.

The combined upper tier will hold test pins that are approximately 55 cm long. Four pins use instrumentation with leads, while the remaining two are non-instrumented. A hafnium shroud, approximately 21.6 cm long, will be used to adjust the flux near the core center line to limit axial peaking along the test pin. The fuel stacks will be composed of approximately 40 pellets with a diameter of 0.819 cm and a height of approximately 1.05 cm each, enriched to 4.95%, and extending from approximately 9 cm above the core centerline to 52 cm above core centerline. Two of the instrumented pins will contain type N TCs. The other two instrumented pins will contain pressure bellows and a linear variable differential transducer (LVDT) measurement assemblies.

3. MATERIALS AND METHODS

3.1 Test Materials and Operating Conditions

The first cycle irradiation of ATF-2C saw the irradiation of 24 integral fuel test pins. The irradiation involved 6 long chrome coated cladding test pins irradiated under a CRADA with the Japan Atomic Energy Agency (JAEA) and Mitsubishi Heavy Industries (MHI) in tier 4. In tier 3 there were 6 SiC-SiC cladding pins (unfueled) provided by General Atomics, and in tiers 1 & 2 there were 12 chrome coated cladding pins supplied by Framatome. Location of the pins is shown below in Table 1. All test pins, except the SiC-SiC pins, contain UO_2 fuel pellets enriched to between 4.9% and 4.95% U-235 and heavy metal densities between 10.4 grams/cm^3 and 10.5 grams/cm^3. Some of the UO_2 pellets contained sintering additives to increase their grain size and provide improved fission gas retention and better pellet plasticity at high temperature. The irradiation is planned to occur over 4 steady state ATR cycles starting with cycle 171A which began on April 26, 2023. Table 2 below documents the cycle start and stop days. Plots of hourly averages of reactor power (in the center lobe), inlet and outlet coolant temperature, flow velocity, and coolant pressure for cycle 171 shown below in Figure 5. A data file is provided as an attachment to this report.

Table 1) ATF-2C Test Pin Position

Tier	Position	Rodlet ID
4	NE	2C-T1
	E	2C-B2
	SE	2C-T7
	NW	ATF-2C-P3
	W	2C-B1
	SW	ATF-2C-P2
3	NE	G13
	E	G15
	SE	G16
	NW	G05
	W	G10
	SW	G11
2	NE	AR-18
	E	AR-16
	SE	AR-04
	NW	AR-05
	W	AR-17
	SW	AR-15
1	NE	AR-20
	E	AR-21
	SE	AR-19
	NW	AR-06
	W	AR-07
	SW	AR-08

Table 2) ATR Cycles with ATF-2C Test Train

Cycle	Start Date	End Date	Un-planned Mid Cycle Outages	Effective Full Power Days
171A	26-April-2023	19-June-2023	0	54
171B	21-July-2023	26-Sept-2023	1	64
173A	25-July-2019	24-Sept-2019	0	60
173B	11-Nov-2019	10-Jan-2020	0	60

*Shaded dates and durations are planned only

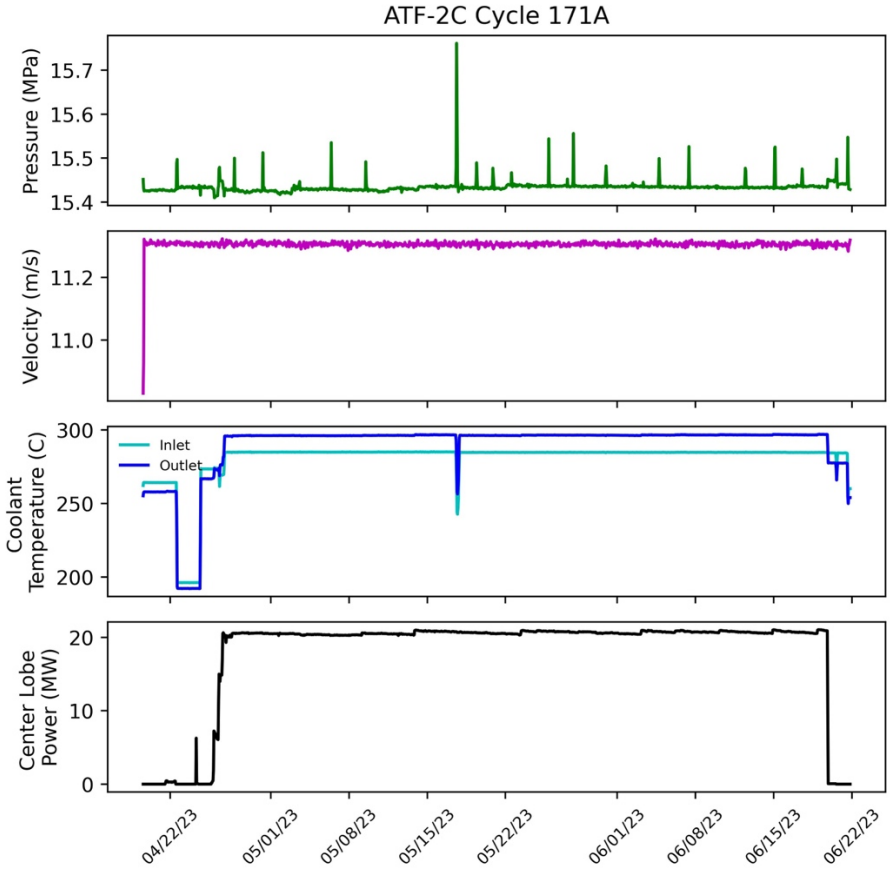


Figure 5) Loop-2A Operating Conditions During First Three Cycles of ATF-2b

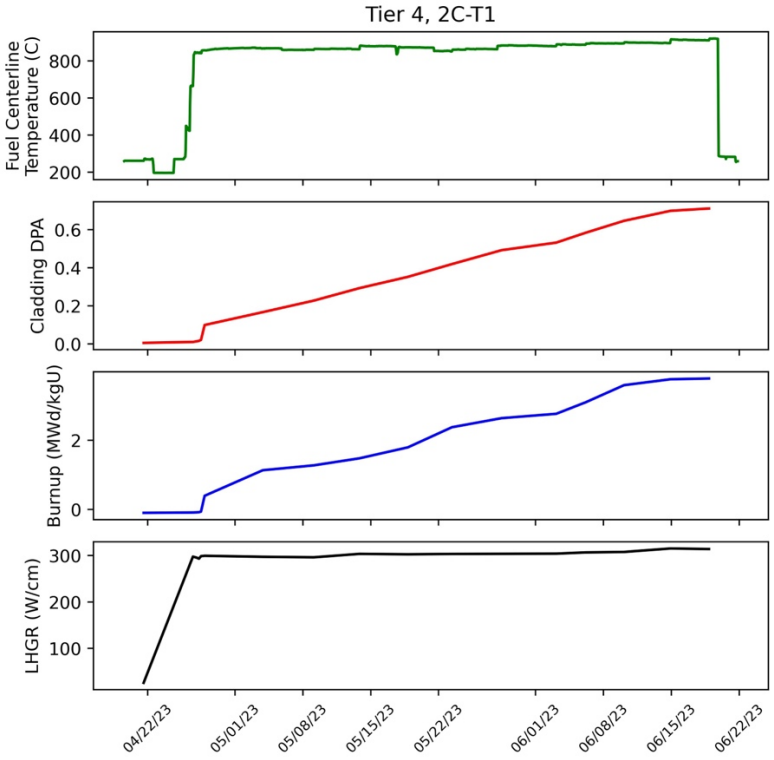
Table 3) Cycle Average Water Chemistry Values for Loop2A During ATF-2b Irradiation

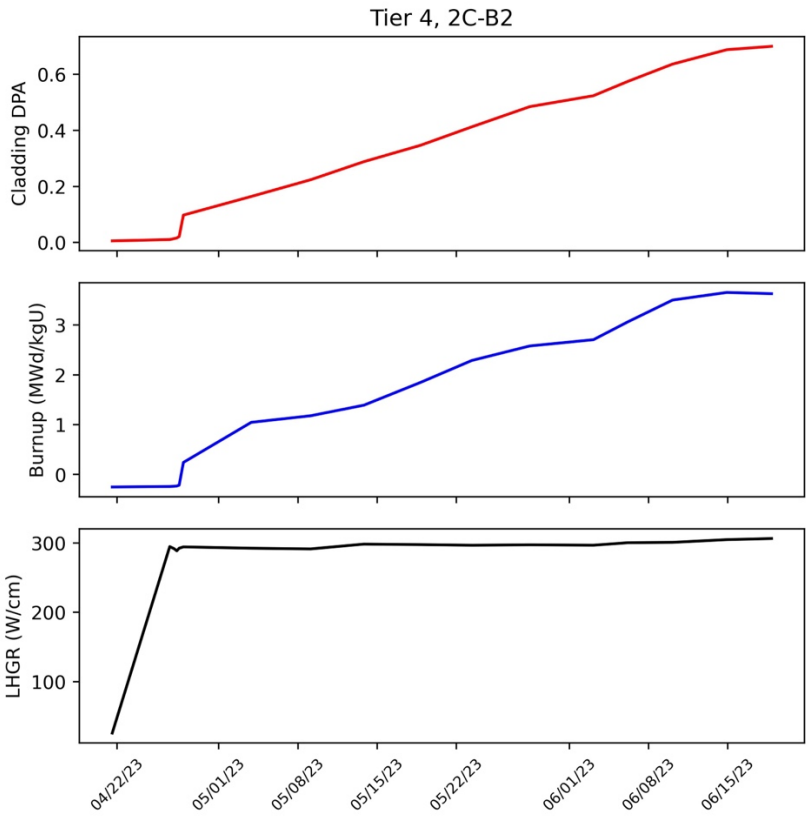
Cycle	**O2 (ppb)**	**H2 (cm3/g)**	**LiOH (ppm)**	**Boron (ppm)**	**VCC (ppb)**	**pH**
171A	0 +/- 0	52.28 +/- 9.39	4.29 +/- 0.253	1225 +/- 17.87	0.39 +/- 2.12	6.67 +/- 0.075

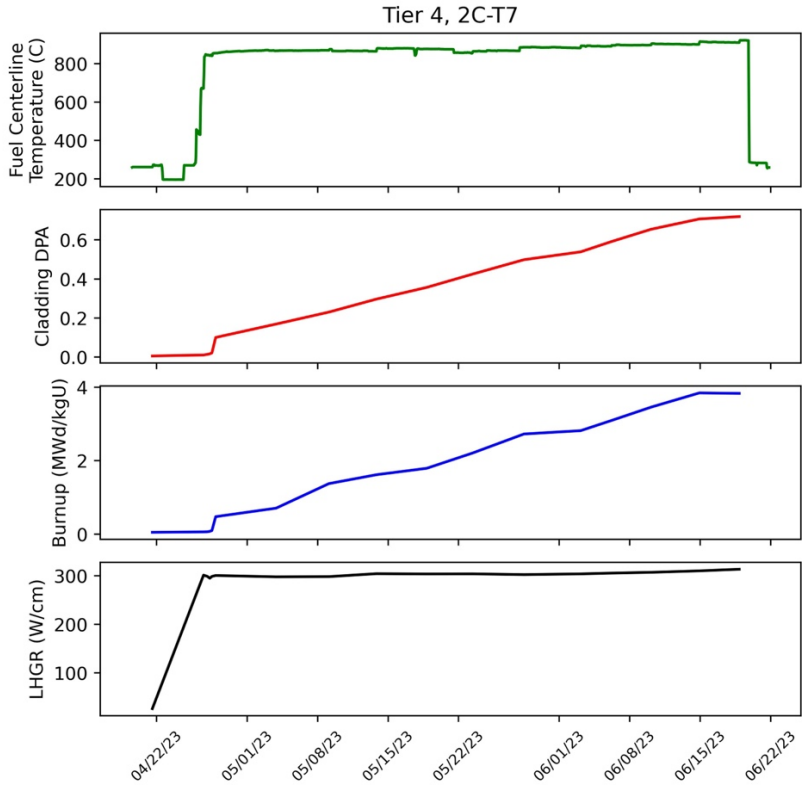
4. TEST PIN IRRADIATION HISTORIES

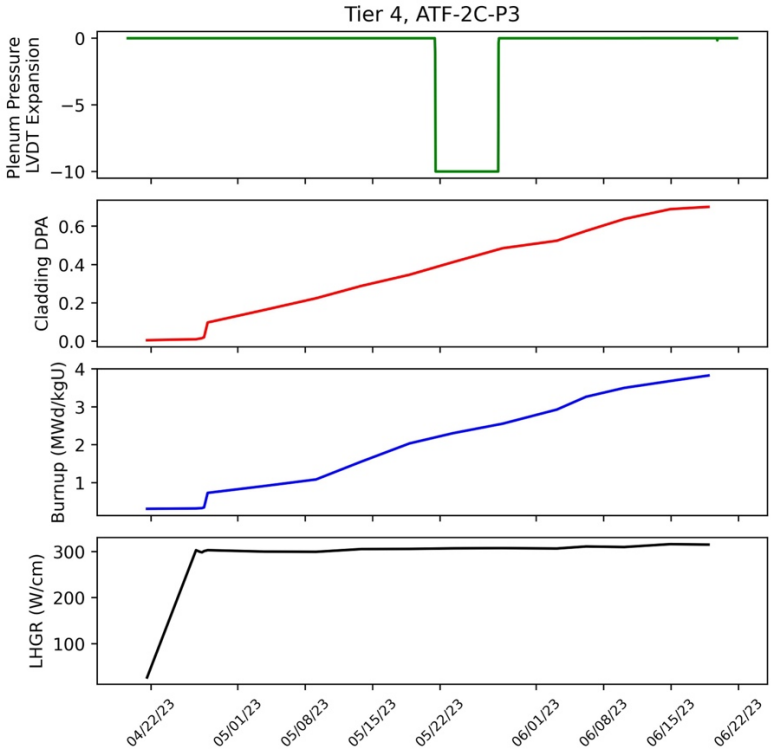
Power histories, neutron fluxes, and test pin depletions are calculated for each cycle using a coupled Monte Carlo N-Particle (MCNP) and ORIGEN methodology. Preliminary test pins power and irradiation histories for all the test pins irradiated in ATF-2C are shown below. For pins with in-situ instrumentation, plots of instrument reading are plotted with power histories. DPA's are not reported for Framatome test pins in tiers 1 and 2 as dpa histories from previous cycles are not available, fast fluxes are reported instead. For the unfueled SiC-SiC test pins DPA and Fast Flux is reported. A data file is provided as an attachment to this report.

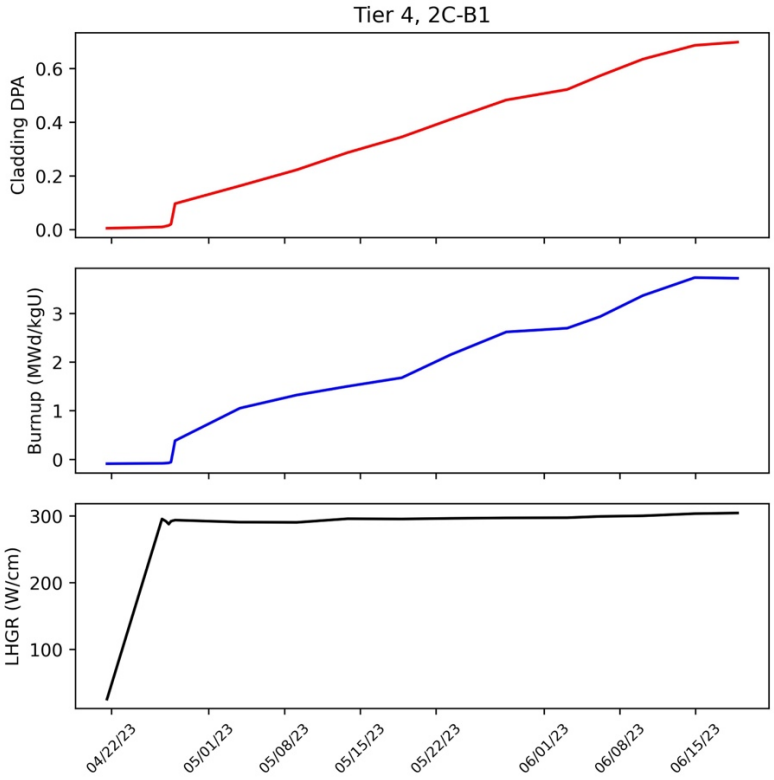
4.1 Tier 4 Irradiation Histories for JAEA/MHI Pins

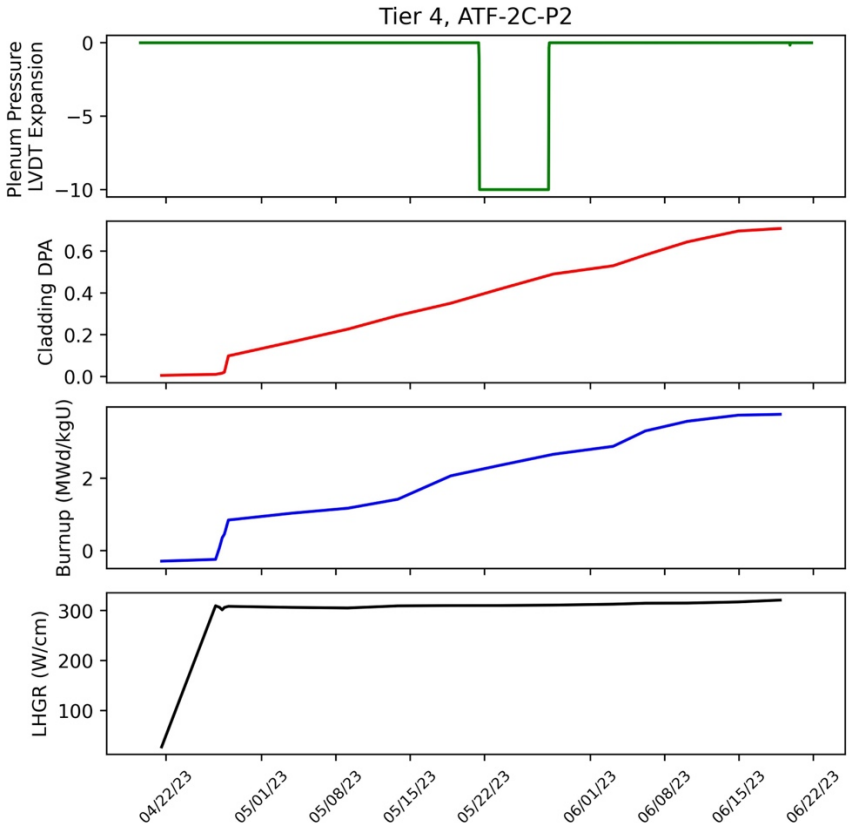



Tier 4, 2C-B2
Cladding DPA
0.0
0.2
0.4
0.6
Burnup (MWd/kgU)
0
1
2
3
LHGR (W/cm)
100
200
300
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23

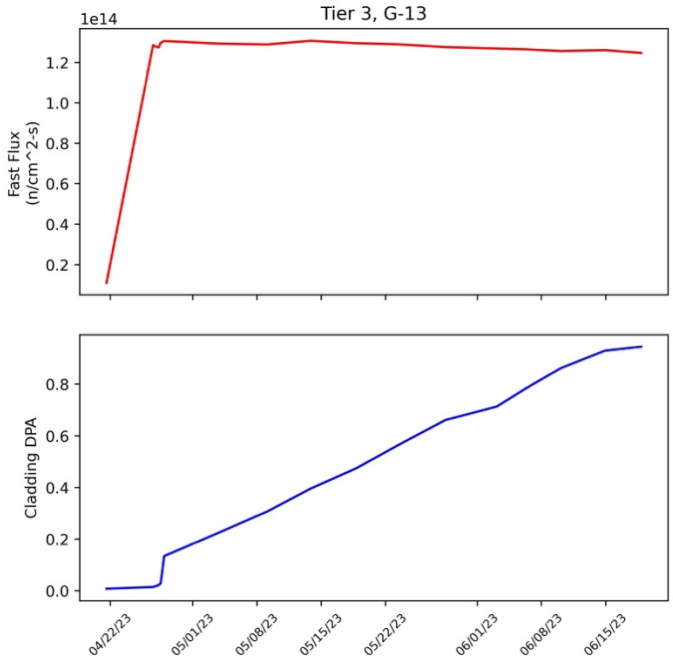

Tier 4, 2C-T7
Fuel Centerline Temperature (C)
200
400
600
800
Cladding DPA
0.0
0.2
0.4
0.6
Burnup (MWd/kgU)
0
2
4
LHGR (W/cm)
100
200
300
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23
06/22/23

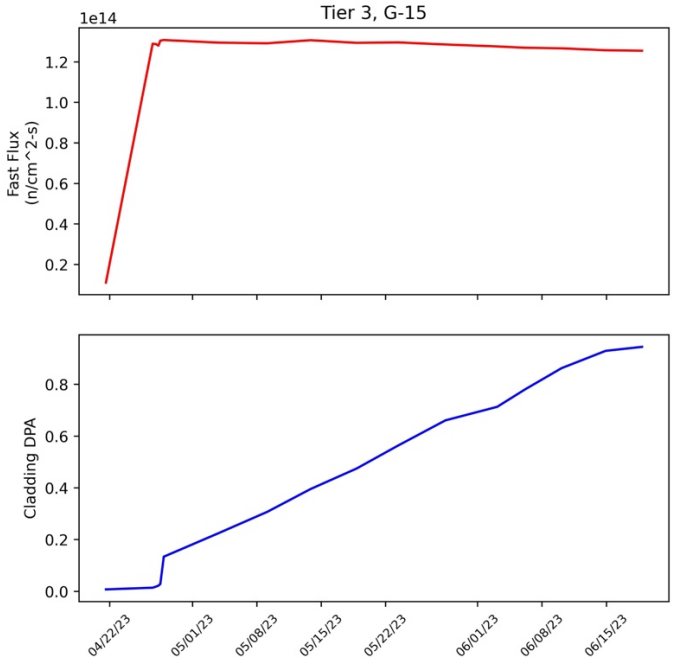

Tier 4, ATF-2C-P3
Plenum Pressure LVDT Expansion
0
−5
−10
Cladding DPA
0.6
0.4
0.2
0.0
Burnup (MWd/kgU)
4
3
2
1
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23
06/22/23

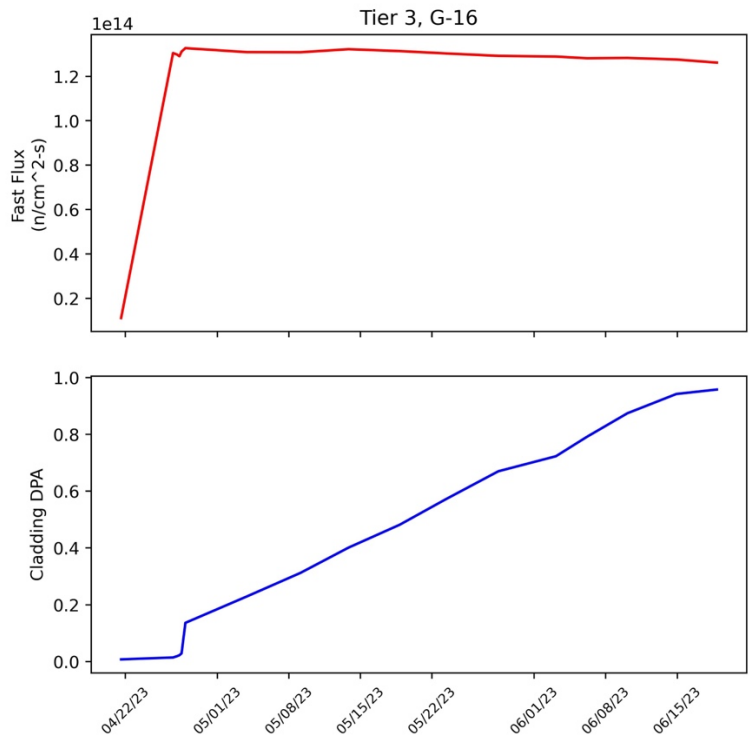

Tier 4, 2C-B1
Cladding DPA
0.6
0.4
0.2
0.0
Burnup (MWd/kgU)
3
2
1
0
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23

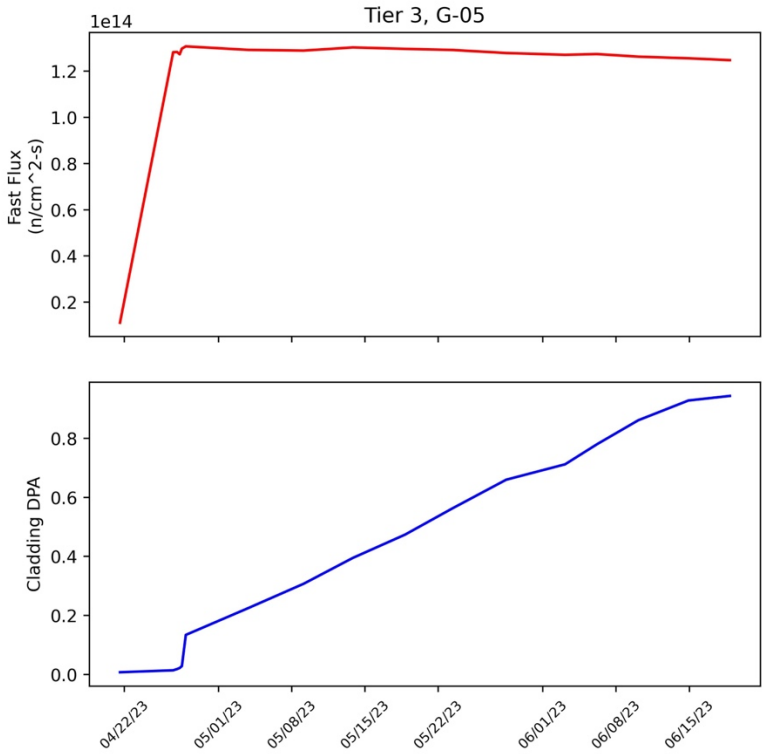

Tier 4, ATF-2C-P2
Plenum Pressure
LVDT Expansion
0
−5
−10
Cladding DPA
0.6
0.4
0.2
0.0
Burnup (MWd/kgU)
2
0
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23
06/22/23

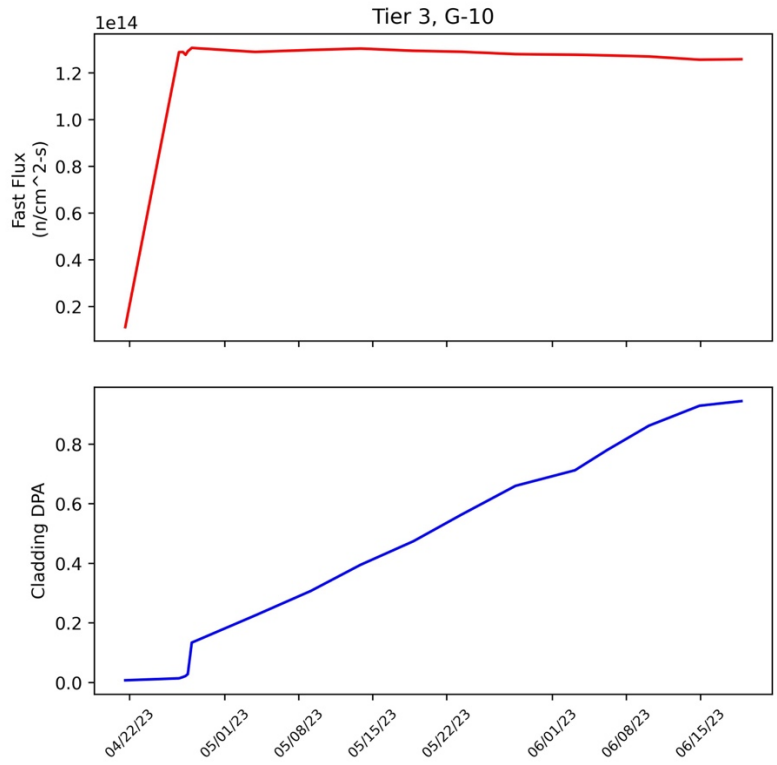
4.2 Tier 3 Irradiation Histories for GA SiC-SiC Pins

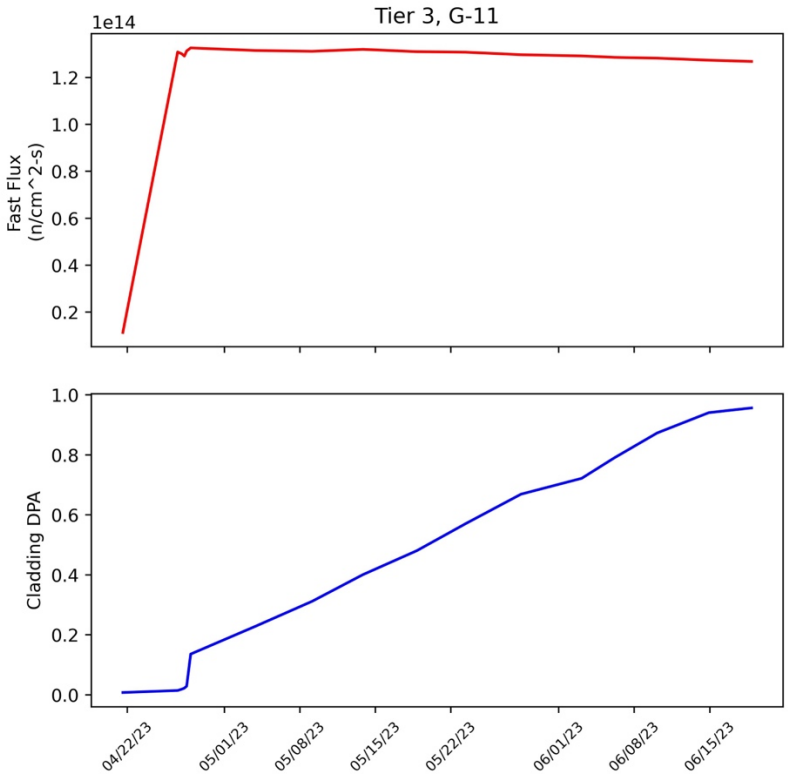




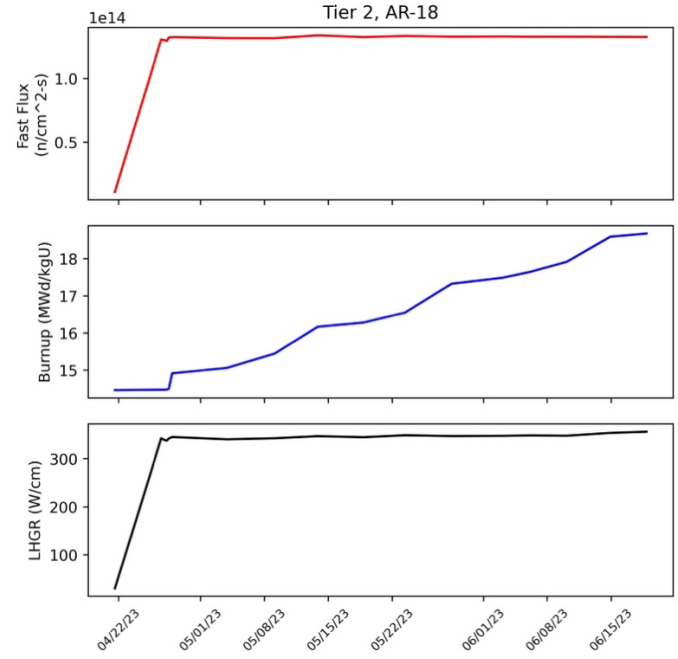

Tier 3, G-16
1e14
Fast Flux
(n/cm^2-s)
1.2
1.0
0.8
0.6
0.4
0.2
Cladding DPA
1.0
0.8
0.6
0.4
0.2
0.0
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23

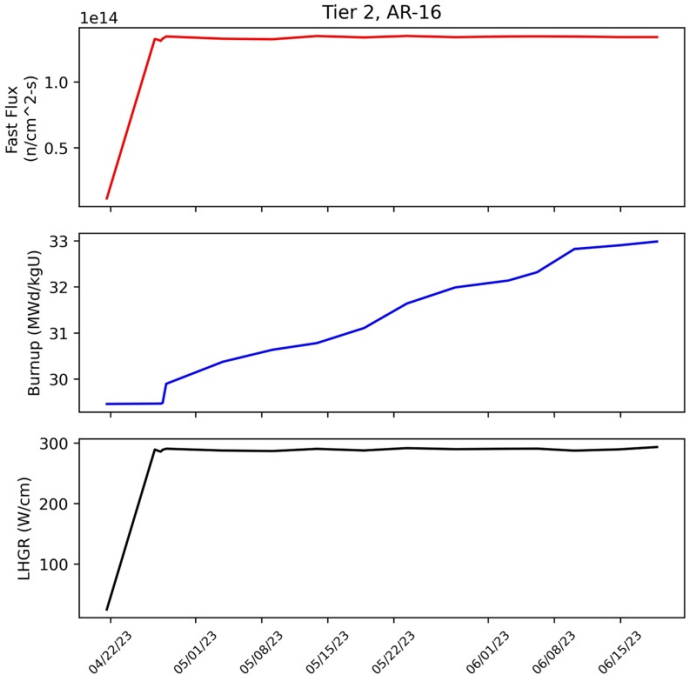

Tier 3, G-05
1e14
Fast Flux
(n/cm^2-s)
1.2
1.0
0.8
0.6
0.4
0.2
Cladding DPA
0.8
0.6
0.4
0.2
0.0
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23

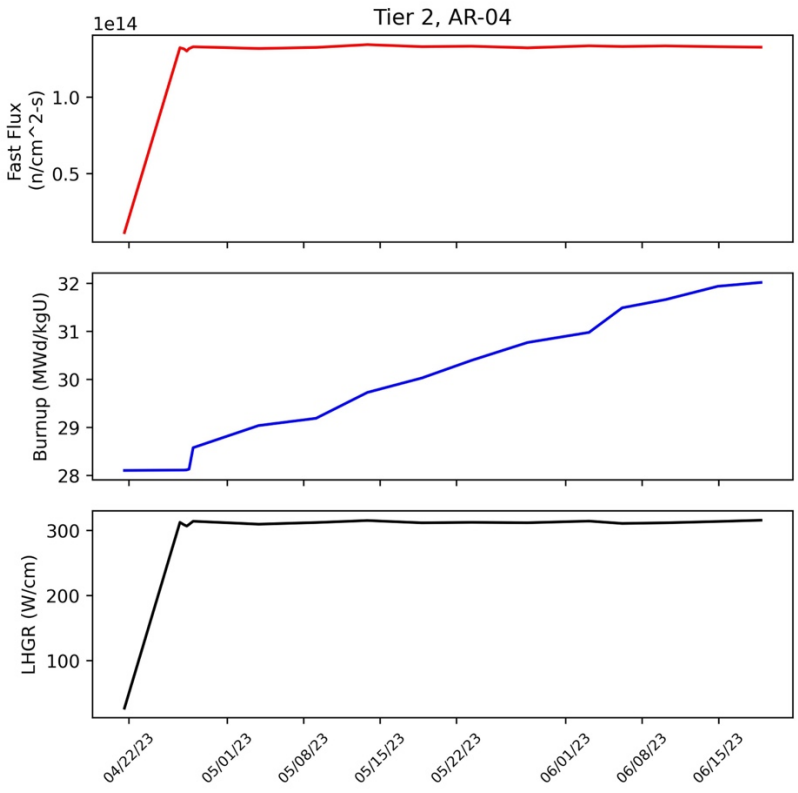

Tier 3, G-10
1e14
Fast Flux
(n/cm^2-s)
1.2
1.0
0.8
0.6
0.4
0.2
Cladding DPA
0.8
0.6
0.4
0.2
0.0
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23

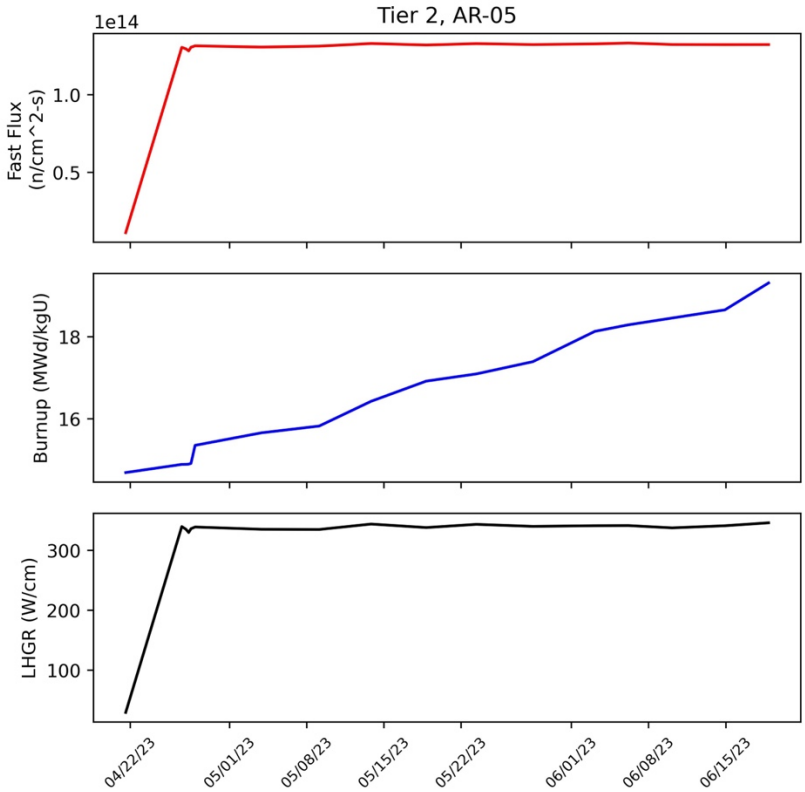

Tier 3, G-11
1e14
Fast Flux
(n/cm^2-s)
1.2
1.0
0.8
0.6
0.4
0.2
Cladding DPA
1.0
0.8
0.6
0.4
0.2
0.0
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23

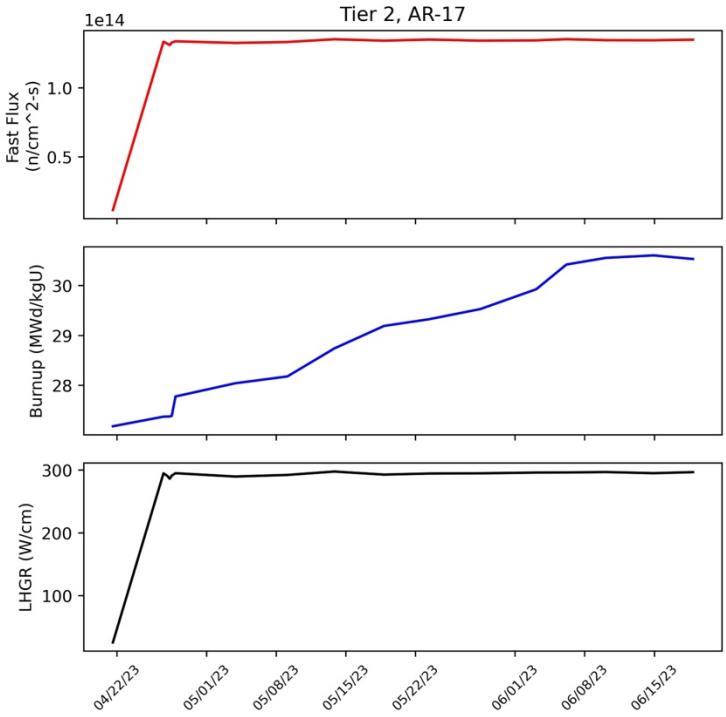
4.3 Tiers 1 & 2 Irradiation Histories for Framatome Pins

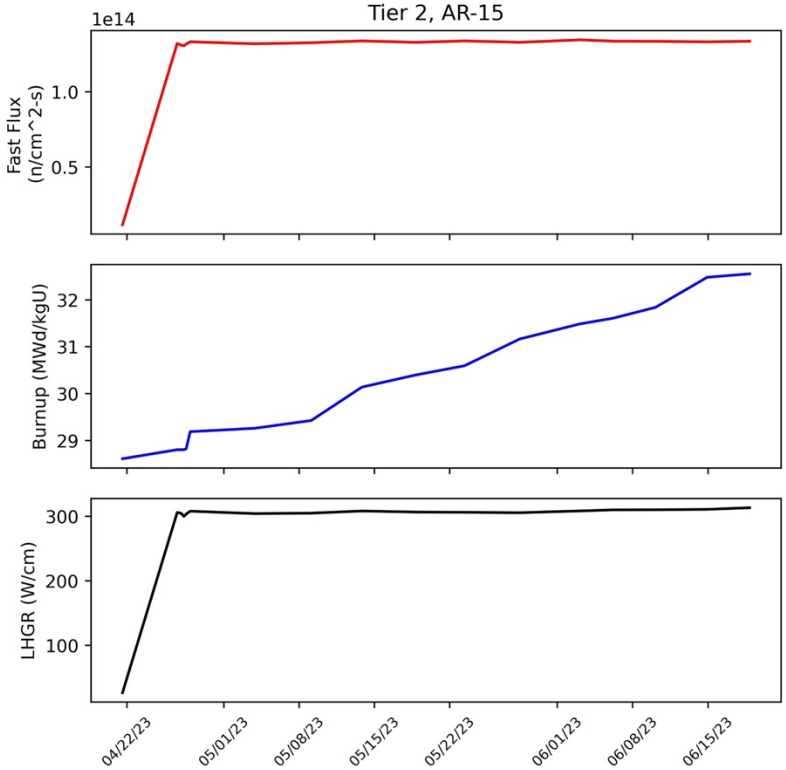





Tier 2, AR-04
1e14
Fast Flux (n/cm^2-s)
1.0
0.5
Burnup (MWd/kgU)
32
31
30
29
28
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 2, AR-05
1e14
Fast Flux (n/cm^2-s)
1.0
0.5
Burnup (MWd/kgU)
18
16
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 2, AR-17
1e14
Fast Flux (n/cm^2-s)
1.0
0.5
Burnup (MWd/kgU)
30
29
28
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 2, AR-15
1e14
Fast Flux (n/cm^2-s)
1.0
0.5
Burnup (MWd/kgU)
32
31
30
29
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
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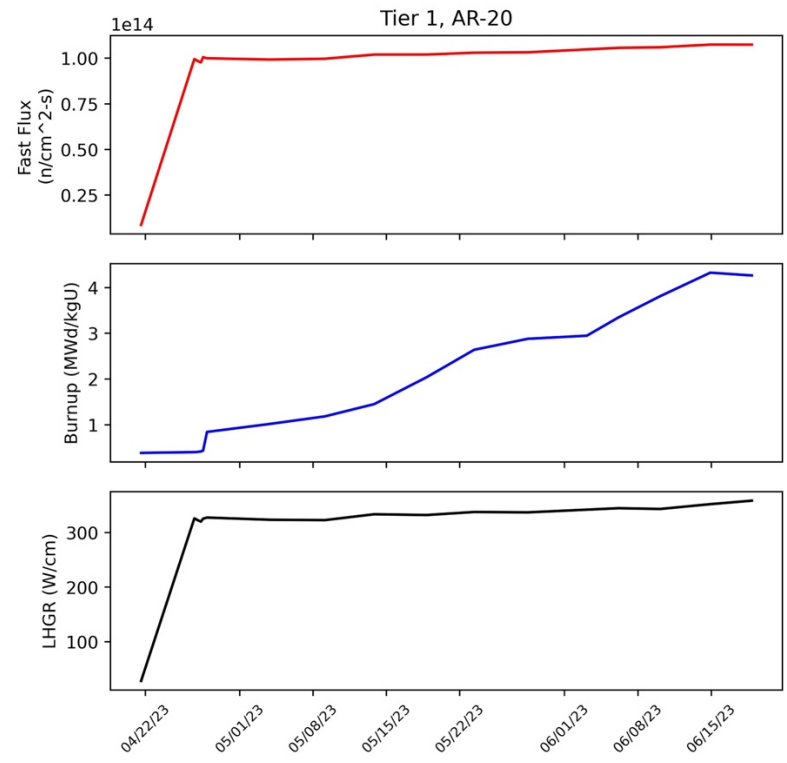
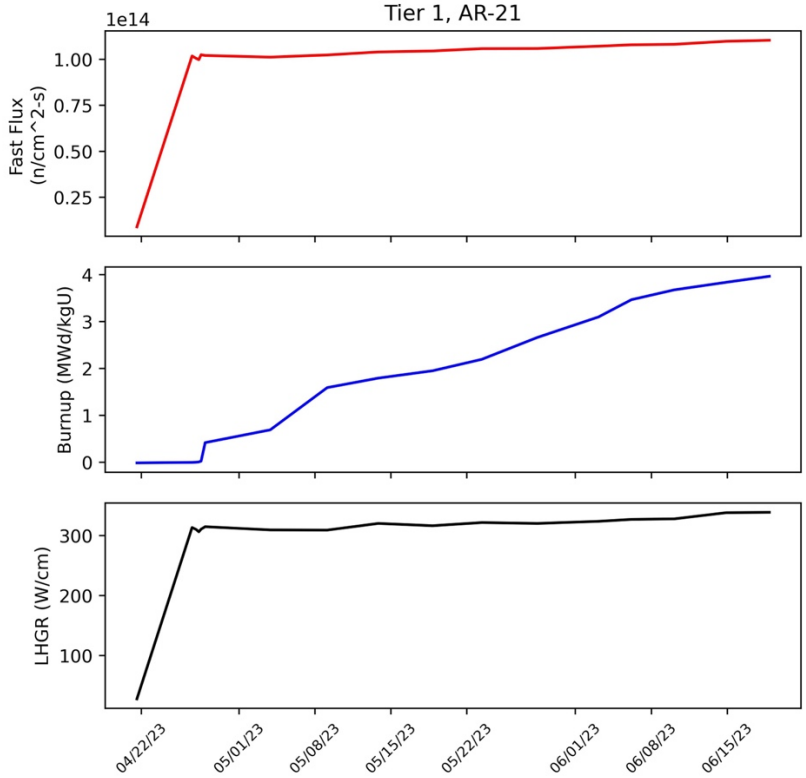
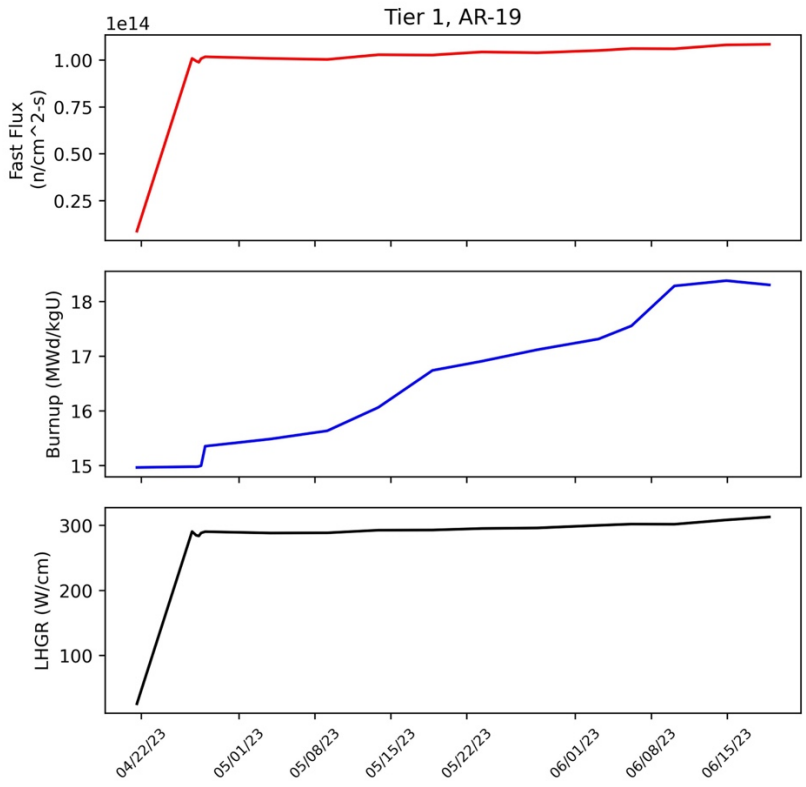
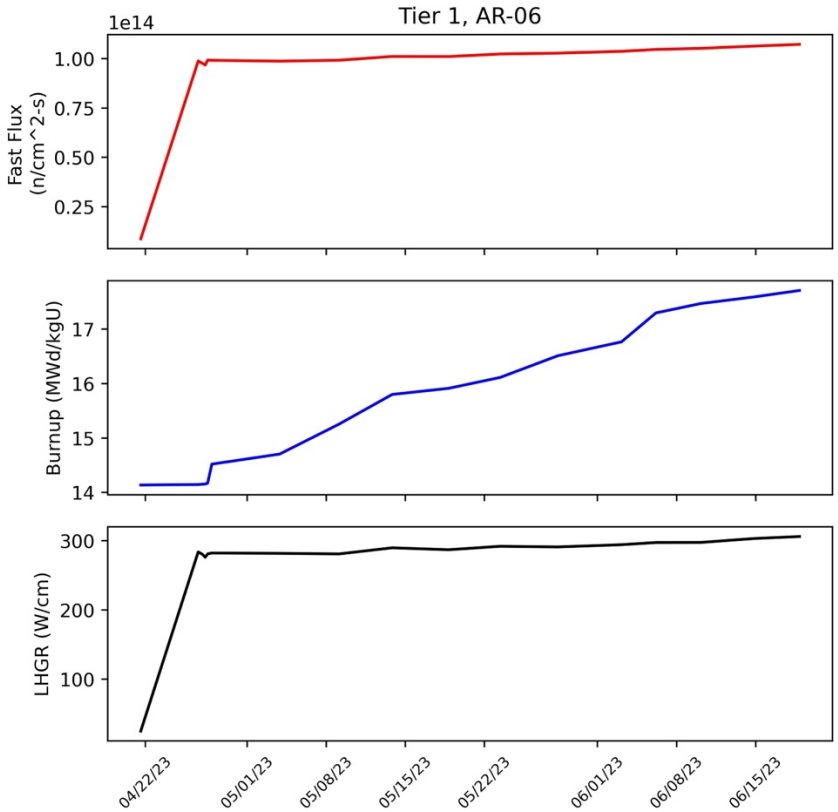
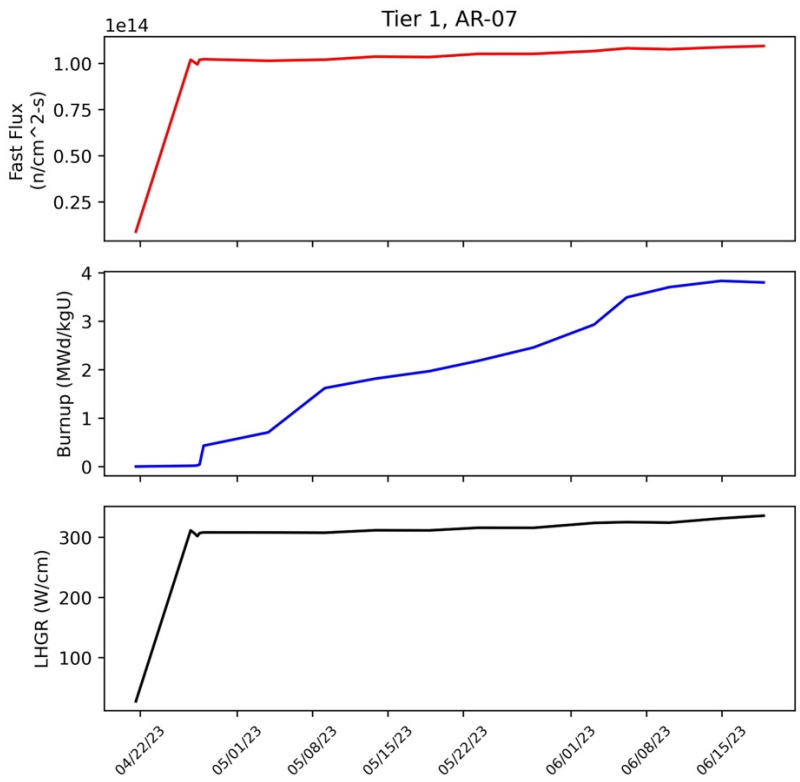
05/22/23
06/01/23
06/08/23
06/15/23

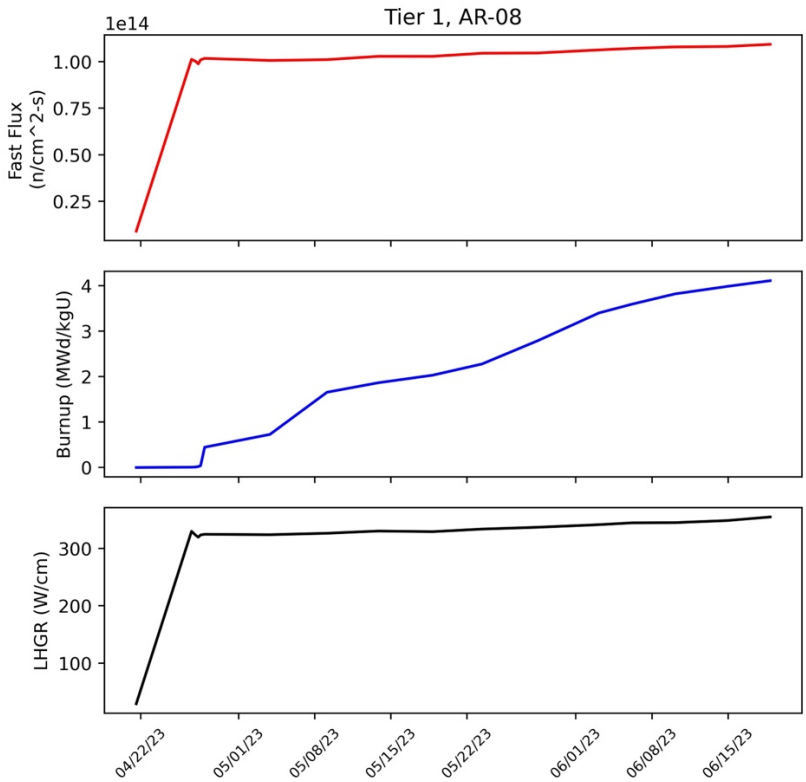

Tier 1, AR-20
1e14
Fast Flux (n/cm^2-s)
1.00
0.75
0.50
0.25
Burnup (MWd/kgU)
4
3
2
1
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 1, AR-21
1e14
Fast Flux (n/cm^2-s)
1.00
0.75
0.50
0.25
Burnup (MWd/kgU)
4
3
2
1
0
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 1, AR-19
1e14
Fast Flux (n/cm^2-s)
1.00
0.75
0.50
0.25
Burnup (MWd/kgU)
18
17
16
15
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 1, AR-06
1e14
Fast Flux (n/cm^2-s)
1.00
0.75
0.50
0.25
Burnup (MWd/kgU)
17
16
15
14
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 1, AR-07
1e14
Fast Flux (n/cm^2-s)
1.00
0.75
0.50
0.25
Burnup (MWd/kgU)
4
3
2
1
0
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23


Tier 1, AR-08
1e14
Fast Flux (n/cm^2-s)
1.00
0.75
0.50
0.25
Burnup (MWd/kgU)
4
3
2
1
0
LHGR (W/cm)
300
200
100
04/22/23
05/01/23
05/08/23
05/15/23
05/22/23
06/01/23
06/08/23
06/15/23