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Accident Tolerant Fuel Test 2B (ATF-2B) Irradiation Test Report

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Changing the World's Energy Future

D. Kamerman, B. Durtschi, B. Curnutt, A. Carter, S. Wilson, G. Hoggard, and F. Cappia
Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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SUMMARY

A 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-2, has completed seven cycles of prototypic steady-state irradiation of 41 test pins to burnups as high as 30 MWd/kgU. 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 41 test pins has been calculated using a combined Monte Carlo N-Particle, and ORIGIN methodology to provide accurate and reliable power histories on a per-pin basis.

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ACRONYMS

ATF	accident tolerant fuel
ATR	Advanced Test Reactor
BWR	boiling-water reactor
DOE	Department of Energy
INL	Idaho National Laboratory
LHGR	linear heat generation rate
MCNP	Monte Carlo N-Particle (code)
NFCF	neutron flux conversion factor
PHNF	prompt heating normalization factor
PID	proportional-Integral-derivative
PIE	post-irradiation examination
PWR	pressurized water reactor
VCC	visual crud concentration

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1. INTRODUCTION/BACKGROUND

Following the core damage events that occurred at 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 would better withstand severe accident conditions [1]. The development of these accident-tolerant fuels (ATFs) in the United States is an industry-led initiative with cooperative agreements issued to the three nuclear fuel vendors in the U.S.: Westinghouse, Framatome, and General Electric. To support these industry-led initiatives, the Idaho National Laboratory (INL) developed an irradiation testing plan to support the development of both near-term and long-term ATF concepts [2]. For the development and qualification phase of the near-term ATF concepts, which consist principally of coated zirconium alloy claddings and doped UO_2 fuels [3][4], a fully prototypic irradiation testing environment was required. 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 a pressured water coolant at ~15 MPa, between 250 and 350°C, 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 that was recently installed in the center flux trap of the Advanced Test Reactor (ATR), designated as Loop 2A [5]. The ATR is a water-cooled plate-type materials test reactor that achieved first criticality in 1967. The fuel plates are curved and arranged in a serpentine arrangement that creates nine flux traps. In addition to the flux traps, several experimental positions in the reactor's beryllium reflector. The reactor is approximately 1.3 m tall and 1.3 m in diameter; it is cooled with a top-down flow of pressurized water at approximately 4–5 bars of pressure and an inlet temperature of 55°C. The serpentine arrangement is achieved with 40 fuel assemblies, which are divided into five lobes of eight fuel elements each (four corner lobes and one center lobe). Power in each of the four corner lobes is controlled independently with a maximum power split between any of the four lobes of 3:1. The reactor operates both normal and transient power cycles. The normal cycles consist of 60-day runs with a nominal full reactor power of 100–125 MW, with limited power splits between the four quadrants. Reactor power in each of the four corner lobes, as well as the center lobe, is reported in real time from N-16 detectors in each lobe. The values are compensated by the core waterpower calculator, which determines power based on temperature rise in the primary coolant. The transient cycles last anywhere from 7–15 days, with high operating powers and wider variations between the spatial and temporal power profiles. ATR generally operates three steady-state cycles and two transient power cycles per year. A core map of ATR showing the location of Loop 2A and the fuel elements that make up the center lobe power comprises Figure 1.

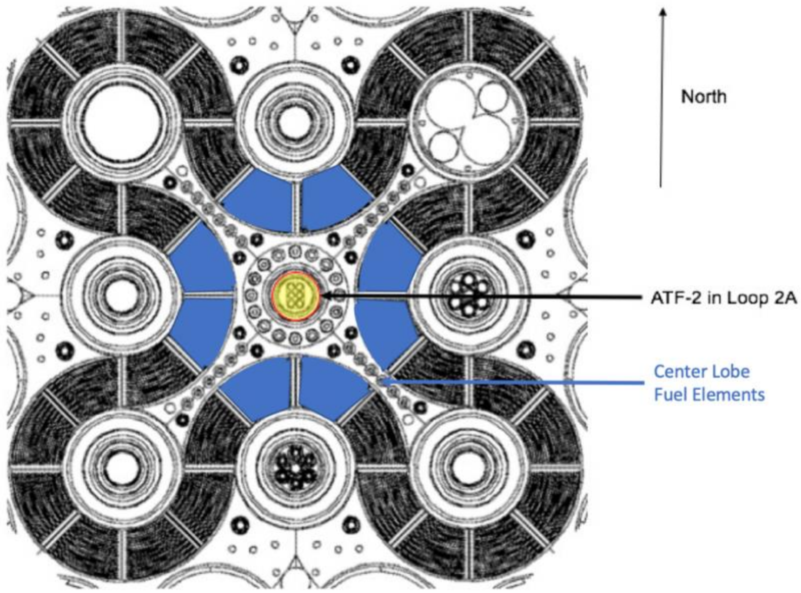

Figure 1. Core map of ATR showing center-lobe fuel elements and Loop 2A installed in the center flux trap.

The ATF-2 test train consists of six tiers that are arranged axially in the core, each of which contains a 2 × 3 array of test pins that are nominally 15 cm in length and contain 10 fuel pellets. The tiers are numbered 1–6, with Tier 1 at the bottom and Tier 6 at the top. At various times, two of the tiers are combined so that longer test pins with up to 20 fuel pellets can be irradiated. The six tiers are joined together with dovetail joints and held in place by spring clamps. The flow area in the tiers when configured with standard 17 × 17 pressurized water reactor (PWR)-sized fuel pins is ~2.677 cm^2 and ~2.509 cm^2 when configured with larger, boiling-water reactor (BWR)-sized fuel pins. This arrangement allows for disassembly of the test train in the ATR canal so that individual test pins can be removed at various time in their irradiation life and be replaced with new fresh pins. The entire design is modular, allowing for large reconfigurable test matrixes. The in-core portion of the test train is attached at the bottom to a follower rod that extends to the bottom of the center flux trap in-pile tube and at the top to a hanger rod and flange that extend up to the top of the center flux trap in-pile tube, where the test is anchored to the ATR's top head-closure plate. The fueled tiers were originally fabricated from stainless steel, but were later replaced with a zirconium alloy so that higher test pin powers could be achieved. Figure 2 and Figure 3 show the salient features of the test train, including the reconfigurable test tiers and installation at the top of the reactor.

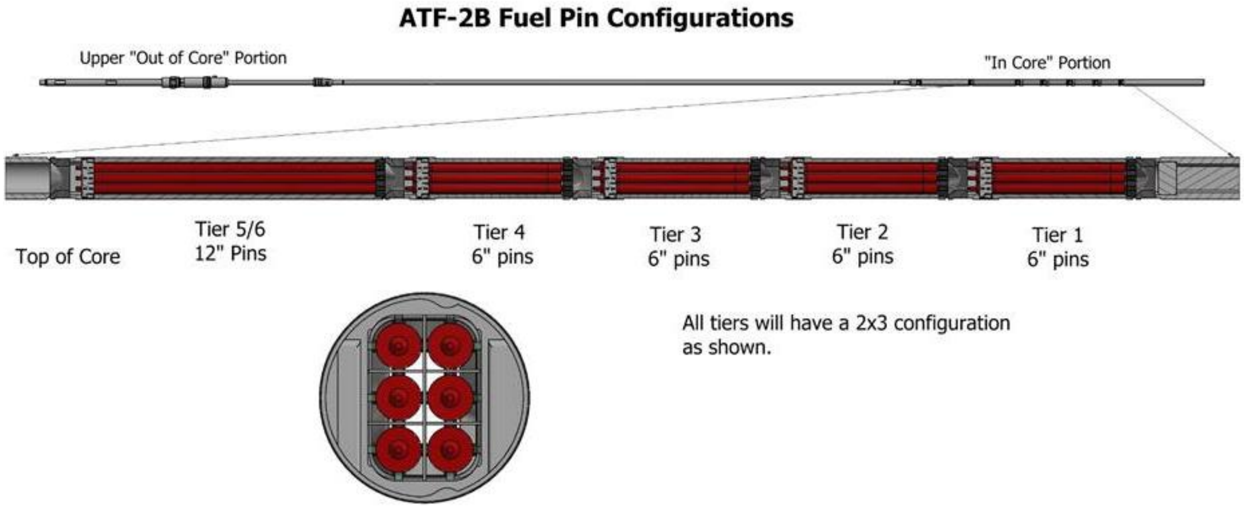

Figure 2. ATF-2C test train.

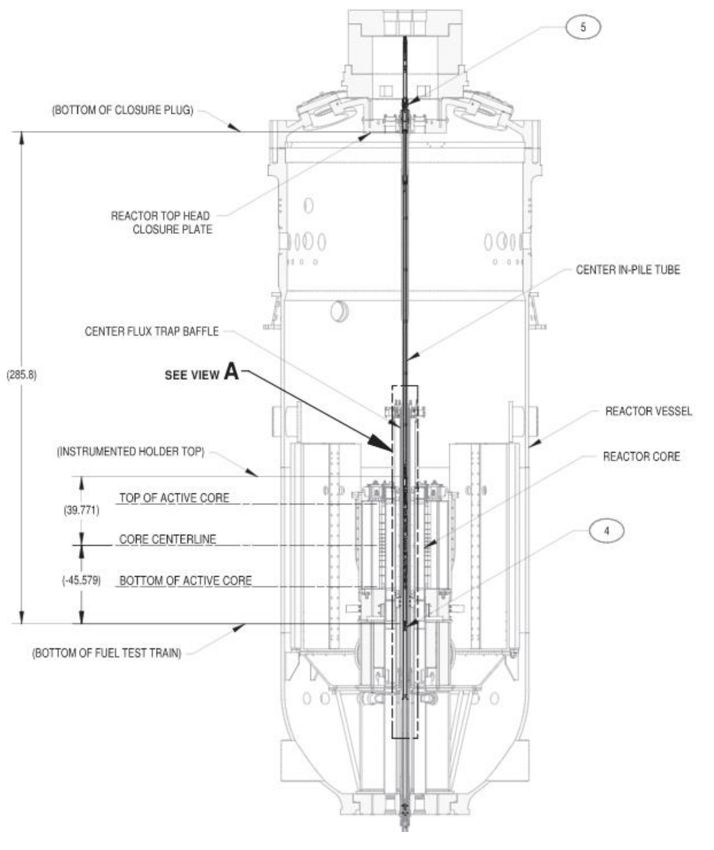

Figure 3. ATF-2C installation.

Loop-2A supplies pressurized water coolant to the ATF-2 test train via an annular in-pile tube, entering 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 flows down through the test section and out of the core through the bottom of the ATR pressure vessel. Loop-2A controls coolant in the ATR-2 test completely independent from the ATR primary coolant. The system is complete with a pressurizer, heat exchangers, line heaters, pumps and a feed-and-bleed secondary-coolant circuit for chemistry control. Gas bottles can be attached to the loop to control the concentrations of non-condensable gases such as hydrogen, oxygen, and nitrogen. Boric acid (depleted) and lithium hydroxide are also added to simulate PWR chemistry conditions inside the loop. Figure 4 shows a simplified proportional-Integral-derivative (PID) of Loop-2A. Real time measurements of coolant flow, coolant pressure, inlet and outlet coolant temperature, oxygen, nitrogen, and hydrogen concentrations are all documented and stored in a database compliant with Nuclear Quality Assurance–1 standards. Periodic water samples are taken during the irradiation cycle and sent for chemical analysis of boron, lithium hydroxide (LiOH), pH, and visual crud concentration (VCC).

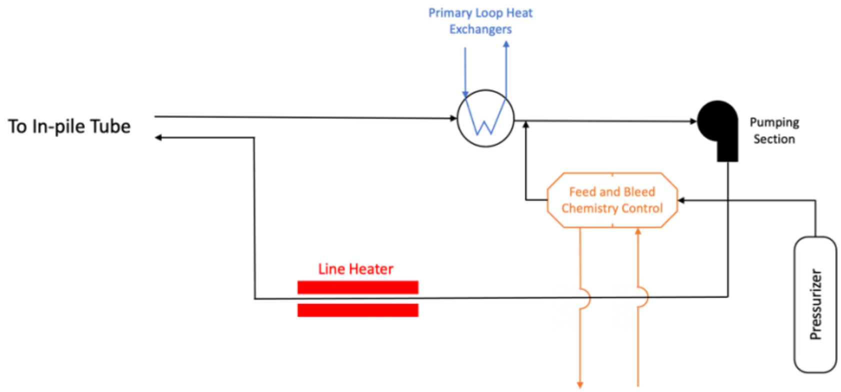

Figure 4. Simplified PID of Loop 2A.

3. MATERIALS AND METHODS

3.1 Test Materials and Operating Conditions

The irradiation phase of ATF-2, termed ATF-2B saw the irradiation of 41 integral fuel test pins. The irradiation involved 16 test pins with baseline zirconium alloys, 19 test pins with coated-zirconium alloys, and six test pins with FeCrAl alloys. All test pins contain UO_2 fuel pellets enriched to between 4.9 and 4.95% U-235 and heavy metal densities between 10.4 and 10.5 grams/cm^3. Some UO_2 pellets contained sintering additives to increase their grain size and provide both improved fission-gas retention and better pellet plasticity at high temperature.

The irradiation occurred over seven steady-state ATR cycles, beginning with Cycle 164A on June 12, 2018, and concluding with Cycle 169A on April 23, 2021. Table 1 documents the cycle start and stop days for each cycle, including the number of unplanned midcycle outages and effective full power days per cycle.

Table 1. ATR cycles with ATF-2B test train.

Cycle	Start Date	End Date	Unplanned Midcycle Outages	Effective Full-Power Days
164A	12 June 2018	17 Aug 2018	2	54
164B	19 Sept 2018	17 Jan 2019	2	63
166A	25 July 2019	24 Sept 2019	1	62
166B	11 Nov 2019	10 Jan 2020	0	60
168A	15 Apr 2020	22 July 2020	2	60
168B	26 Aug 2020	29 Oct 2020	1	57.1
169A	19 Feb 2021	23 Apr 2021	0	62

The initial experimental loading in Cycle 164A contained 12 baseline zirconium-alloy test pins and 10 coated zirconium-alloy test pins. The first three cycles were irradiated with modest test-pin powers (~200 to ~250 w/cm) and with coolant temperatures (~250°C) on the lower end of prototypic PWR operating conditions. Plots of reactor power (in the center lobe), inlet (red) and outlet (blue) coolant temperature, coolant pressure, and volumetric flow rate for these first three cycles are shown in Figure 5.

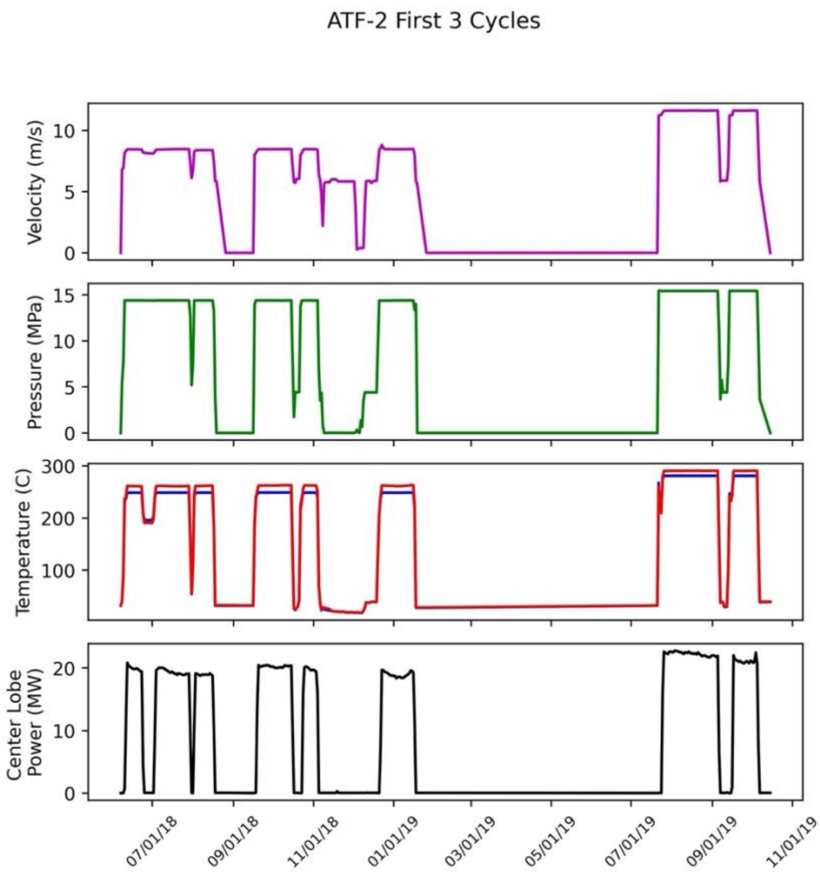

Figure 5. Loop-2A operating conditions during first three cycles of ATF-2B.

Starting at Cycle 166B, the test train was reconfigured with seven of the baseline zirconium-alloy pins and three of the coated zirconium-alloy pins removed. Twelve new pins were added, six of a FeCrAl design, four of a coated zirconium-alloy design, and two of a baseline zirconium design. Additionally, new tiers made of a zirconium alloy, instead of stainless steel, allowed for much higher test-pin powers (~450 w/cm) to be reached. The coolant inlet temperature was also increased to 280°C, allowing for an more aggressive irradiation overall. Prior to Cycle 168A, another minor reconfiguration was made to remove two additional baseline zirconium-alloy pins and two chrome-coated zirconium-alloy test pins. These pins were substituted with fresh test pins of the same type. Plots of reactor power (in the center lobe), inlet (red) and outlet (blue) coolant temperature, coolant pressure, and flow velocity (magenta for PWR tiers, cyan for BWR tiers) for these last four cycles are shown in Figure 6. Plots show reactor power (in the center lobe), inlet (red) and outlet (blue) coolant temperature, coolant pressure, and flow velocity. Cycle-average values and standard deviations of boron, LiOH, pH, and VCC for all ATF-2B irradiation cycles are shown below in Table 2. Zero values in the table indicate that values are below the detection limits.

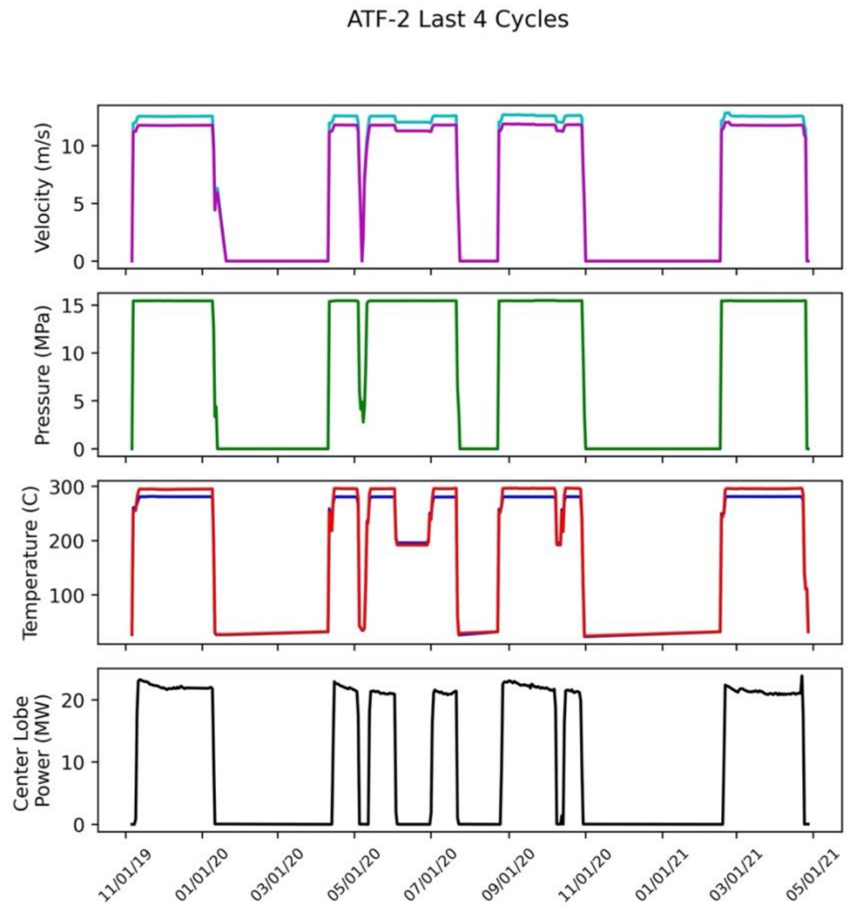

Figure 6. Loop-2A operating conditions during last four cycles of ATF-2B

Table 2. Cycle average water chemistry values for Loop2A during ATF-2B irradiation.

Cycle	O_2 (ppb)	H_2 (cm^3/g)	LiOH (ppm)	Boron (ppm)	VCC (ppb)	pH
164A	0 ±0	52.28 ±9.39	4.29 ±0.253	1225 ±17.87	0.39 ±2.12	6.67 ±0.075
164B	0.299 ±2.43	49.76 ±7.59	4.55 ±0.810	1182 ±153.24	3.44 ±7.45	6.67 ±0.054
166A	0 ±0	52.54 ±5.02	4.55 ±0.301	1150 ±127.9	42.67 ±116.07	6.68 ±0.068
166B	0 ±0	50.51 ±4.02	4.47 ±0.267	1193 ±33.46	0 ±0	6.71 ±0.0432
168A	0.26 ±1.15	50.11 ±5.14	4.2 ±0.48	1163.5 ±60.37	0 ±0	6.68 ±0.06
168B	0 ±0	49.57 ±4.32	4.43 ±0.83	1150 ±241.03	0.01 ±0.01	6.68 ±0.07
169A	0 ±0	54.61 ±8.18	4.67 ±0.48	1244 ±136	0 ±0	6.65 ±0.1

Following their removal from the ATF-2 test train, the test pins were shipped to INL's Hot Fuels Examination Facility (HFEF), where they will be subject to nondestructive and destructive examinations to determine how well they performed in pile. Descriptions of the kinds of examinations that take place at INL can be found references from similar post-irradiation examination (PIE) campaigns [6][7]. Data from the ATF-2 PIE campaigns are protected for each fuel vendor as these relates to the licensing and qualification of their specific fuel designs. Figure 7 shows some of the test pins from the ATF irradiation in HFEF during PIE.

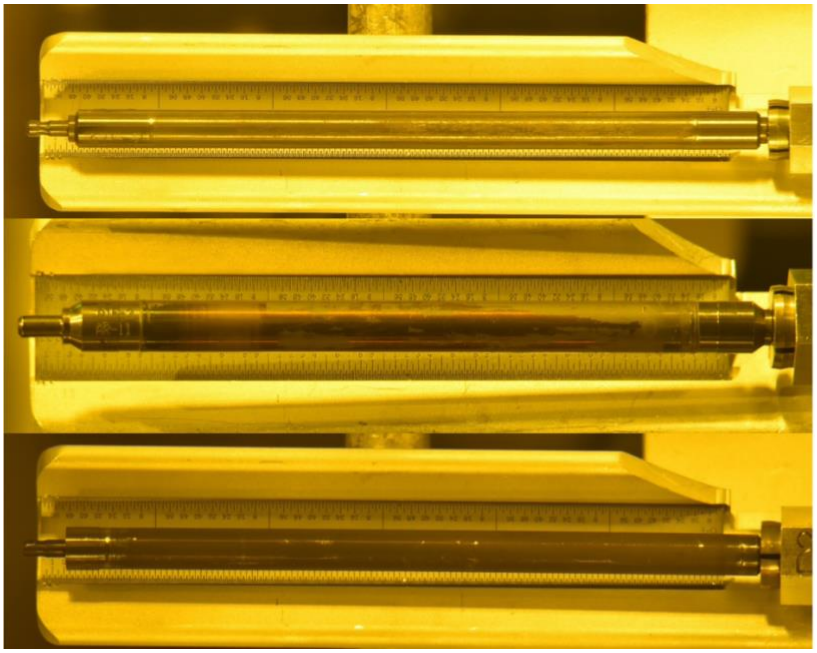

Figure 7. Irradiated ATF-2B pins prior to destructive PIE.

3.2 Test Pin Nuclear Analysis Methodology

Power histories, neutron fluxes, and test pin depletions are calculated each cycle using a coupled Monte Carlo N-Particle (MCNP) and Origin methodology, documented in INL Guide-594 [8]. An MCNP Type 7 fission-energy tally is used to calculate an energy-deposition value in terms of MeV/g per source neutron. A prompt heating normalization factor (PHNF) is then used to calculate the fission heating per fission neutron, as shown below in Equation (1). The F7 tally is multiplied by the PHNF and scaled to the center-lobe power at a given timestep to determine the test-pin heat rate in watts/gram as shown in Equation (2), which can in turn be scaled by the test pin's linear density to provide a linear-heat generation rate (LHGR).

$$PHNF = \frac{2.43\ Fission\ Neutrons}{Fission}\left(\frac{1\ Fission}{200\ MeV}\right)(Unit\ Conversions) = 1.215e4\ \frac{Fission\ Neutrons{-}W}{MeV\ MW} \tag{1}$$

$$Test\ Pin\ Specific\ Heat\ Rate = (f7\_tally)(PHNF)(Core\ Power) \tag{2}$$

MCNP Type 4 tallies are used to calculate the total flux, thermal flux (<0.625 eV), and fast flux (>1 MeV). Type 4 tallies in MCNP have units of n/cm^2-s per source particle (fission neutrons). A neutron-flux conversion factor (NFCF) is necessary to determine the given flux for a specified core power, as shown in Equation (3). The F4 tally is then multiplied by the NFCF and the center-lobe power at a given timestep to determine the test-pin neutron flux in the three energy bins in n/cm^2-s as shown in Equation (4).

$$NFCF = \frac{2.43\ Fission\ Neutrons}{Fission}\left(\frac{1\ Fission}{200\ MeV}\right)(Unit\ Conversions) = 7.583e16\ \frac{Fission\ Neutrons}{MW*sec} \tag{3}$$

$$Test\ Pin\ Specific\ Flux = (f4\_tally)(NFCF)(Core\ Power) \tag{4}$$

The MCNP-calculated heat rates are fed into an Origin input file and depleted over a given time interval with stable reactor power with a maximum time interval of ~10 days. Origin output files report the depletion of the U-235 atoms and buildup of actinide atoms in units of mol/cm^3. These values are multiplied by the volume of fuel in the test pin and Avogadro's constant. Burnup is determined by subtracting the number of heavy-metal isotopes at the end of the origin run to those present at the beginning of the origin run to determine the number of fissions that took place. Assuming 200 MeV per fission, burnup in units of MWd/kgU can be calculated. Isotopic inventories from the origin output are fed back into the MCNP input file so that accurate heat rates can be determined at the next time interval. Thus, test-pin heat rates, neutron fluxes, and burnup can all be calculated and correlated with recorded reactor powers.

4. TEST-PIN IRRADIATION HISTORIES

Test pins power and irradiation histories for all the test pins irradiated in ATF-2B are shown below.

Table 3. ATF-2B test pin power histories.

	164A	164B	166A	166B	168A	168B	169A
	Cycle Avg LHGR (W/cm) Fast (> 1 MeV) Fluence (n/m^2) Burnup (MWd/kgU)						
Zr-1	216 5.55E+24 2.6	231 1.22E+25 5.8	256 1.95E+25 9.3				
Zr-2	217 5.64E+24 2.6	229 1.24E+25 5.8	255 1.98E+25 9.3				
Zr-3	221 5.65E+24 2.7	235 1.25E+25 6	262 2.00E+25 9.5				
Zr-4	216 5.60E+24 2.6	229 1.24E+25 5.8	253 1.98E+25 9.2				
Zr-5	220 5.64E+24 2.7	233 1.24E+25 5.9	260 1.99E+25 9.4				
Zr-6	218 5.53E+24 2.6	232 1.22E+25 5.9	256 1.94E+25 9.4				
Zr-7	244 4.34E+24 3	257 9.59E+24 6.5	273 1.52E+25 10.3				
Zr-8	233 4.46E+24 2.9	242 9.85E+24 6.4	259 1.56E+25 10	359 2.16E+25 14.9	352 2.78E+25 19.6	341 3.36E+25 24	315 3.96E+25 28.5

Zr-9	207	220	241	415			
	4.90E+24	1.08E+25	1.72E+25	2.51E+25			
	2.6	5.8	9.1	14.8			
Zr-10	210	221	244	422			
	4.95E+24	1.09E+25	1.74E+25	2.56E+25			
	2.6	5.8	9.2	14.9			
Zr-11	230	240	255	335	397	386	361
	4.38E+24	9.68E+24	1.54E+25	2.15E+25	2.95E+25	3.70E+25	4.49E+25
	2.9	6.3	9.9	14.4	19.8	24.8	29.9
Zr-12	180	187	198	351	398	389	361
	2.91E+24	6.42E+24	1.01E+25	1.62E+25	2.40E+25	3.14E+25	3.92E+25
	2.3	4.9	7.8	12.5	17.9	23	28.1
Zr-13					366	366	340
					6.12E+24	1.19E+25	1.80E+25
					5	9.8	14.6
Zr-14					352	348	327
					6.22E+24	1.22E+25	1.84E+25
					4.8	9.4	14.1
Zr-15				426	431	436	415
				8.09E+24	1.61E+25	2.38E+25	3.19E+25
				4.8	9.7	14.3	19.2
Zr-16				445	448	453	431
				8.61E+24	1.71E+25	2.52E+25	3.38E+25
				5	10	14.9	19.9
Coated Zr-1	173	180	190				
	3.00E+24	6.62E+24	1.04E+25				
	2.3	5.2	8.1				
Coated Zr-2	170	175	186				
	3.04E+24	6.69E+24	1.06E+25				
	2.3	5.1	8				
Coated Zr-3	175	181	192				
	3.05E+24	6.72E+24	1.06E+25				
	2.4	5.2	8.2				
Coated Zr-4					322	319	300
					5.39E+24	1.06E+25	1.60E+25
					4.8	9.3	14
Coated Zr-5					323	321	340
					5.29E+24	1.04E+25	1.64E+25
					4.8	9.3	13.9

Coated Zr-6					317	314	295
					5.39E+24	1.06E+25	1.60E+25
					4.7	9.1	13.6
Coated Zr-7				422	423	426	407
				8.29E+24	1.65E+25	2.43E+25	3.26E+25
				4.7	9.5	14	18.8
Coated Zr-8				437	438	440	421
				8.29E+24	1.64E+25	2.43E+25	3.25E+25
				4.9	9.8	14.5	19.4
Coated Zr-9				442	440	443	423
				8.81E+24	1.75E+25	2.58E+25	3.45E+25
				5	9.9	14.6	19.5
Coated Zr-10				458	456	458	438
				8.81E+24	1.75E+25	2.58E+25	3.44E+25
				5.1	10.2	15.1	20.2
Coated Zr-11	207	217	239	402			
	4.95E+24	1.09E+25	1.74E+25	2.56E+25			
	2.6	5.6	9	14.4			
Coated Zr-12	213	224	248	429	412	397	370
	4.95E+24	1.09E+25	1.75E+25	2.57E+25	3.36E+25	4.12E+25	4.91E+25
	2.6	5.8	9.3	15	20.5	25.6	30.8
Coated Zr-13	210	224	243	418	405	393	365
	4.85E+24	1.07E+25	1.71E+25	2.50E+25	3.29E+25	4.03E+25	4.81E+25
	2.6	5.8	9.2	14.8	20.2	25.2	30.3
Coated Zr-14	207	218	238	401			
	4.95E+24	1.09E+25	1.74E+25	2.56E+25			
	2.6	5.7	9	14.3			
Coated Zr-15	240	249	266	358	351	337	314
	4.45E+24	9.81E+24	1.55E+25	2.17E+25	2.78E+25	3.36E+25	3.98E+25
	3	6.5	10.2	15	19.7	24.1	28.4
Coated Zr-16	238	248	264	355	378	368	344
	4.43E+24	9.78E+24	1.55E+25	2.16E+25	2.96E+25	3.72E+25	4.51E+25
	3	6.5	10.2	14.9	19.9	24.6	29.4
Coated Zr-17	181	189	198	342	383	373	349
	2.86E+24	6.32E+24	9.97E+24	1.61E+25	2.41E+25	3.17E+25	3.96E+25
	2.3	5	7.8	12.4	17.5	22.3	27.1
Coated Zr-18					357	353	331
					6.22E+24	1.22E+25	1.84E+25
					4.9	9.5	14.2

Coated Zr-19		371	367	345
		6.17E+24	1.20E+25	1.82E+25
		5.1	9.8	14.7
FeCrAl-1	465	470	477	456
	8.09E+24	1.61E+25	2.38E+25	3.19E+25
	4.7	9.4	14	18.8
FeCrAl-2	456	457	462	443
	8.29E+24	1.65E+25	2.44E+25	3.27E+25
	4.6	9.2	13.6	18.2
FeCrAl-3	470	472	477	458
	8.29E+24	1.64E+25	2.43E+25	3.25E+25
	4.8	9.5	14	18.8
FeCrAl-4	485	487	495	472
	8.61E+24	1.71E+25	2.52E+25	3.38E+25
	4.9	9.7	14.5	19.4
FeCrAl-5	477	475	480	460
	8.86E+24	1.75E+25	2.59E+25	3.46E+25
	4.8	9.6	14.1	18.9
FeCrAl-6	491	491	494	475
	8.86E+24	1.75E+25	2.58E+25	3.44E+25
	5	9.9	14.6	19.5

5. CONCLUSIONS

A fully prototypic testing platform for testing new ATF designs for light-water reactors has been established in the center flux trap of INL's ATR. The irradiation experiment, named ATF-2, has completed seven cycles of prototypic steady-state irradiation of 41 test pins to burnups as high as 30 MWd/kgU. 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 41 test pins has been calculated using a combined MCNP and ORIGIN methodology to provide accurate and reliable power histories on a per pin basis.

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