

Accident Tolerant Fuels Series 1 (ATF-1) Irradiation Testing FY 2019 Status Report

**Nuclear Technology
Research and Development**

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SUMMARY

This report contains a summary of irradiation testing in the Advanced Test Reactor (ATR) of Nuclear Technology Research & Development Accident Tolerant Fuels (ATF-1) experiments performed at the Idaho National Laboratory (INL) in FY 2019. Additionally, three capsules met the sponsor-specified burnup targets, and five capsules were shipped from the ATR to the Hot Fuels Examination Facility (HFEF) at INL.

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ACRONYMS

AFC	Advanced Fuels Campaign
ATF	Accident Tolerant Fuels
ATF-1	Accident Tolerant Fuels Series 1
ATR	Advanced Test Reactor
CFT	Center Flux Trap
CIC	Core Internals Changeout
DOE-NE	Department of Energy Office of Nuclear Energy
ECAR	Engineering Calculations and Analysis Report
EFPD	Effective Full-Power Days
ESA	Experiment Safety Analysis
FAST	Fission Accelerated Steady-state Test
FCCI	Fuel-Cladding Chemical Interaction
FME	Fissile Material Equivalent mass
FY	Fiscal Year
GWd/MTU	GigaWatt days per Metric Ton Uranium
HFEF	Hot Fuels Examination Facility
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LHGR	Linear Heat Generation Rate
LOCA	Loss of Coolant Accident
LTA	Lead Test Assemblies
LTR	Lead Test Rod
LWR	Light Water Reactor
MCNP	Monte Carlo N-Particle
MFC	Materials and Fuels Complex
NDMAS	Nuclear Data Management and Analysis System
NTRD	Nuclear Technology Research and Development
ORNL	Oak Ridge National Laboratory
PALM	Powered Axial Locator Mechanism
PCS	Primary Coolant System
PIE	Post-Irradiation Examination
PWR	Pressurized Water Reactor
RD&D	Research, Development, and Demonstration
TREAT	Transient Reactor Test Facility
WEC	Westinghouse Electric Company, LLC

Accident Tolerant Fuels Series 1 (ATF-1) Irradiation Testing FY 2019 Status Report

1. INTRODUCTION

The ultimate goal of the Accident Tolerant Fuels (ATF) program is to demonstrate improved fuel and/or cladding concepts offering the potential to replace the Zircaloy-UO₂ system currently used throughout the Light Water Reactor (LWR) industry. To support this goal, the congressional appropriation language for FY 2012 included specific language for DOE-NE to initiate an aggressive Research, Development, and Demonstration (RD&D) program for LWR fuels with enhanced accident tolerance. The test data collected as part of the ATF program will support demonstration of lead test rods (LTRs) or lead test assemblies (LTAs) in a commercial LWR within 10 years (i.e., by the end of FY 2022).

As a step toward this goal, a Phase 1 (Figure 1) feasibility irradiation test series of drop-in capsule experiments, denoted ATF-1, was fabricated and inserted into the Idaho National Laboratory (INL) Advanced Test Reactor (ATR) beginning in FY 2015 to demonstrate fabricability and viability for ATF-2 (Series 2) water loop testing (e.g., hermeticity, fuel/clad performance, structural stability). As part of feasibility testing, ATF-1 experiment fuel cladding is not exposed to the ATR Primary Coolant System (PCS) as the fueled rodlets are encapsulated in stainless steel. The ATF-2 water loop experiments are a continuation of the ATF-1 drop-in capsule feasibility experiments with the primary objective of testing fuel system concepts under conditions prototypic of PWRs to demonstrate concept viability, thus exposing the fuel pins (rodlets) directly to the PWR water chemistry and flow.

Upon reaching pre-defined irradiation test objectives, the experiments will be discharged from ATR and shipped to the INL Materials and Fuels Complex (MFC) for PIE and/or transient testing in the INL Transient Reactor Test (TREAT) facility.

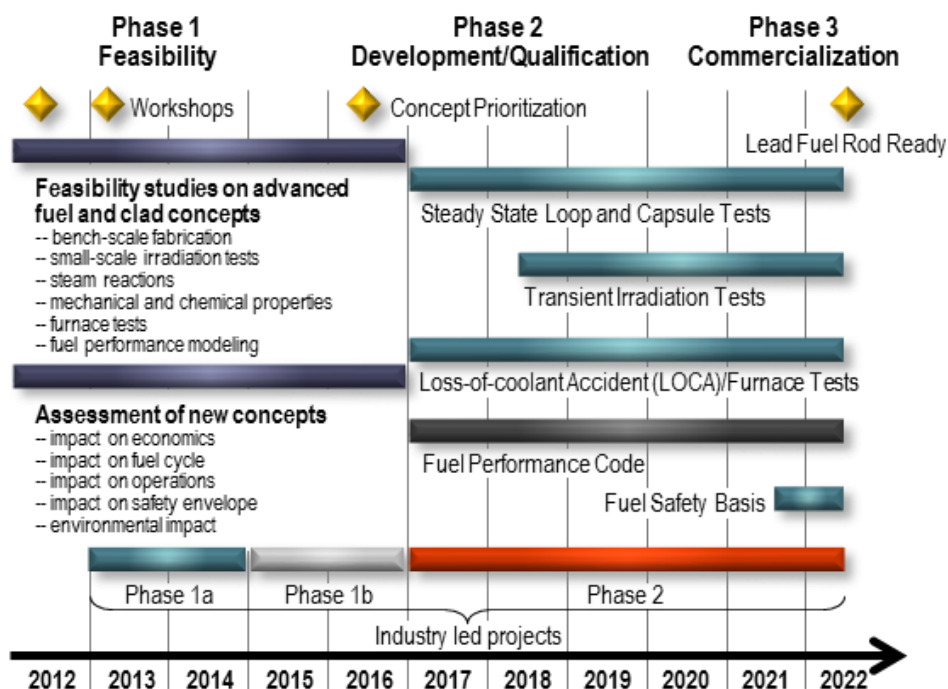


Figure 1. RD&D Strategy for Enhanced Accident Tolerant Fuels – 10 Year Goal [1].

1.1 Advanced Test Reactor Description

ATR has a unique core configuration and offers 77 possible irradiation positions, including a pressurized water loop designed specifically for RD&D experiment testing in the ATR Center Flux Trap (CFT).

Figure 2 identifies the Small-I Positions utilized to irradiate ATF-1 capsules.

The irradiation environment for the drop-in capsule experiment assemblies is the ATR PCS. ATR PCS is clean water sampled three times per day and maintained at a slightly acidic pH of 5.0-5.3. Chlorides are controlled to <0.1 ppm (normal <0.05 ppm). Normal Gross Beta-Gamma activity is <0.16 $\mu\text{Ci/ml}$. Control of pH, solids, and chlorides is maintained using ion exchange columns, filters, and chemistry control additives within the system boundaries.

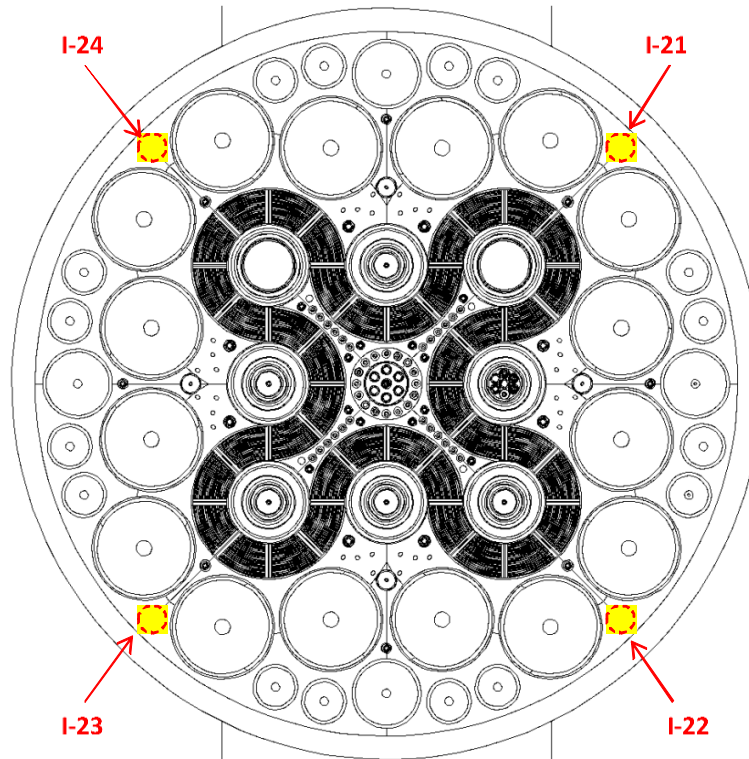


Figure 2. ATR Cross Section Showing Location of the Small I Positions (I-21, I-22, I-23, I-24) Designated for the ATF-1 Experiments.

1.2 Experiment Description

The irradiation experiment assembly loaded into the ATR consists of the basket, top spacer, and seven vertically-stacked capsule assemblies and/or dummies in each of the three channels (for a total of twenty-one (21) capsules/dummies per basket). The capsule used in the experiment provides the pressure boundary for the experimental materials located within. In the event of a rodlet cladding failure, the stainless steel (316L) capsule prevents fission products from entering the ATR PCS. The test rodlet is intended to represent a miniature length PWR fuel rod, nominally prototypic in the radial dimension. For the ATF-1 irradiation test series, the test rodlet generally contains fuel in the form of pellets or slices, holdown springs, insulator pellets, and a gas plenum. The rodlets were fabricated from various cladding materials and fuel forms outlined in the test matrix shown in Table 1. A typical ATF-1 capsule and rodlet assembly is shown in Figure 3 below. The basket of the experiment assembly maintains the capsule assembly configuration within the ATR. The current basket design is an aluminum three-hole basket with additional flux wire monitor channels as displayed in Figure 4 and Figure 5. Figure 6 identifies the basket channel numbering scheme for capsule and flux monitor wire insertion.

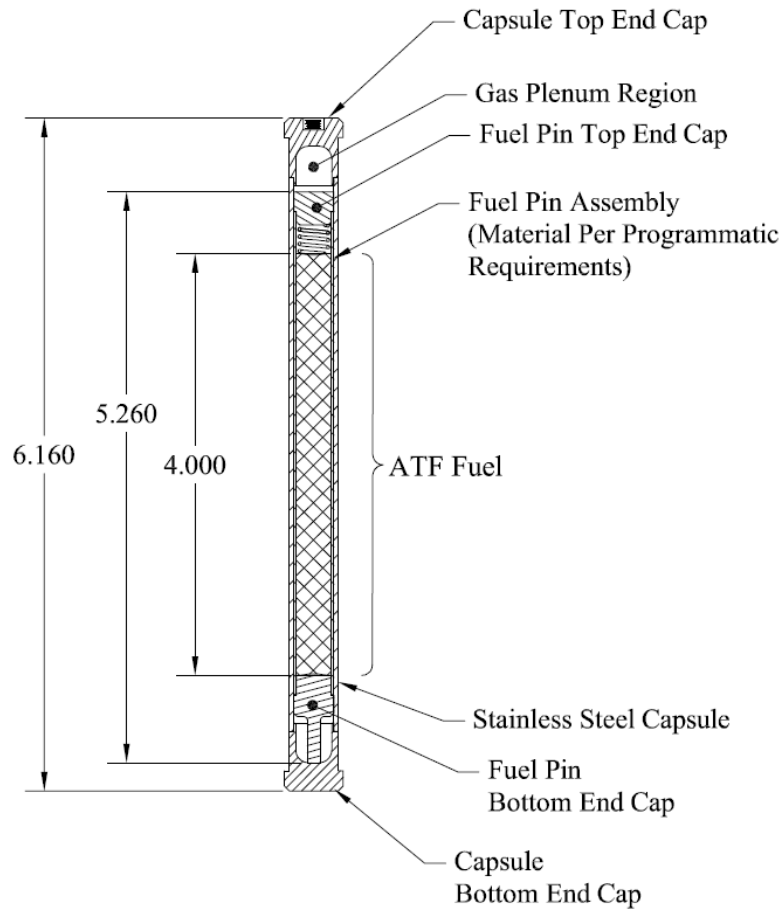


Figure 3. ATF-1 Capsule and Rodlet Assembly.

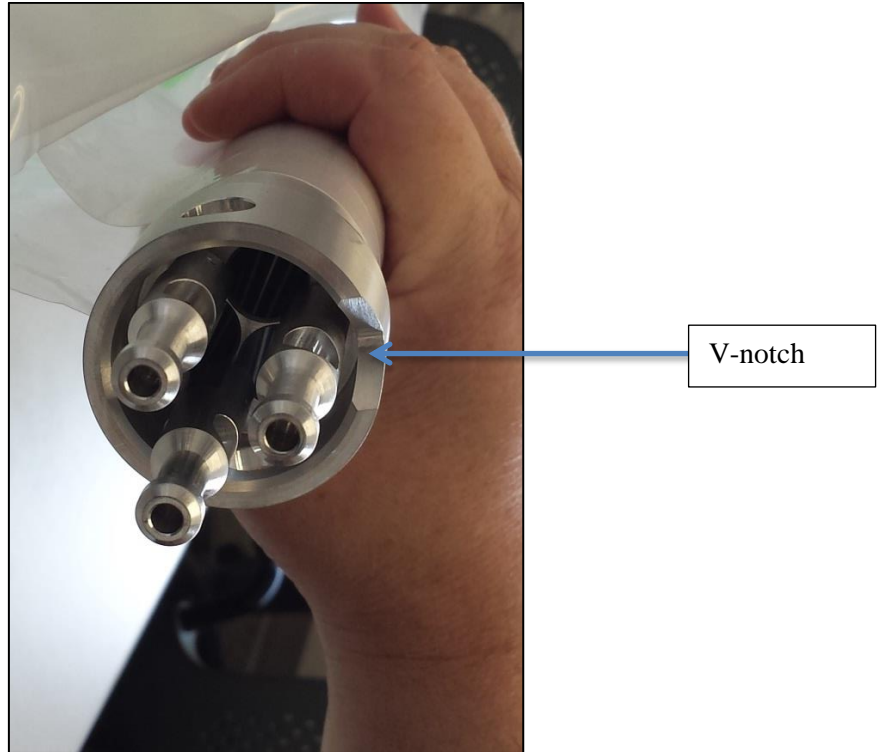


Figure 4. ATF-1 basket loaded with flux wire holders showing V-notch, which is oriented toward core centerline during core insertion.

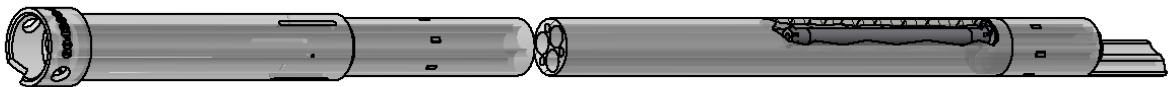


Figure 5. Cutaway and Cross-cut of ATF-1 Basket.

The cross-cut towards the center of the basket depicted in Figure 5 clearly shows the three capsule channels and the much smaller three flux monitor wire channels. An ATF-1 capsule loaded into the basket can be seen via the cutaway portion of the figure.

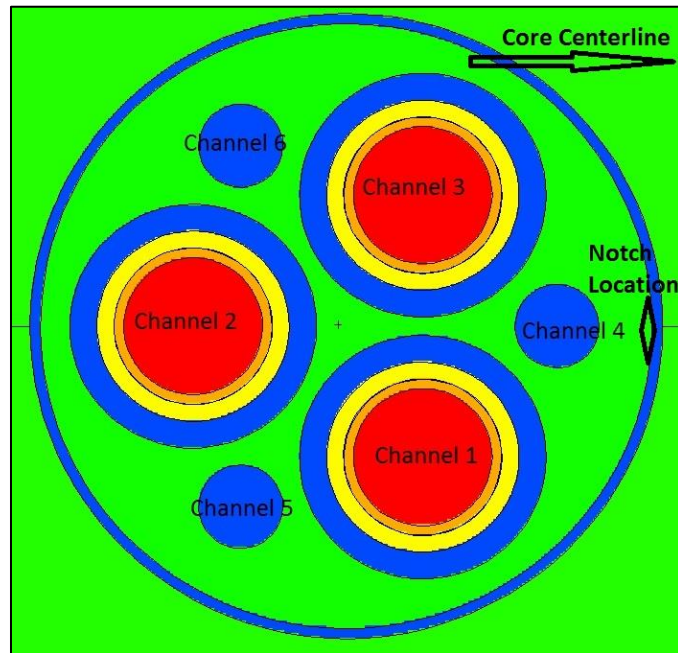


Figure 6. ATF Basket Channel Numbering System Diagram.

Figure 6 shows the v-notch of the top of the basket which is always directed toward core centerline. Capsule channels are 1, 2, and 3. Flux monitor wire channels are 4, 5, and 6.

2. ATF-1 IRRADIATION TESTING

2.1 Capsule Fabrication and Irradiation Status

The fabrication of the initial ATF-1 experiments deemed “1A” was completed in FY 2015. Additional fueled specimens, referred to as the “1B” experiments, were fabricated and delivered to the ATR during FY 2016. In FY 2017, three Oak Ridge National Lab-Fuel-Cladding Chemical Interaction (ORNL-FCCI) rodlets were encapsulated (Figure 7) and delivered to the ATR. A summary and irradiation status of all ATF-1 capsules are provided in Table 1. This table details the specific design concept for each capsule as well as the organization of the concept’s lead.

Table 1. Summary and Status of ATF-1 Capsules.

Capsule ID	Concept Lead	Fuel Type	Cladding Type	ATR Insertion Cycle	Status
ATF-00	AREVA ^b	UO ₂	Zirc-4	157C-1	PIE Complete
ATF-01	AREVA	UO ₂	Zirc-4	157C-1	In Irradiation
ATF-02	AREVA	UO ₂ +SiC	Zirc-4	157C-1	In Irradiation
ATF-03	AREVA	UO ₂ +SiC	Zirc-4	157C-1	PIE Complete
ATF-04	AREVA	UO ₂ +Diamond	Zirc-4	157C-1	PIE Complete
ATF-05	AREVA	UO ₂ +Diamond	Zirc-4	157C-1	In Irradiation
ATF-06	GE	UO ₂	Alloy-33 (UNS R200033)	157C-1	PIE
ATF-07	GE	UO ₂	Alloy-33 (UNS R200033)	157C-1	In Irradiation
ATF-08	GE	UO ₂	APMT (FeCrAl Alloy)	157C-1	PIE
ATF-09	GE	UO ₂	APMT (FeCrAl Alloy)	157C-1	In Irradiation
ATF-10	Westinghouse	U ₃ Si ₂	ZIRLO	157C-1	PIE
ATF-11	Westinghouse	U ₃ Si ₂	ZIRLO	157D-1	In Irradiation
ATF-12	Westinghouse	U ₃ Si ₂	ZIRLO	157C-1	In Irradiation
ATF-13	Westinghouse	U ₃ Si ₂	ZIRLO	157C-1	PIE Complete
ATF-14	Westinghouse	U ₃ Si ₂	ZIRLO	157C-1	In Irradiation
ATF-15	Westinghouse	U ₃ Si ₂	ZIRLO	157C-1	PIE
ATF-17	ORNL	UO ₂	FeCrAl Alloy	157D-1	In Irradiation
ATF-18	ORNL	UO ₂	FeCrAl Alloy	157C-1	PIE Complete
ATF-20	ORNL	UO ₂	FeCrAl Alloy	157C-1	In Irradiation
ATF-29	Westinghouse	UN-U ₃ Si ₂	ZIRLO	160A-1	In Irradiation
ATF-30	Westinghouse	UN-U ₃ Si ₂	ZIRLO	160A-1	PIE
ATF-31	Westinghouse	UN-U ₃ Si ₂	ZIRLO	160A-1	In Irradiation
ATF-32	Westinghouse	UN-U ₃ Si ₂	ZIRLO	160A-1	In Irradiation
ATF-33	Westinghouse	UN-U ₃ Si ₂	ZIRLO	160A-1	In Irradiation
ATF-34	Westinghouse	UN-U ₃ Si ₂	ZIRLO	160A-1	PIE
ATF-41	LANL	UN-U ₃ Si ₅	Kanthal-AF (FeCrAl Alloy)	160A-1	PIE
ATF-44	LANL	UN-U ₃ Si ₅	Kanthal-AF (FeCrAl Alloy)	160B-1	PIE
ATF-45	LANL	U ₃ Si ₅	Kanthal-AF (FeCrAl Alloy)	160A-1	PIE
ATF-73	ORNL	UO ₂	FeCrAl Alloy ^a	160B-1	PIE Complete
ATF-74	ORNL	UO ₂	FeCrAl Alloy ^a	160B-1	In Irradiation
ATF-75	ORNL	UO ₂	FeCrAl Alloy ^a	160B-1	In Irradiation

a. These rodlets contain multiple fuel cladding chemical interaction experiments. The rodlet is Type 304 Stainless Steel, but small FeCrAl coins lie next to fuel slices inside of the rodlet.

b. In January 2018, the AREVA NP subsidiary holding the AREVA group’s nuclear reactor operations has been renamed Framatome. Despite this name change, the name AREVA is used throughout this report.



Figure 7. As-Fabricated ORNL-FCCI ATF-1 Capsules.

2.2 FY 2015 ATF-1 Irradiation Testing

Seventeen (17) capsules were shipped to the ATR in January 2015 for initial irradiation testing in Cycle 157C-1, and two (2) additional capsules were shipped to ATR in May 2015 for initial insertion in Cycle 157D-1. As shown in Figure 1, Phase 1 of the ATF program is associated with the development (Phase 1a) and assessment (Phase 1b) of different fuel system concepts. These capsule insertions were consistent with the development plan to support commercial demonstration of ATF concepts by 2022.

In FY 2015, the ATR ran for 2 cycles, 157C-1 and 157D-1. Cycle 157C-1 reached full power on February 10, 2015 and ran for 5.4 Effective Full-Power Days (EFPD), followed by a long maintenance outage (179 days) to replace a leaking in-pile tube and to upgrade ATR to use off-site generated commercial power rather than on-site diesel generated power. Cycle 157D-1 reached full power on May 29, 2015, had a mid-cycle SCRAM on July 23, 2015 due to valve operational issues, then reached full power again on August 6, 2015, and ran until August 12, 2015. The Cycle 158A-1 outage lasted longer than scheduled due to issues in completing reactor physics calculations and an extent of condition assessment of leaking valves.

2.3 FY 2016 ATF-1 Irradiation Testing

In FY 2016, the ATR ran for three complete cycles, 158A-1, 158B-1, and 159A-1, with an additional cycle, 160A-1, scheduled to begin prior to the end of FY 2016. Cycle 158A-1 reached full power on November 11, 2015, and ran for 52.2 EFPD. Cycle 158B-1 reached full power on February 9, 2016, and ran until April 1, 2016, yielding 51.4 EFPD. The ATF-1 experiments remained in the ATR during the Powered Axial Locator Mechanism (PALM) Cycle 159A-1. PALM cycles can operate at higher lobe powers relative to traditional ATR cycles. Cycle 159A-1 operated with the higher powers in the south lobes, and lower powers in the north lobes of ATR. The ATF-1 experiments in the I-21 and I-24 positions

of ATR operated at the lower northeast (NE) and northwest (NW) lobe powers and saw an additional 7.51 EFPD during this cycle. Cycle 159A-1 ran from June 17, 2016, to June 28, 2016, including a mid-cycle shutdown during June 23 through June 27.

Eight (8) capsules were shipped to ATR in July 2016 for initial irradiation testing in Cycle 160A-1. These eight capsules included six (6) Westinghouse “1B” experiments along with two (2) Los Alamos National Lab (LANL)-led capsules.

Additionally, in FY 2016, the experiment completed an AFC Level 3 milestone on February 29th by shipping the first set of irradiated ATF-1 capsules from the ATR to the MFC’s Hot Fuels Examination Facility (HFEF) to begin PIE. As shown in Table 1, three capsules from AREVA’s ATF-1 campaign (ATF-00, ATF-03, and ATF-04) are currently undergoing PIE.

2.4 FY 2017 ATF-1 Irradiation Testing

In FY 2017, the ATR ran for three complete cycles, 160A-1, 160B-1, and 161A-1, with an additional cycle, 162A-1, scheduled to begin prior to the end of FY 2017. Cycle 160A-1 reached full power on September 16, 2016 and ran for 52.7 EFPD, concluding operation on November 8, 2016 [2]. Cycle 160B-1 reached full power on December 20, 2016 [2], and ran until a mid-cycle SCRAM occurred on January 18, 2017. This outage continued for roughly 5.5 days and the reactor returned to operation on January 24, 2017. The shutdown of Cycle 160B-1 occurred on February 23, 2017, yielding a cumulative 59.5 EFPD for the cycle. A subset of ATF-1 experiments remained in the ATR during the PALM Cycle 161A-1 (the ATF-1 experiments in the I-23 lobe were removed for high power SW lobe operation). Due to the placement of this subset in the ATR, the experiments did not experience the high reactor lobe powers typically associated with PALM cycles and saw an additional 12.82 EFPD during this cycle. Cycle 161A-1 ran from May 30, 2017 to June 11, 2017 [3].

Four (4) additional capsules, including one (1) LANL-led capsule and three (3) ORNL-FCCI capsules were shipped to the ATR in the first quarter of FY 2017, bringing the total number of “1B” ATF-1 experiments fabricated and inserted into the ATR to twelve (12). These four (4) additional capsules began irradiation in Cycle 160B-1. The completion of the 1B insertions equates to a total of thirty-one (31) ATF-1 capsules fabricated by the program and inserted into the ATR for irradiation testing.

The experiment team built upon earlier successes in irradiated capsule shipments by shipping three (3) irradiated capsules (ATF-13, ATF-15, and ATF-18) from ATR to HFEF on February 21, 2017. The completion of this activity resulted in meeting an AFC Level 3 milestone to ship low-burnup Westinghouse-1A capsules to HFEF. Table 1 now indicates that two (2) Westinghouse-1A capsules and one (1) ORNL capsule are undergoing PIE, along with the three (3) capsules in AREVA’s ATF-1 campaign currently undergoing PIE.

2.5 FY 2018 ATF-1 Irradiation Testing

In FY 2018, the ATR ran for four complete cycles, 162A-1, 162B-1, 163A-1, and 164A-1, with an additional cycle, 164B-1, started just prior to the end of FY 2018. Cycle 162A-1 reached full power on October 6, 2017 and ran for 62 EFPD, concluding operation on December 7, 2017 [11]. Cycle 162B-1 reached full power on February 16, 2017 [13], and ran until a mid-cycle SCRAM occurred on March 9, 2018. This outage continued for roughly 2.5 days and the reactor returned to operation on March 12, 2018. The shutdown of Cycle 162B-2 occurred on March 29, 2018, yielding a cumulative 37 EFPD for the cycle. For the PALM Cycle 163A-1, all ATF-1 experiments were removed from the ATR to avoid the high reactor lobe powers normally experienced with a PALM cycle. Cycle 163A-1 ran from April 30, 2018 to May 8, 2018. Cycle 164A-1 reached full power on June 12, 2018 and ran until a mid-cycle SCRAM occurred on June 24, 2018. This outage continued for approximately 9.5 days and the reactor returned to operation on July 3, 2018. Cycle 164A-1Xe reached full power on July 3, 2018 and ran until another mid-cycle SCRAM occurred on July 30, 2018. This outage continued for approximately 3.1 days and the reactor returned to operation on August 2, 2018. The shutdown of Cycle 164A-1Xe2

occurred on August 17, 2018, yielding a cumulative 54 EFPD for the cycle [15]. Cycle 164B-1 reached full power on September 19, 2018.

No additional capsules were fabricated in FY 2018. The total number of ATF-1 capsules remains thirty-one (31) fabricated by the program and inserted into the ATR for irradiation testing.

The experiment team shipped four (4) irradiated capsules (ATF-6, ATF-8, ATF-45, and ATF-73) from ATR to HFEF on March 22, 2018. The completion of this activity resulted in meeting the Level 3 milestone of the third shipment of irradiated ATF-1 capsules from ATR to MFC (HFEF). Table 1 now indicates that three (3) AREVA-1A capsules have now completed PIE, two (2) GE-1B capsules, one (1) LANL-1 capsule, and one (1) ORNL-FCCI capsule are now in PIE, along with two (2) Westinghouse-1A capsules and one (1) ORNL-Loss of Coolant Accident (LOCA) capsule already undergoing PIE.

2.6 FY 2019 ATF-1 Irradiation Testing

In FY 2019, the ATR ran for nearly three complete cycles, 164B-1/Xe1/Xe2, 165A-1/Xe1, and 166A-1/2, with the last cycle, 166A-2, nearly finishing at the end of FY 2019. Cycle 164B-1 reached full power on September 19, 2018 and ran until a mid-cycle SCRAM occurred on October 15, 2018. This outage continued until October 24, 2018, when the reactor returned to operation. The reactor experienced an additional mid-cycle SCRAM on November 4, 2018. This outage continued until December 23, 2018, when the reactor returned to operation. The reactor completed the cycle January 17, 2019, yielding a cumulative 63 EFPD for the cycle. For the PALM Cycle 165A-1, all ATF-1 experiments were removed from the ATR to avoid the high reactor lobe powers normally experienced with a PALM cycle. Cycle 165A-1 reached full power March 1, 2019, experienced a mid-cycle SCRAM on March 3, 2019, and went into a long outage period. The reactor again reached full power June 8, 2019 and completed the cycle June 20, 2019. Cycle 166A-1 reached full power on July 25, 2019 and ran until a mid-cycle SCRAM occurred on September 6, 2019. This outage continued until September 17, 2019, when the reactor returned to operation. Cycle 166A-2 is anticipated to conclude October 5, 2019, and is expected to yield a cumulative 63 EFPD for the cycle.

No additional capsules were fabricated in FY 2019. The total number of ATF-1 capsules remains thirty-one (31) fabricated by the program and inserted into the ATR for irradiation testing.

The experiment team shipped five (5) irradiated capsules (ATF-41, ATF-10, ATF-30, ATF-34, and ATF-44) from ATR to HFEF on April 22, 2019. The completion of this activity resulted in meeting the Level 3 milestone of the fourth shipment of irradiated ATF-1 capsules from ATR to MFC (HFEF). Table 1 now indicates additionally that one (1) Westinghouse Electric Co., LLC (WEC)-1A capsule, one (1) ORNL-LOCA capsule, and one (1) ORNL FCCI capsule have now completed PIE, one (1) WEC-1A capsule, two (2) WEC 1B capsules, and two (2) LANL 1 capsules are now in PIE.

2.7 ATF-1 Cycle Specific Physics Analysis

The ATF-1 Experiment Safety Analysis (ESA) requires basket loading specific physics calculations to verify that the ATF-1 experiments meet the ESA safety limits (see Table 2 for list of ATF-1 ESA safety limits). The ATF-1 basket loading specific fuel heat generation rates, burnup, U-235 equivalent mass, and fuel radionuclide inventory in the ATF-1 experiment ATR positions are calculated using the MCNP full core physics model and ORIGEN2 model. The capsule estimated internal pressure (if a rodlet were to breach) is calculated based on fissile material burnup. The experiment as-run analysis is calculated at the end of each irradiation cycle, and the projections for the next cycle are calculated at the same time. Both are documented in Engineering Calculations and Analysis Reports (ECARs).

Table 2. ATR Safety Parameters for the ATF-1 Experiments,4].

ATR Safety Parameters	Limit
Maximum LHGR for Fuel Specimens Including: - 5.0% Maximum Lobe Power - 8.5% Instrumentation uncertainty - OSCC effects	650 W/cm
Maximum FME	365.0 g
Maximum Capsule Internal Pressure Limit	800 psi
Maximum Experiment Assembly Total Radionuclide Inventory for Fuel Specimens	5.65E7 Ci

2.8 ATF-1 As-Run Results to Date

Neutronics analyses have been performed over the last five fiscal years to document the ATR Cycle as-run results for the ATF-1 capsules. In FY 2017, these results were consolidated into one document, providing a single-source of information for all downstream users [2]. This document will be revised and appended for each subsequent ATR cycle. Results are distributed via letter or reports such as this, and the raw ATF-1 as-run data are available electronically on the ATF Nuclear Data Management and Analysis System (NDMAS) collaboration site.

Generally speaking, the as-run and projection analyses [3,5,6,7,9,11,13,15,17] are executed by creating an MCNP model and applying the power information from the ATR power history letter [8] to calculate the Linear Heat Generation Rate (LHGR) for specific time-steps and the fuel burnup in GWd/MTU for each cycle. Analyses for subsequent cycles followed a similar approach. When as-run data are not found in any of the referenced ECARs, the data are already documented in the ATF-1 Power Histories [2]. Table 3 shows the ATR power and operating history beginning with the initial ATF-1 insertion cycle.

Table 3. ATR Operational History with ATF-1 Experiments Inserted [8].

Cycle	Average Lobe Powers (MegaWatts)					Effective Full Power Days
	NW	NE	C	SW	SE	
157C-1	18.0 ^a	17.0 ^a	21.1	20.1	25.0	5.4
157D-1	18.0 ^a	17.0 ^a	21.6	20.9	25.0	59.7
158A-1	18.0 ^a	19.0 ^a	21.3	20.0	27.0	52.2
158B-1	18.0 ^a	19.0 ^a	19.0	22.7	23.0	51.4
159A-1	22.1 ^a	22.9 ^a	29.1	37.4	35.0	3.1
160A-1	17.5 ^a	21.1 ^a	19.8	20.0 ^a	26.1	52.7 [9]
160B-1	18.0 ^a	21.0 ^a	20.9	23.0 ^a	25.6	59.5 [9]
161A-1	18.0 ^a	20.9 ^a	30.6	42.7	41.5	12.82
162A-1	20.1 ^a	17.9 ^a	22.8	24.0 ^a	26.2	61.9
162B-1	20.0 ^a	14.5 ^a	19.2	23.9 ^a	23.0	38.51
164A-1	20.0 ^a	16.0 ^a	19.4	22.4 ^a	25.7	54.91
164B-1	19.5	16.4	19.7	23.1 ^a	25.1 ^a	64.06

a. Denotes ATF-1 basket present in ATR lobe during cycle.

Using the results of the aforementioned neutronics analyses, thermal analyses were performed on the ATF-1 experiments to determine as-run and projected peak temperatures of the fuel and cladding [2,10,12,14,16,18]. Figure 8 through Figure 18 provide the as-run experiment peak temperatures of the cladding and fuel for each capsule. It is important to note that these temperatures are based on the best-estimate LHGR provided in the neutronics and thermal analyses and do not include uncertainties. Therefore, the temperatures plotted on the following figures may vary by +/- 13.5%. The total uncertainty in temperature is comprised of a 5% uncertainty in temperature associated with maximum lobe power and an 8.5% uncertainty in temperature associated with ATR instrumentation. It should also be noted, in Figure 8 through Figure 15 for Cycle 160B-1, a plotted temperature of 0 degrees C (due to mid-cycle reactor SCRAM) is not reflective of real conditions. The neutronics calculation would be 0 W/cm, but the experiment still experiences temperature effects from decay heat and reactor coolant temperature fluctuations.

Since achieving capsule-specific levels of burnup is also an objective for the ATF-1 series of experiments, the neutronics analyses mentioned above also calculate the burnup for each specific capsule. Table 4 describes the burnup targets and actuals for each capsule shown in Table 1. As discussed previously in this report, three AREVA capsules (ATF-00, ATF-03, and ATF-04), two GE-1B capsules (ATF-6 and ATF-8), three WEC-1A capsules (ATF-13, ATF-15, and ATF-10), one (1) ORNL-LOCA capsule (ATF-18), one (1) ORNL-FCCI capsule (ATF-73), three (3) LANL-1 capsules (ATF-45, ATF-41, and ATF-44), and two (2) WEC-1B capsules (ATF-30 and ATF-34) were agreed to have reached their burnup targets. The capsules were subsequently removed from the ATR and are either in post-irradiation cooldown or have been shipped to HFEF for post-irradiation examination (PIE). Figure 19 through Figure 25 show the capsule-specific burnup accrued through FY 2018 for all ATF-1 capsules. Figure 26 provides a notional schedule of irradiation and subsequent PIE activities for all ATF-1 concepts.

Table 4. Burnup Targets and Actuals (as of June 2019) for ATF-1 Capsules.

Capsule ID	Concept Lead	Burnup Target (GWd/MTU)	Burnup Actuals (GWd/MTU)
ATF-00 ^a	AREVA	10	8.4
ATF-01	AREVA	50	33.8
ATF-02	AREVA	50	31.9
ATF-03 ^a	AREVA	10	6.3
ATF-04 ^a	AREVA	10	9.0
ATF-05	AREVA	50	33.0
ATF-06 ^a	GE	20	18.4
ATF-07	GE	60	32.9
ATF-08 ^a	GE	20	18.3
ATF-09	GE	60	32.9
ATF-10 ^a	Westinghouse	20	21.4
ATF-11	Westinghouse	40	26.5
ATF-12	Westinghouse	70	27.5
ATF-13 ^a	Westinghouse	20	18.9
ATF-14	Westinghouse	70	38.3
ATF-15 ^a	Westinghouse	20	20.1
ATF-17	ORNL	30	23.6
ATF-18 ^a	ORNL	10	10.4
ATF-20	ORNL	50	23.8

Table 4. continued).

Capsule ID	Concept Lead	Burnup Target (GWd/MTU)	Burnup Actuals (GWd/MTU)
ATF-29	Westinghouse	20	13.7
ATF-30 ^a	Westinghouse	20	19.2
ATF-31	Westinghouse	40	20.4
ATF-32	Westinghouse	70	13.8
ATF-33	Westinghouse	70	19.2
ATF-34 ^a	Westinghouse	20	20.4
ATF-41 ^a	LANL	10	10.0
ATF-44 ^a	LANL	10	9.5
ATF-45 ^a	LANL	10	13.2
ATF-73 ^a	ORNL	10	8.7
ATF-74	ORNL	30	19.4
ATF-75	ORNL	50	19.3
a. Capsules have reached burnup target and are no longer undergoing irradiation.			

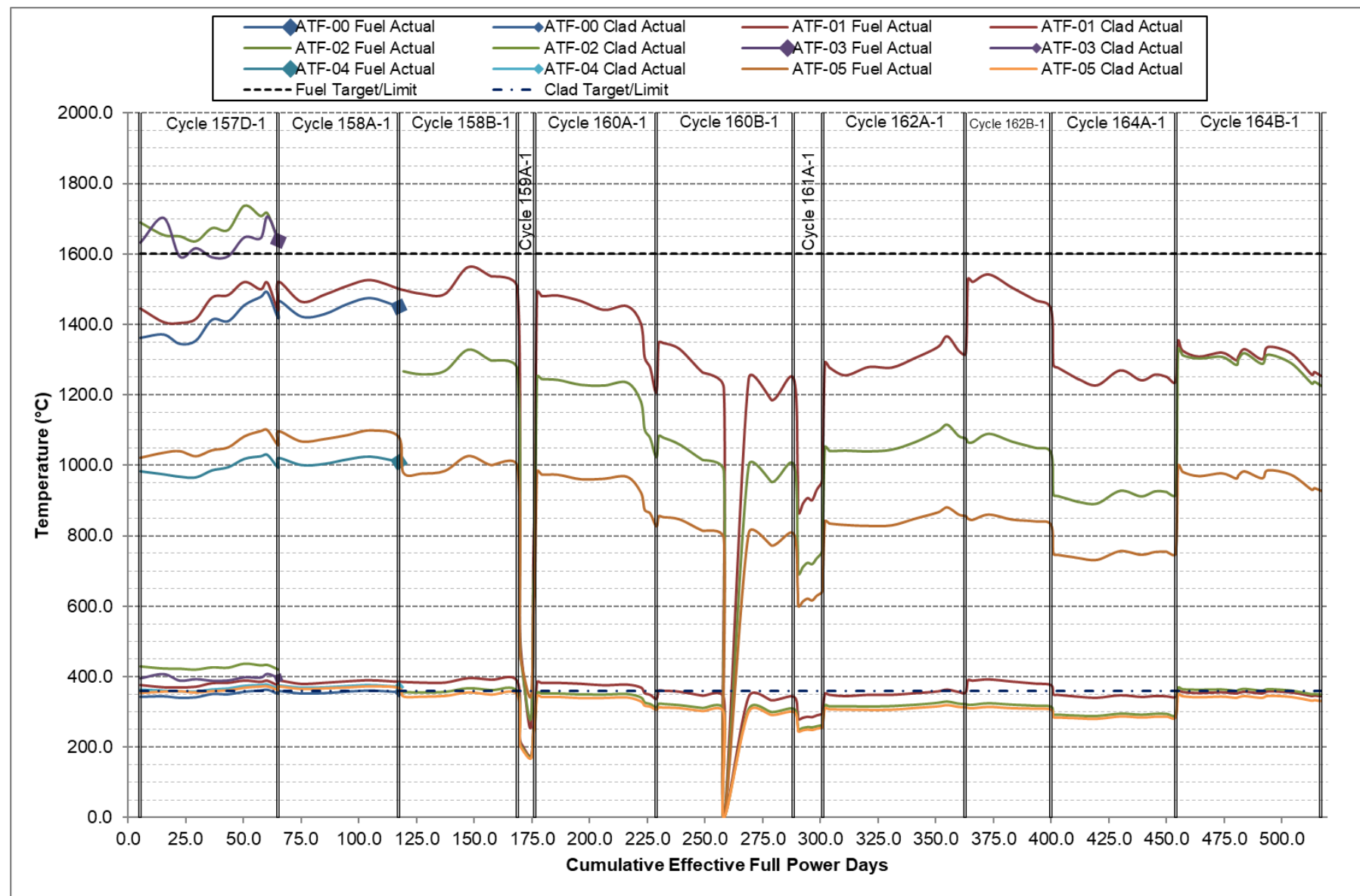


Figure 8. As-Run Experiment Temperatures of AREVA Capsules ATF-00 through ATF-05.

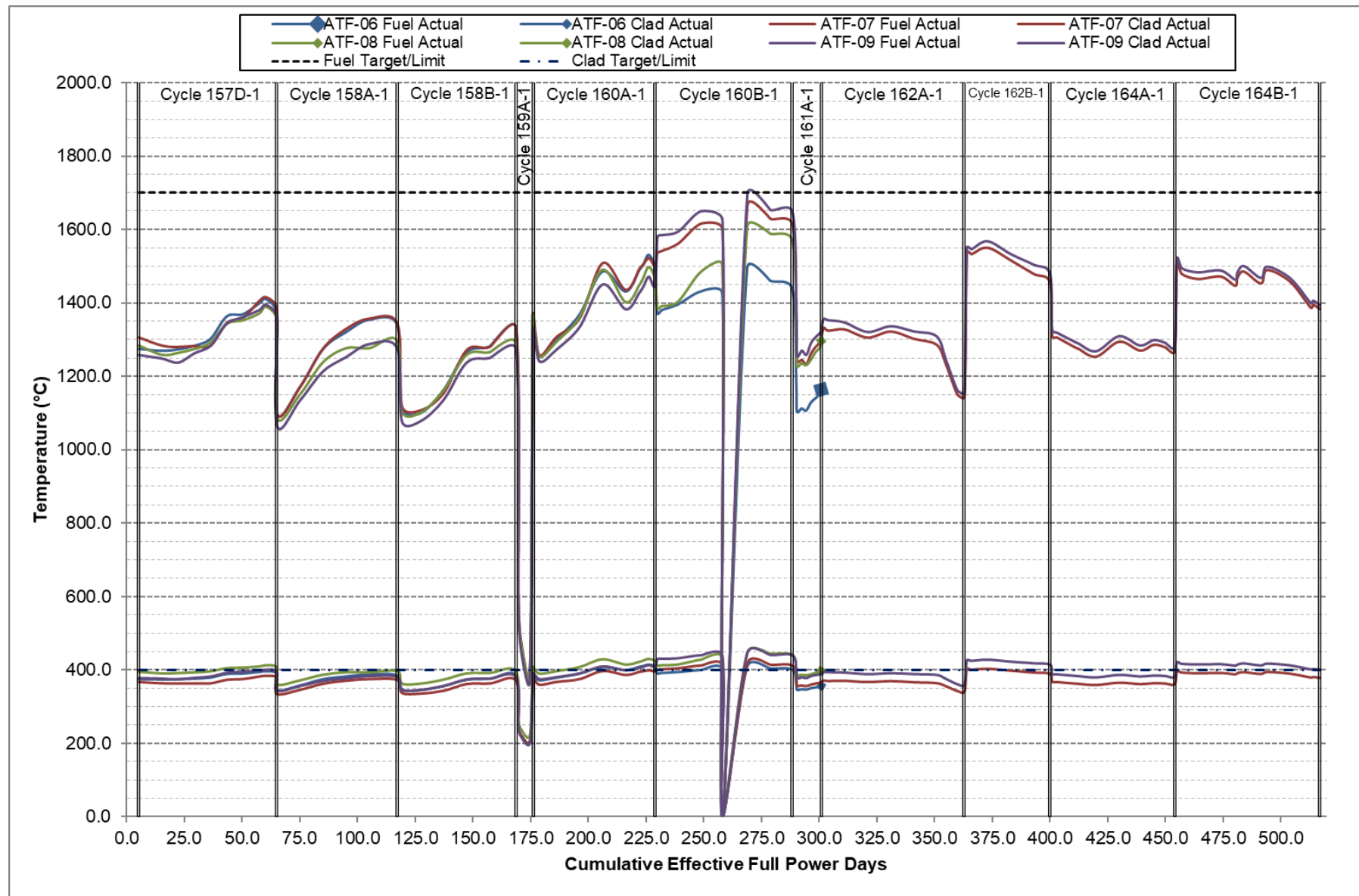


Figure 9. As-Run Experiment Temperatures of GE Capsules ATF-06 through ATF-09.

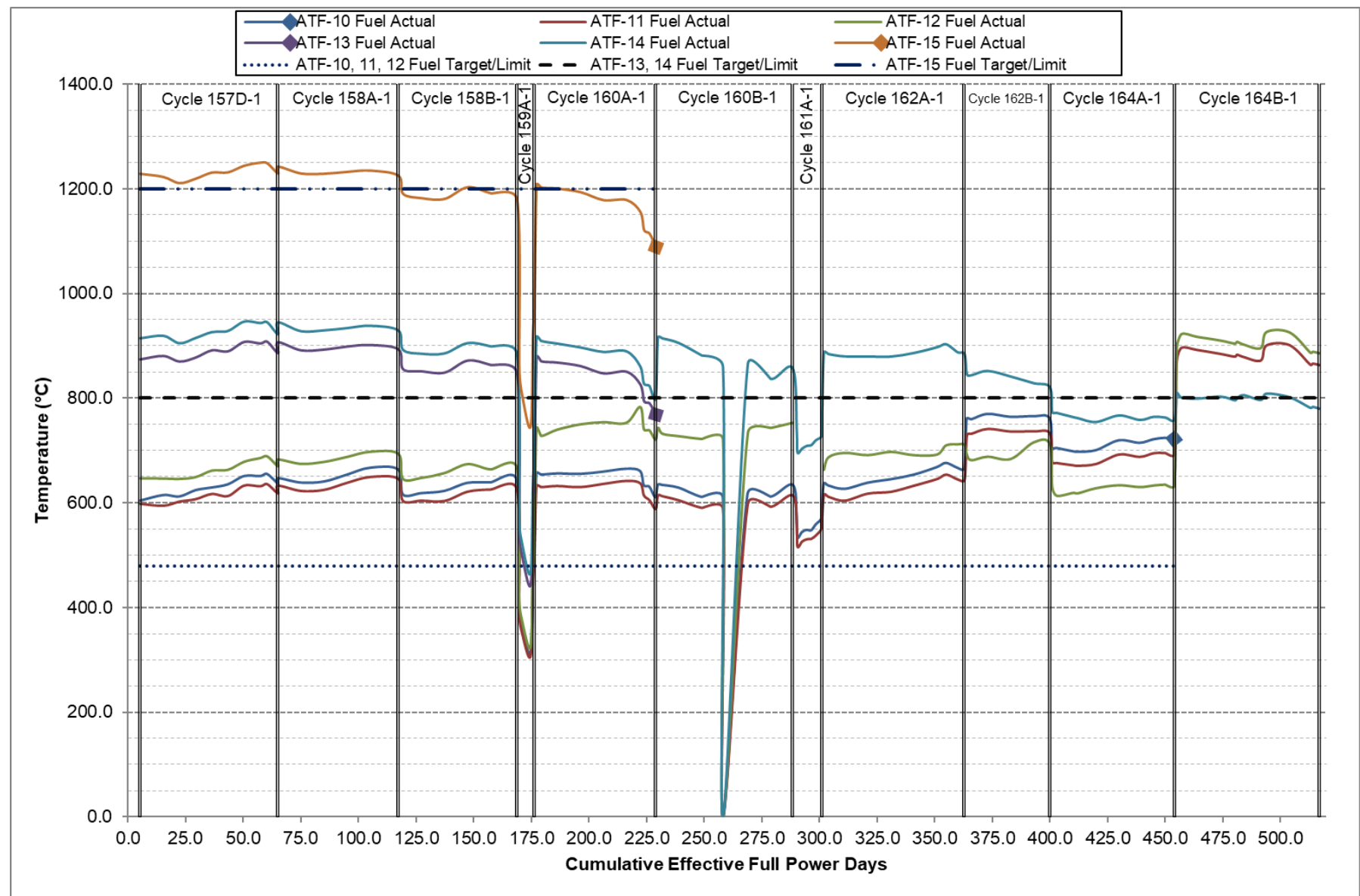


Figure 10. As-Run Fuel Temperatures of Westinghouse 1A Capsules ATF-10 through ATF-15.

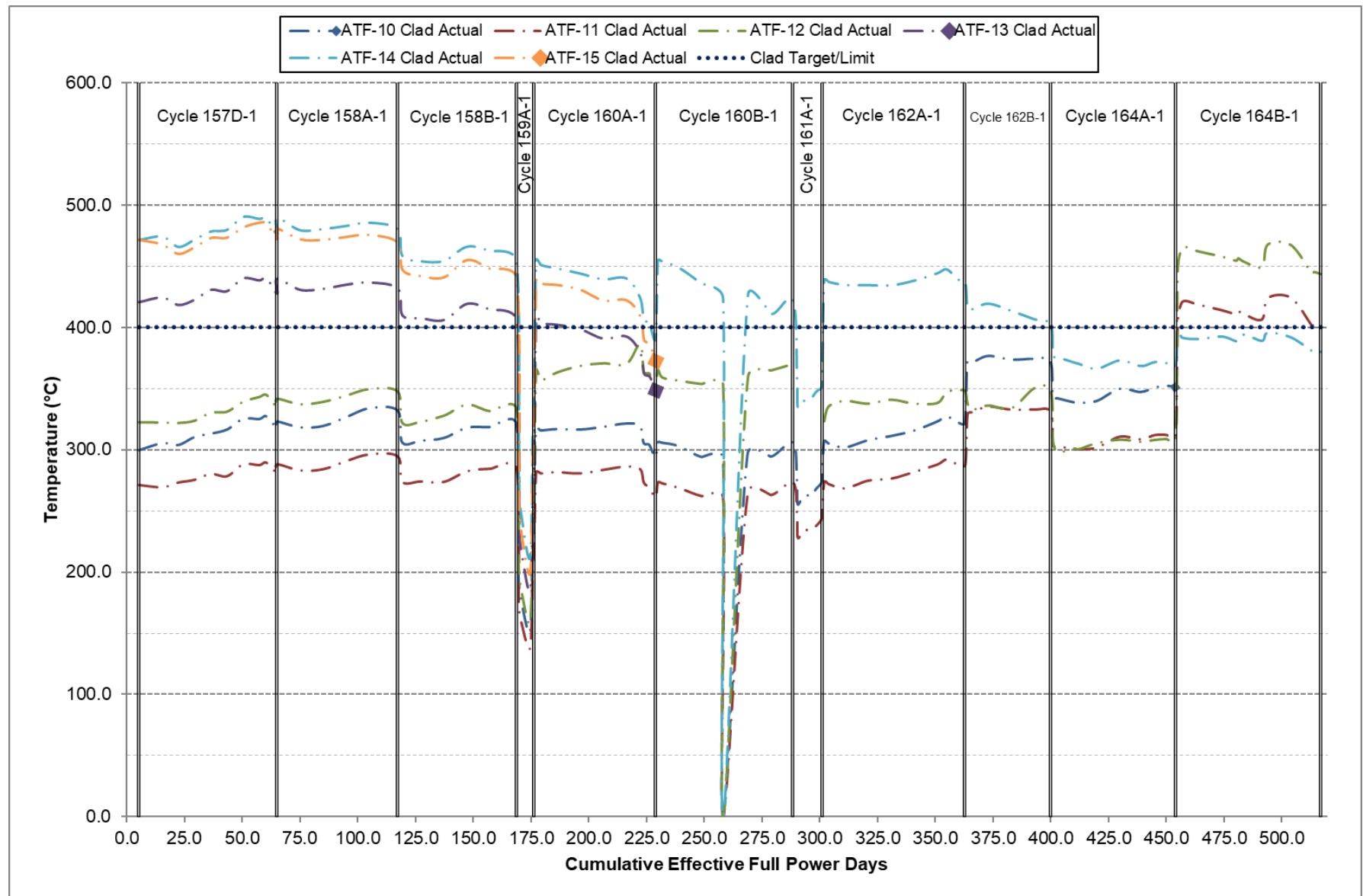


Figure 11. As-Run Cladding Temperatures of Westinghouse 1A Capsules ATF-10 through ATF-15.

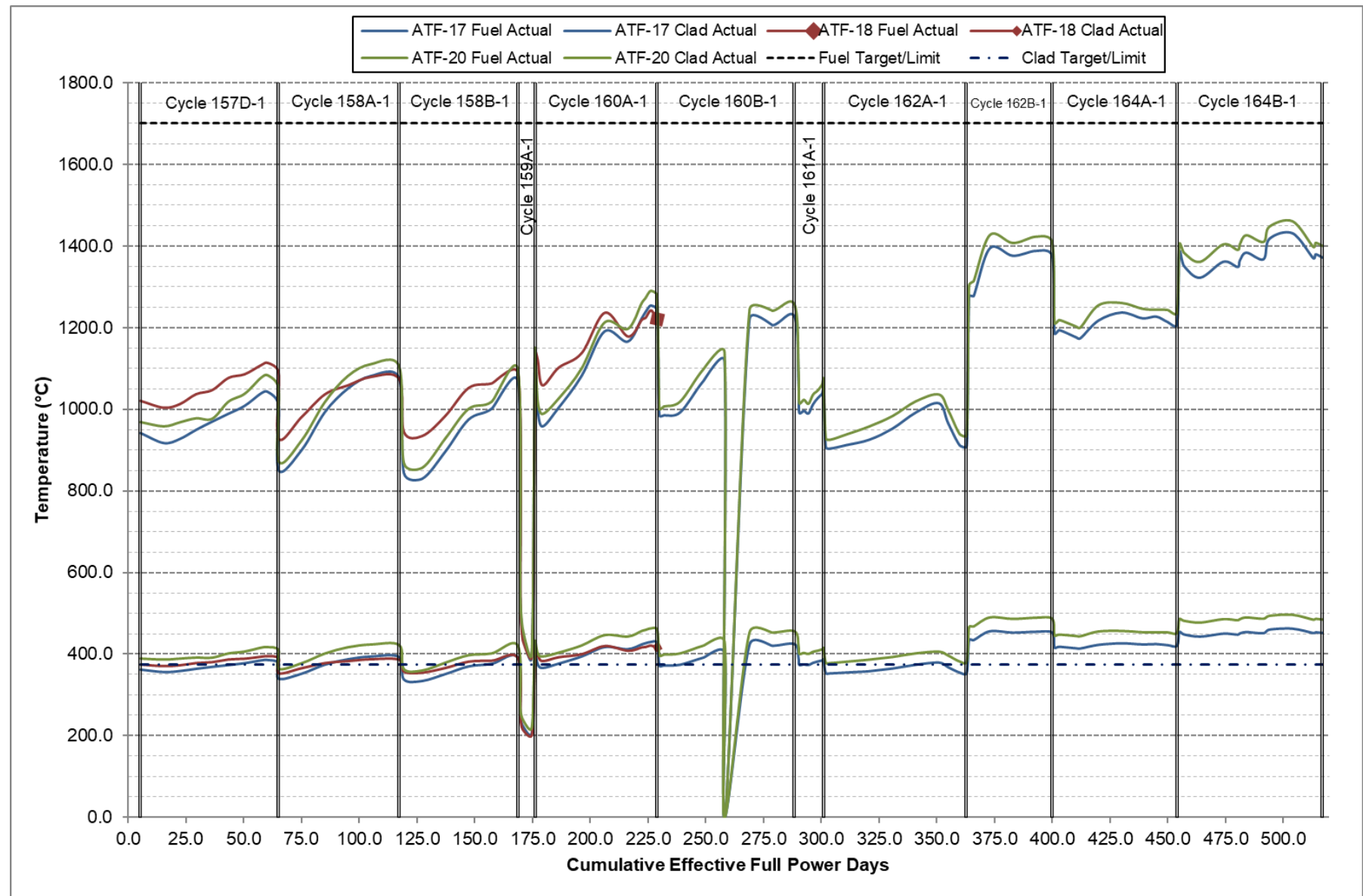


Figure 12. As-Run Experiment Temperatures of ORNL-LOCA Capsules ATF-17, 18, and 20.

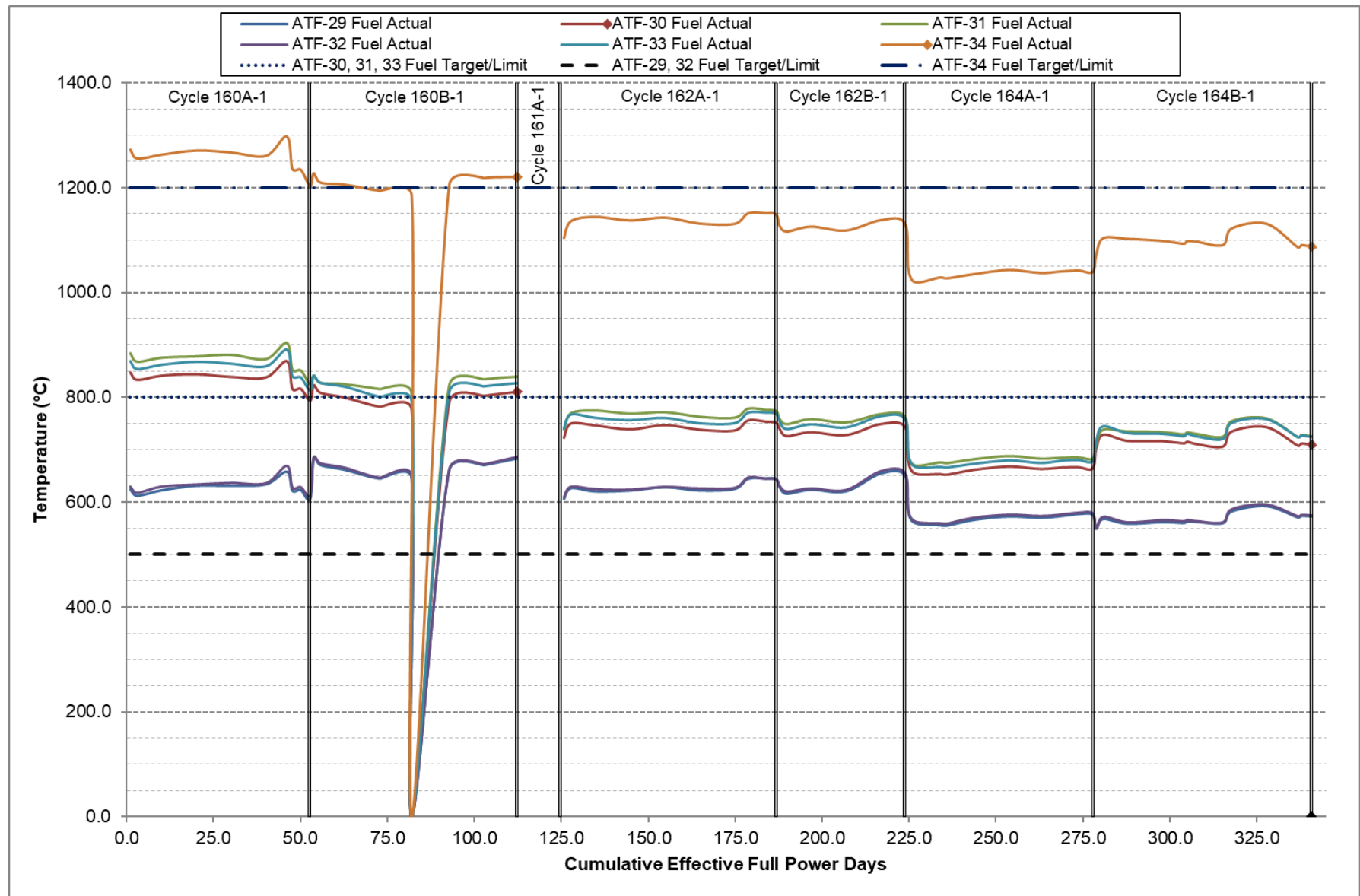


Figure 13. As-Run Fuel Temperatures of Westinghouse 1B Capsules ATF-29 through ATF-34.

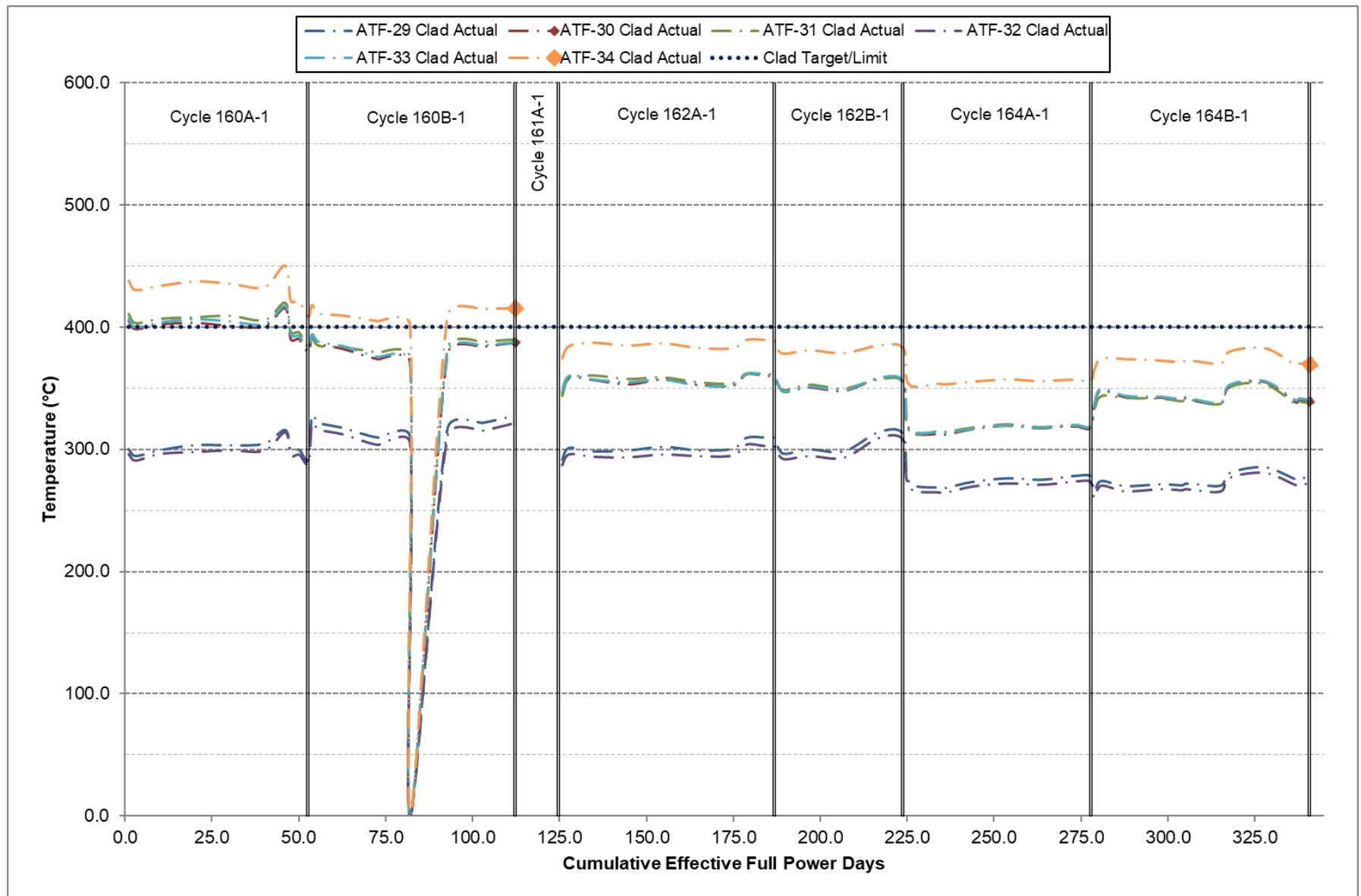


Figure 14. As-Run Cladding Temperatures of Westinghouse 1B Capsules ATF-29 through ATF-34.

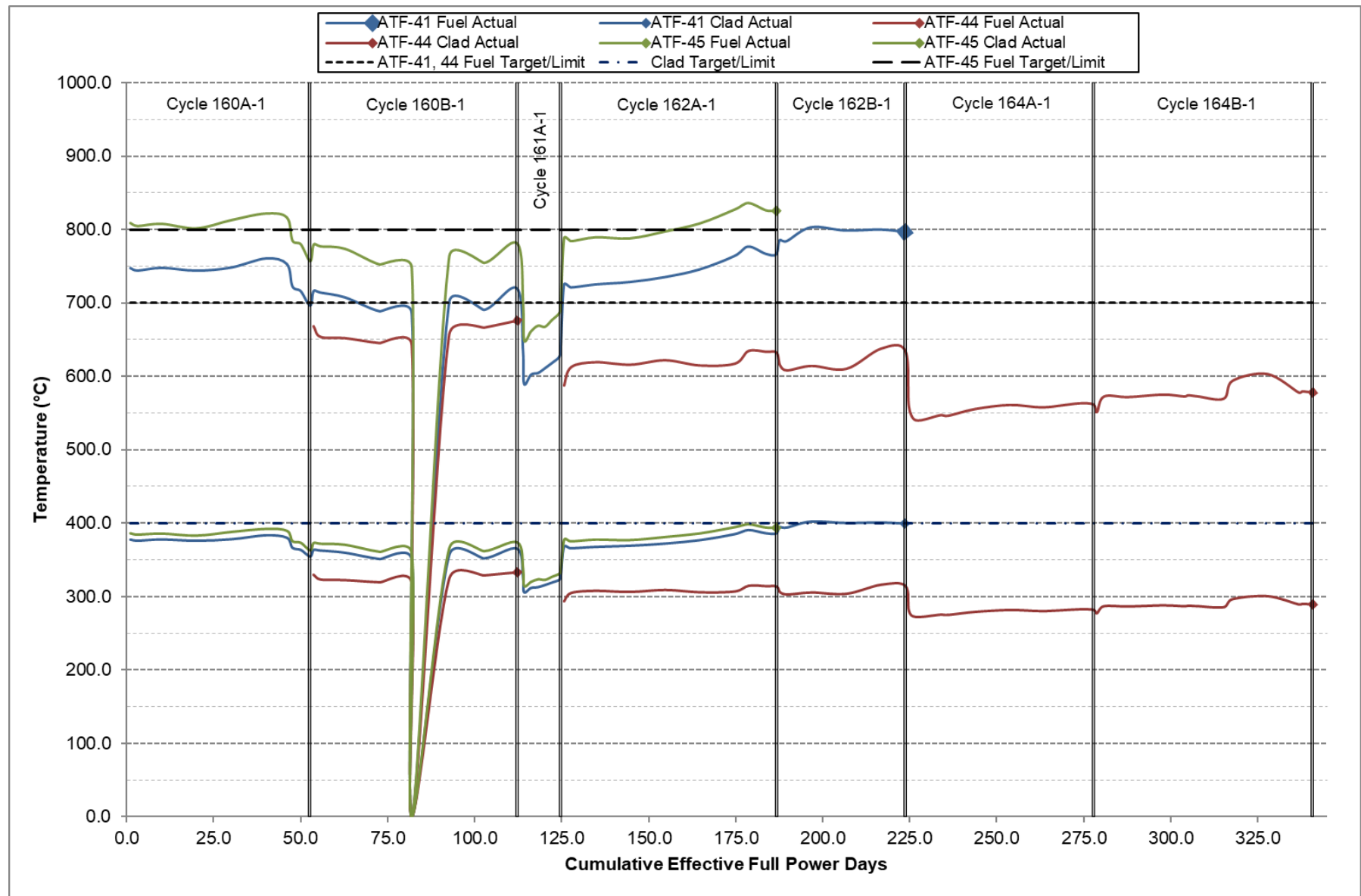


Figure 15. As-Run Experiment Temperatures of LANL Capsules ATF-41, 44, and 45.

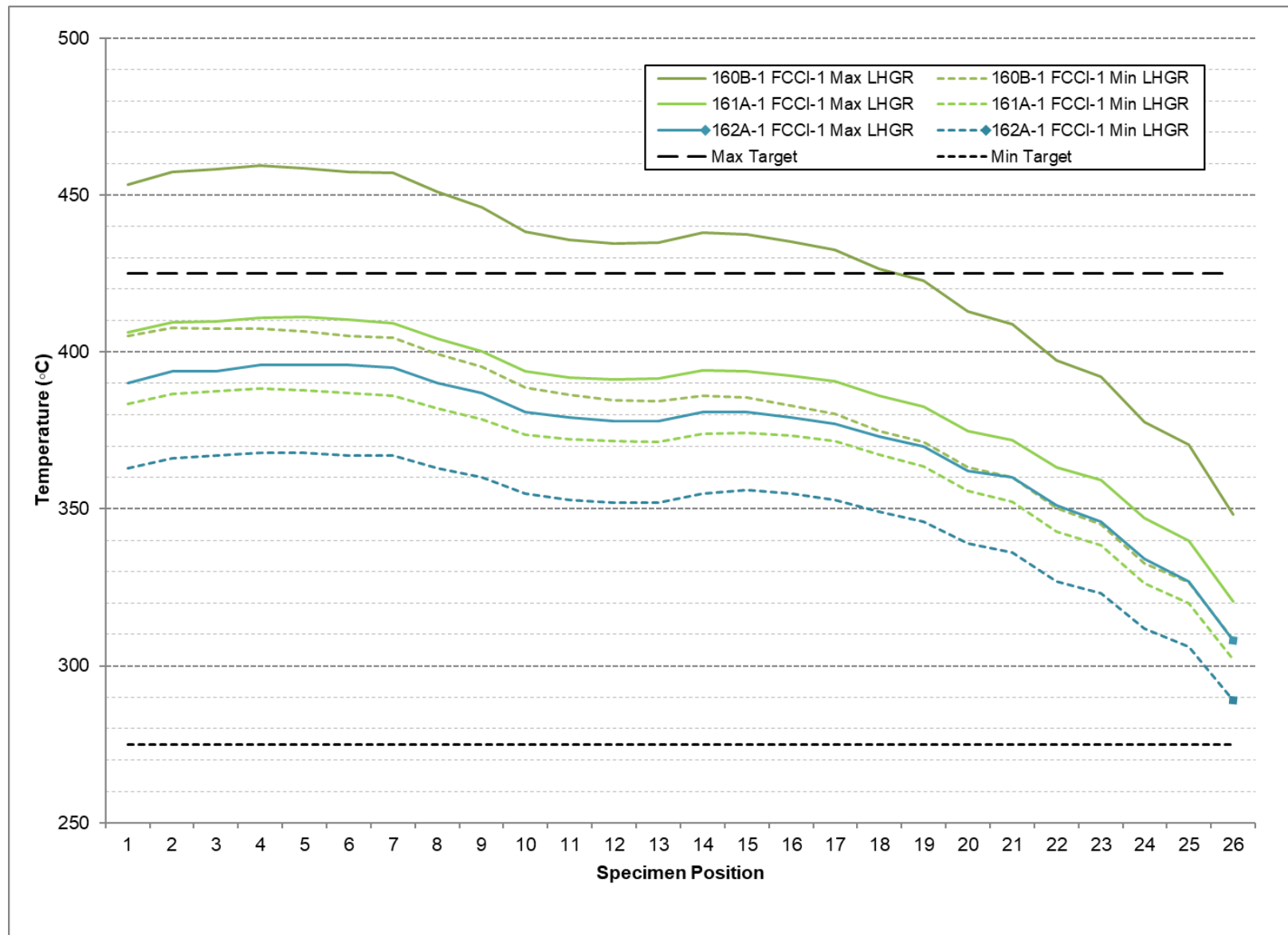


Figure 16. As-Run Experiment Temperatures of ORNL-FCCI Capsule ATF-73.

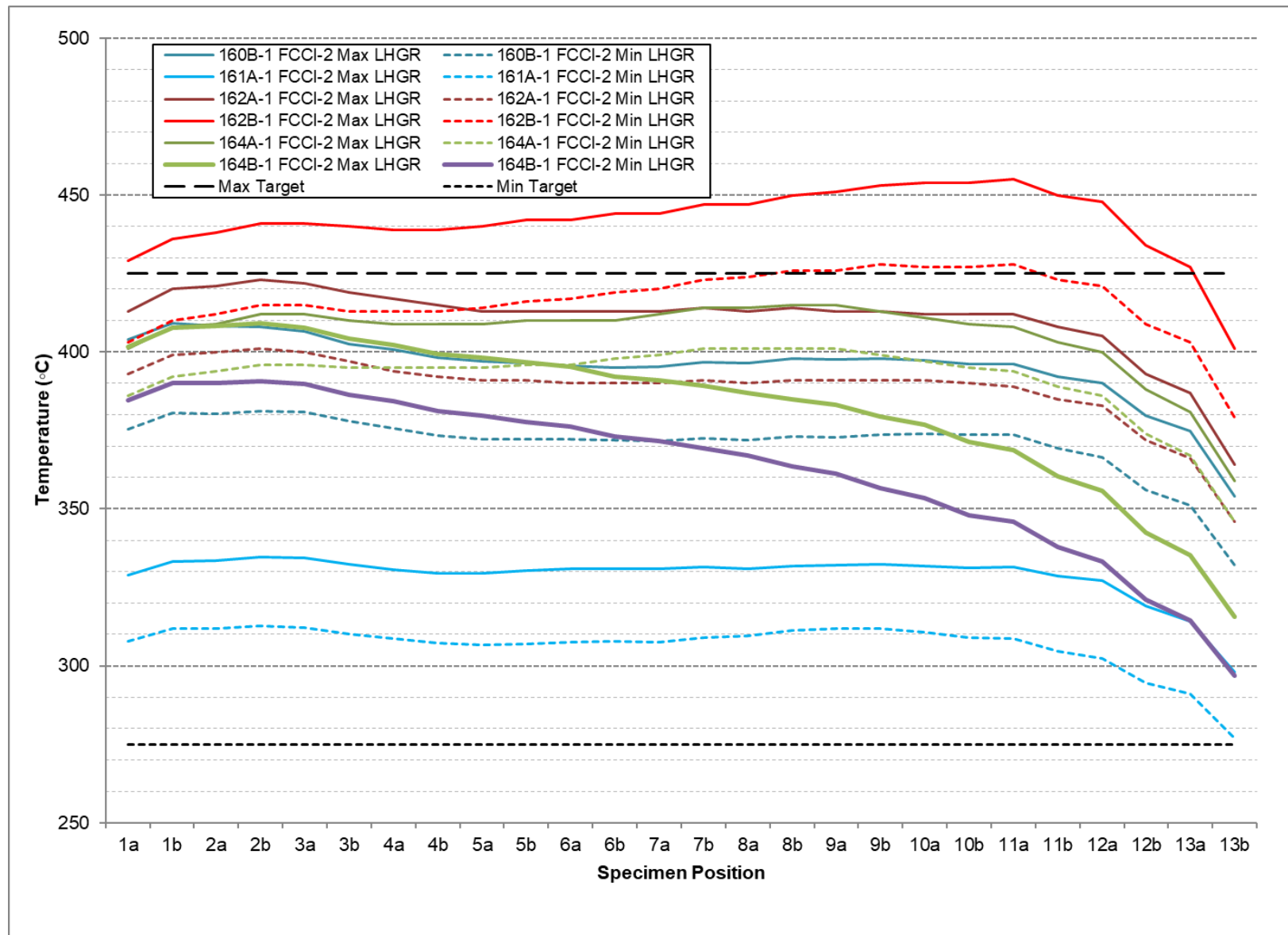


Figure 17. As-Run Experiment Temperatures of ORNL-FCCI Capsule ATF-74.

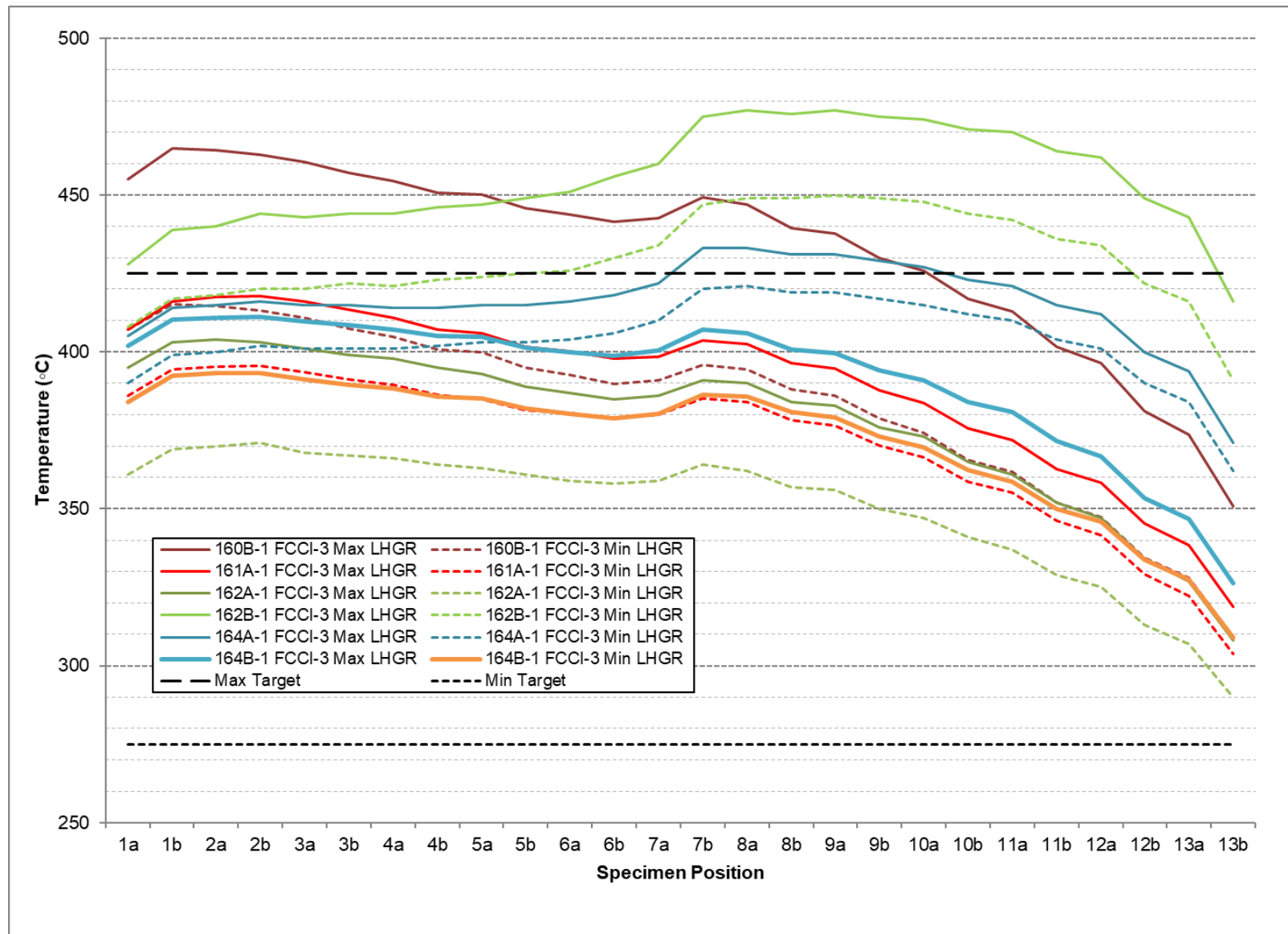


Figure 18. As-Run Experiment Temperatures of ORNL-FCCI Capsule ATF-75.

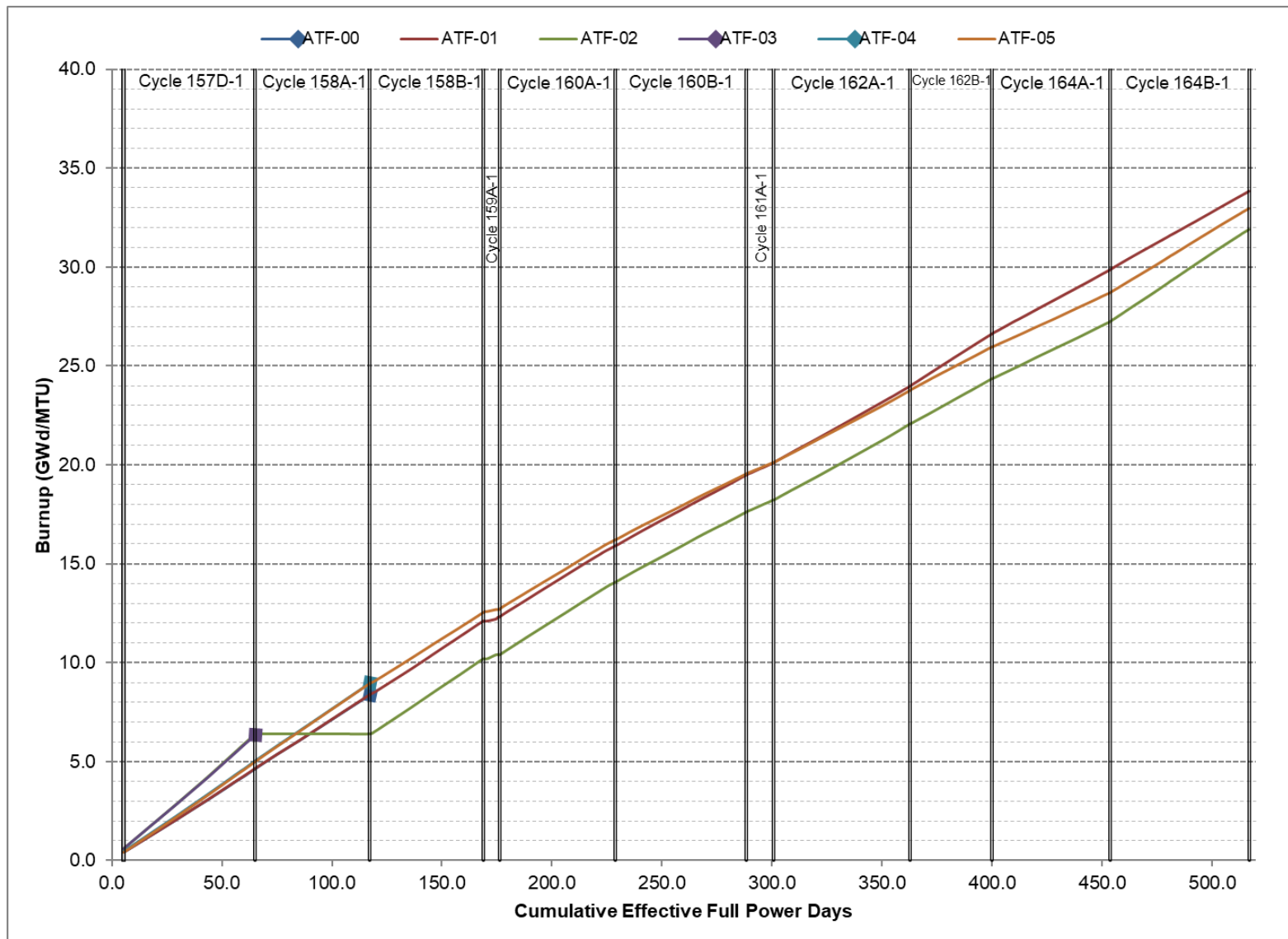


Figure 19. Burnup as a function of Cumulative Effective Full Power Days of AREVA Capsules ATF-00 through ATF-05.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

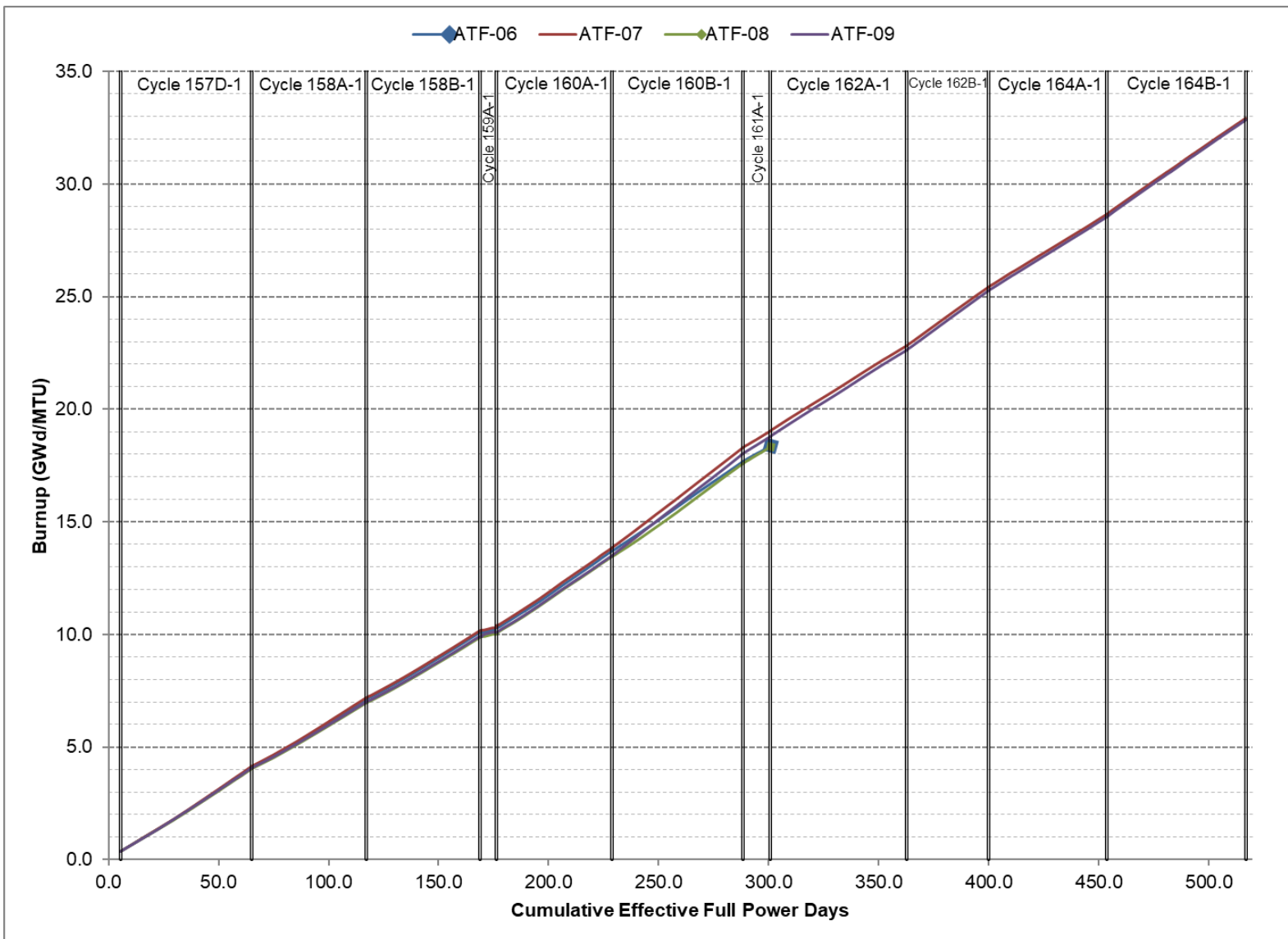


Figure 20. Burnup as a function of Cumulative Effective Full Power Days of GE Capsules ATF-06 through ATF-09.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

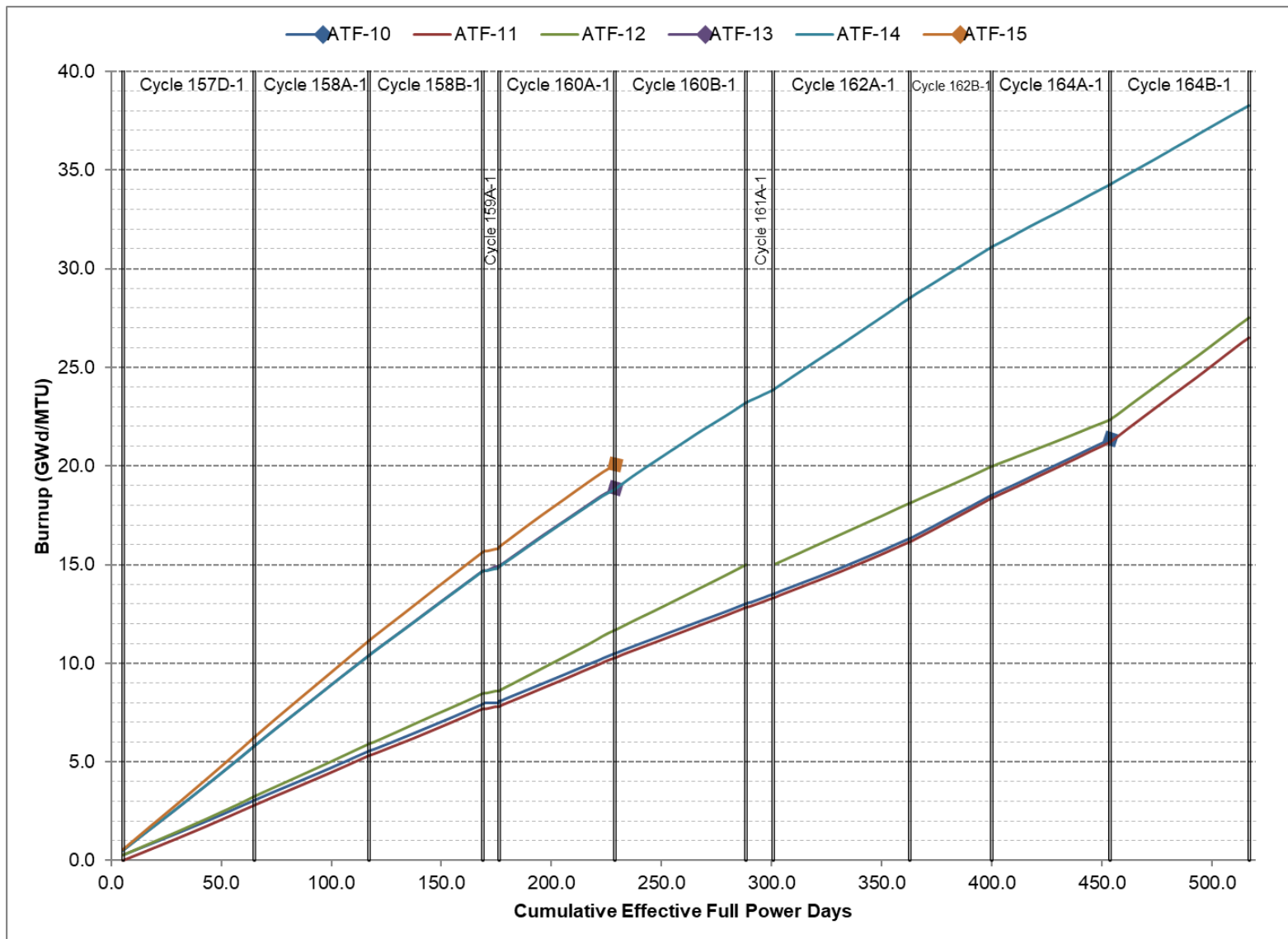


Figure 21. Burnup as a function of Cumulative Effective Full Power Days of Westinghouse 1A Capsules ATF-10 through ATF-15.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

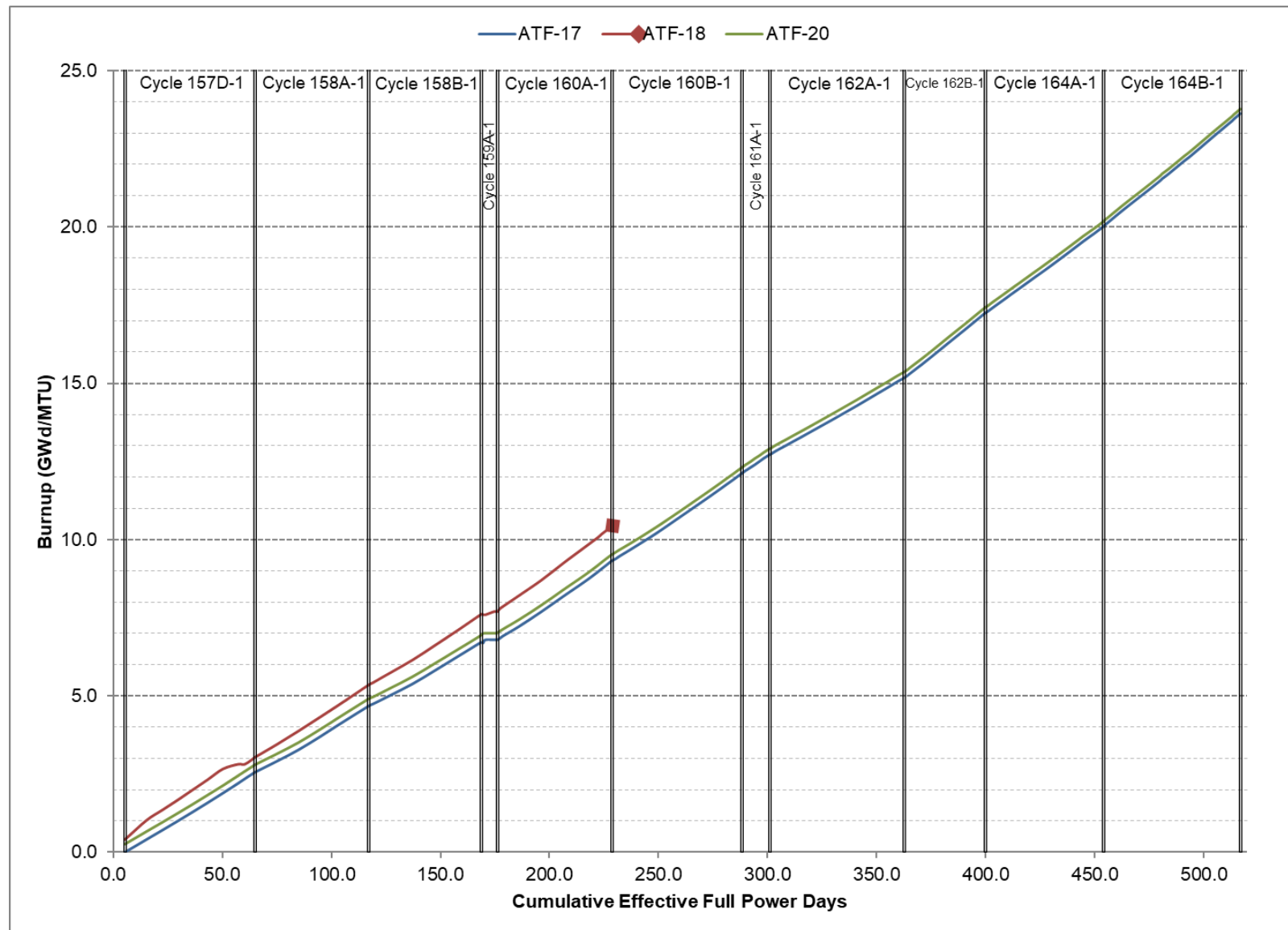


Figure 22. Burnup as a function of Cumulative Effective Full Power Days of ORNL-LOCA Capsules ATF-17, 18, and 20.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

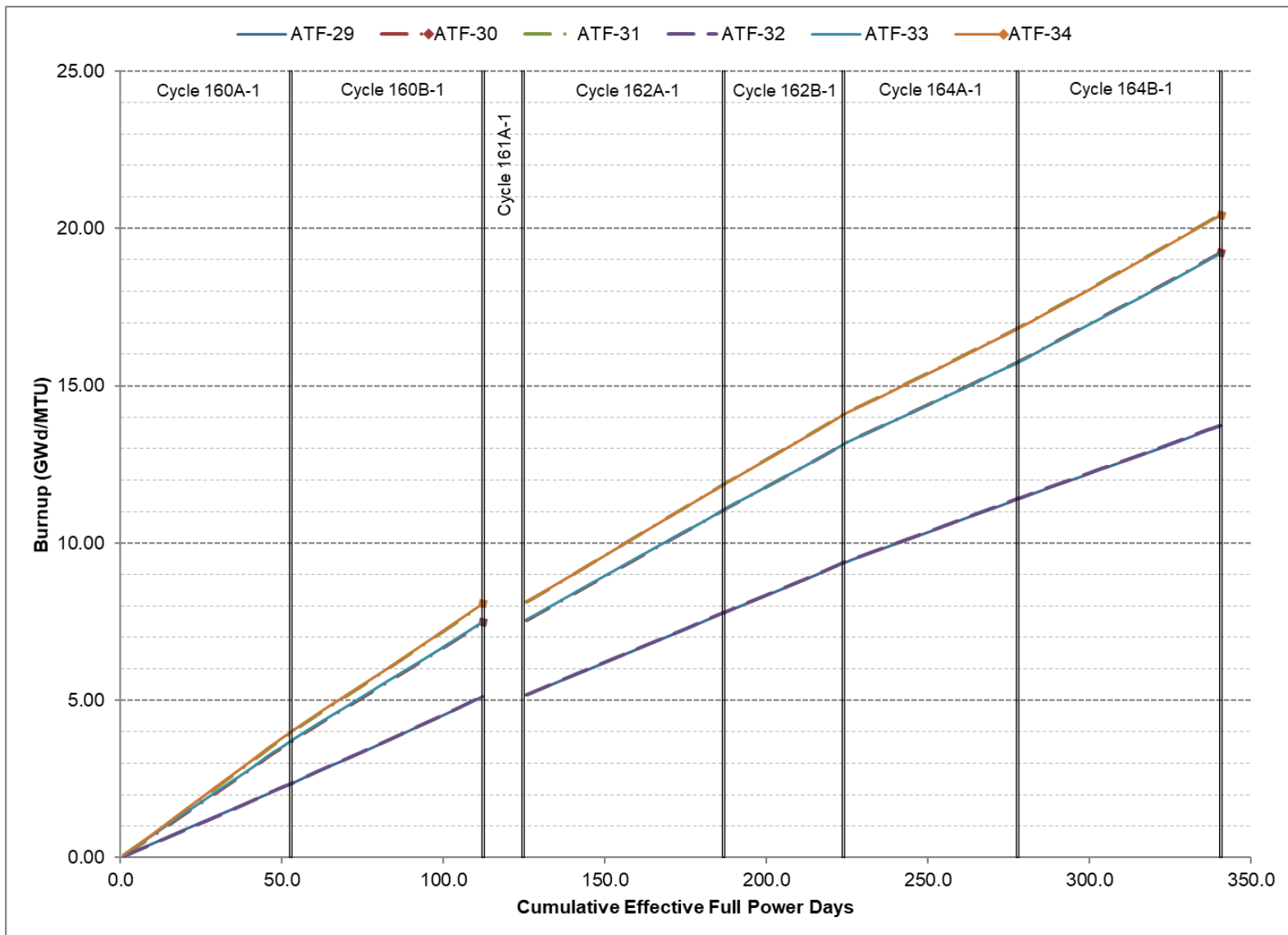


Figure 23. Burnup as a function of Cumulative Effective Full Power Days of Westinghouse 1B Capsules ATF-29 through ATF-34.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

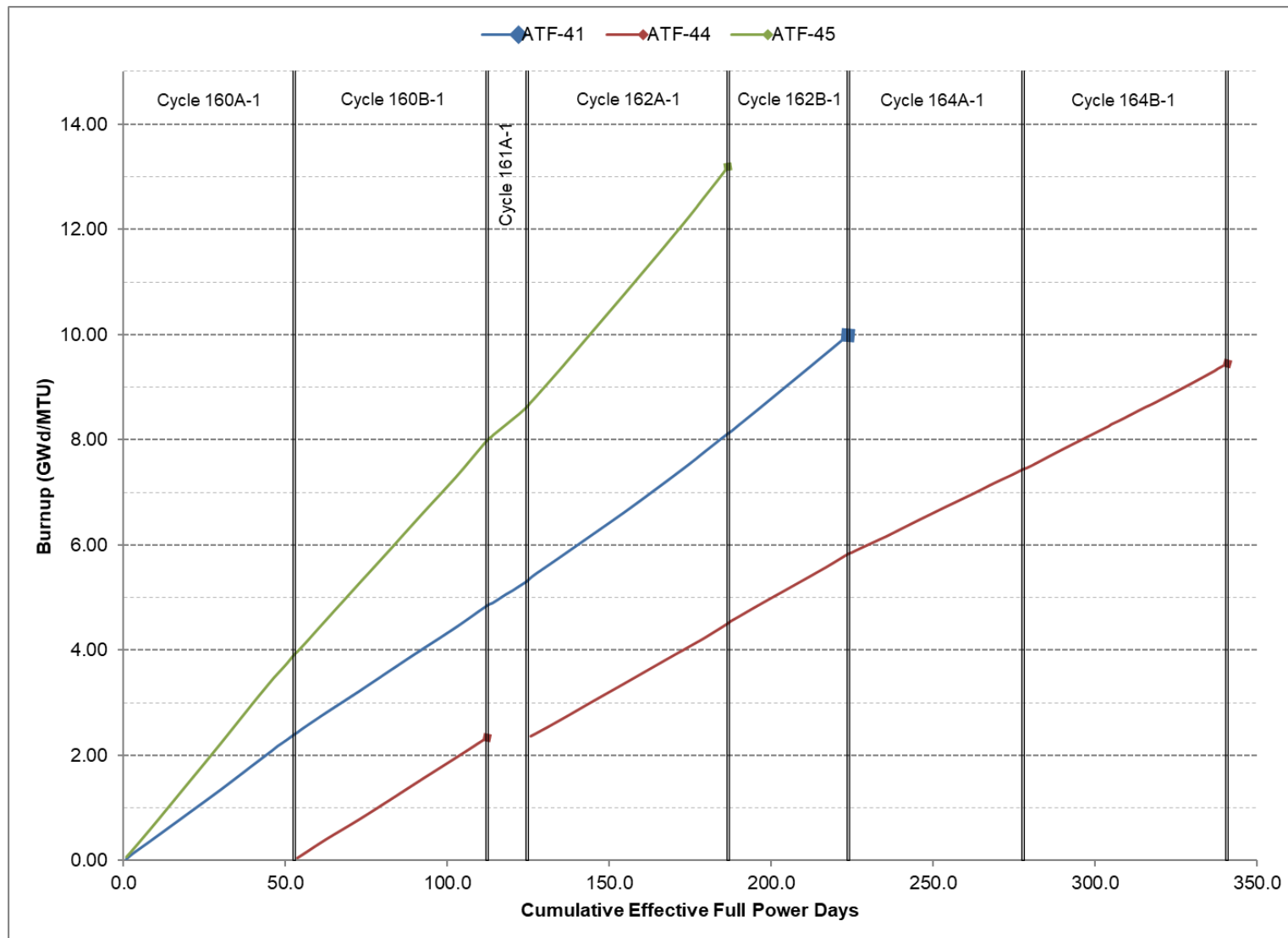


Figure 24. Burnup as a function of Cumulative Effective Full Power Days of LANL Capsules ATF-41, 44, and 45.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

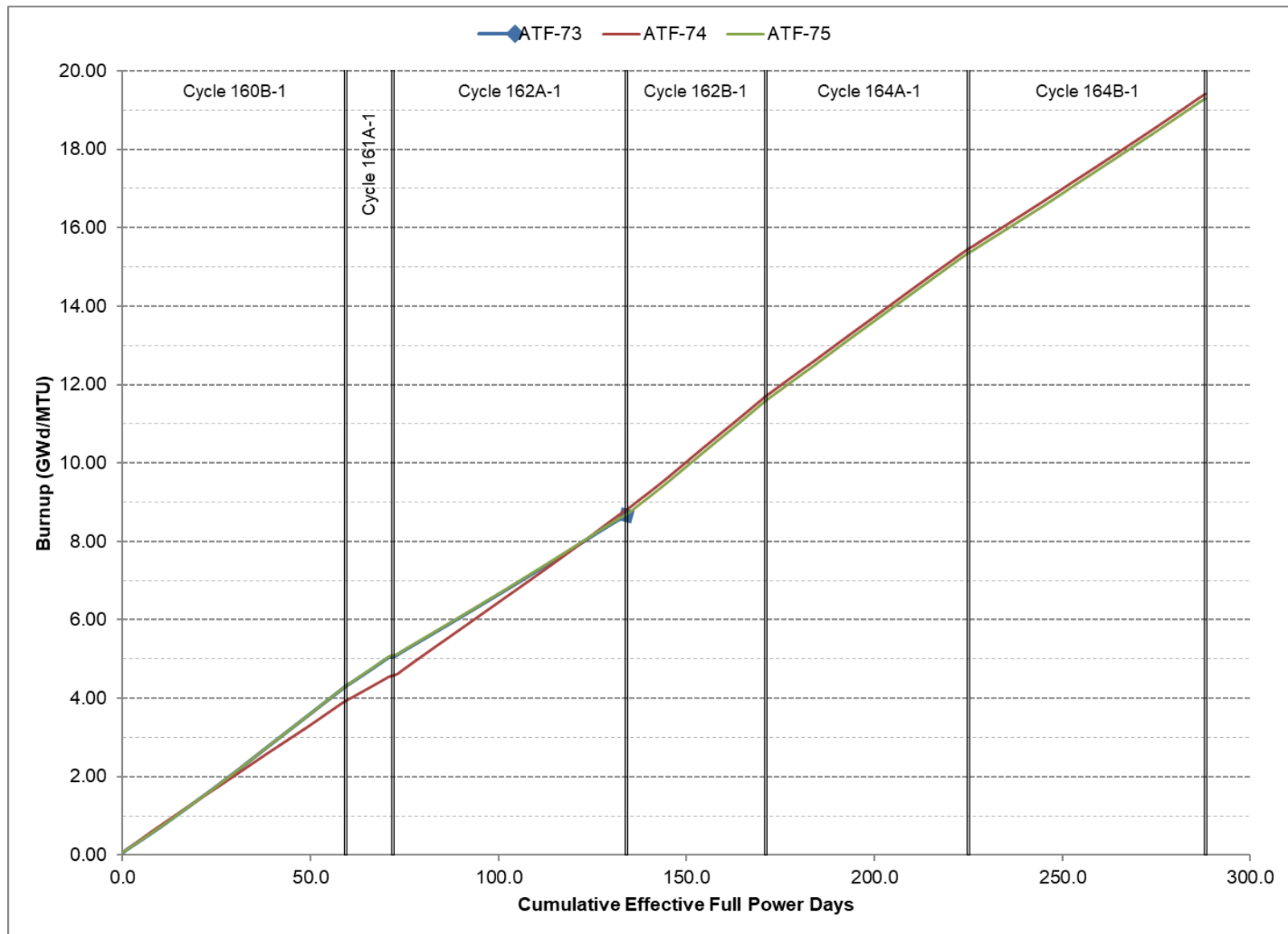


Figure 25. Burnup as a function of Cumulative Effective Full Power Days of ORNL-FCCI Capsules ATF-73, 74, and 75.

NOTE: Markers at the end of a line denotes when the capsule was removed from irradiation.

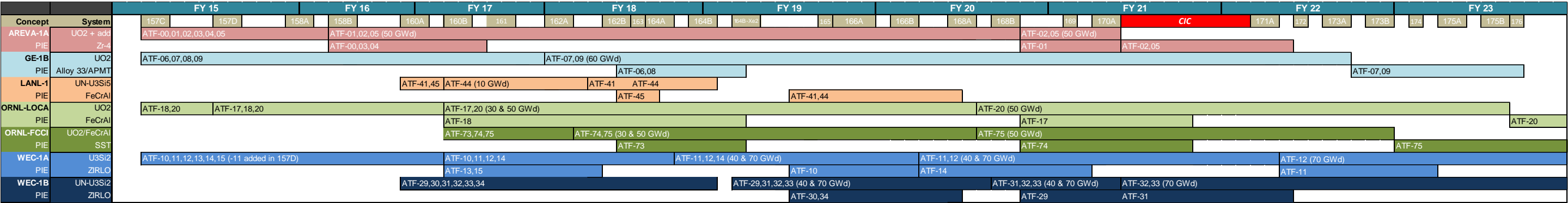


Figure 26. Current Irradiation and Subsequent Post-Irradiation Examination Schedule.
NOTE: The top line in each concept's stripe indicates irradiation time. The bottom line identifies when a specific capsule(s) is scheduled to undergo PIE.

3. FUTURE IRRADIATION TESTING AND SHIPPING

ATF-1 experiment capsules will continue to be irradiated in FY 2020. Two shipments of irradiated ATF-1 capsules to HFEF are currently planned to be completed during mid and end of FY 2020. The first shipment is planned to include WEC-1A capsule ATF-14. The second shipment is planned to include ORNL-LOCA capsule ATF-17, WEC-1B capsule ATF-29, ORNL-FCCI capsule ATF-74, and AREVA-1A capsule ATF-01. These plans are contingent upon the ATR operating as scheduled. In FY 2021, irradiation will continue along with the shipment of any irradiated capsules that reach their burnup targets.

In addition, the new experimental program, denoted as Fission Accelerated Steady-state Testing (FAST), is in progress with plans for implementation mid FY 2020. In the revised experiment design, the approach is to use reduced-diameter rodlets that can in turn enable higher fuel power densities while maintaining prototypical temperatures. The new capsules, however, are of the same diameter as the current ATF-1 capsules, so that the existing thermal-hydraulic analyses and ATF-1 baskets can be used. Although initial testing will be focused on metallic fuels for sodium-cooled fast reactors, the same approach is being considered to accelerate the testing of advanced light water reactor fuels. The FAST capsules will share the same spaces currently occupied by the ATF-1 capsules in the Small-I positions.

Finally, concept lead Framatome plans for additional ATF-1 capsule fabrication in FY 2020. The current ATR insertion schedule is targeting early FY 2021. The potential to fabricate and test additional ATF-1 capsules in the ATR by other concept leads exists, but with likely target insertions post-core internals changeout (CIC) in the ATR.

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Stephen Evans	ATR Representative
Susan Case	Experiment Shipping Coordinator
Michael McGuire	ATF-1 Irradiation Scheduling
Jeff Skinner	ATF-1 PIE Scheduling
Lynn Bailey	Report Editor

5. REFERENCES

1. Roadmap: Development of Light Water Reactor Fuels with Enhanced Accident Tolerance, Idaho National Laboratory Report, INL/EXT-12-25305, September 2012.
2. TEV-3119, "ATF-1 Power Histories," June 2019.
3. ECAR-3773, "ATR Cycle 160B Through 161A As-Run Analysis and Cycle 162A Bounding Physics Evaluation of The Accident Tolerant Fuels ATF-1-21-4, ATF-1-23-2, And ATF-1-24-6 Basket Configurations," August 2017.
4. ESAP-ATF-1, "Experiment Safety Analysis for the ATF-1 Experiment in the ATR," Revision 12, August 2018.
5. ECAR-3074, "Cycle 157D As-Run and Cycle 158A Bounding Physics Evaluation of the Accident Tolerant Fuels (ATF) ATF-1-21-2 and ATF-1-24-2 Basket Configurations with KJRR in the Northeast Flux Trap," November 2015.
6. ECAR-3148, "Cycle 158A-1 As-Run and Cycle 158B Bounding Physics Evaluation of the Accident Tolerant Fuels (ATF) ATF-1-21-2 and ATF-1-24-4 Basket Configurations," January 2016.
7. ECAR-3305, "ATR Cycles 158B and 159A As-Run Analyses and Cycle 160A Bounding Physics Evaluation of the Accident Tolerant Fuels (ATF) ATF-1-21-2, ATF-1-23-1 and ATF-1-24-5 Basket Configurations," August 2016.
8. Letter from N. H. Manwaring to R. R. Little, "Advanced Test Reactor Power History through Cycle 165A-1," RE-38-19, June 2019.
9. ECAR-3499, "ATR Cycle 160A As-Run Analysis and Cycle 160B Bounding Physics Evaluation of The Accident Tolerant Fuels ATF-1-21-3, ATF-1-23-2, And ATF-1-24-6 Basket Configurations," December 2016.
10. ECAR-3791, "Thermal Analysis for Cycle 160B-1 As-Runs, 161A-1 As-Runs, and 162A-1 Projections for The ATF Experiments in the ATR," August 2017.
11. ECAR-3970, "ATR Cycle 162A As-Run Analysis and Cycle 162B Bounding Physics Evaluation of Accident Tolerant Fuels ATF-1-21-5, ATF-1-23-2, and ATF-1-24-7 Basket Configurations," February 2018.
12. ECAR-3982, "Thermal Analysis for Cycle 162A-1 As-Runs and 162B-1 Projections for the ATF-1 Experiments in the ATR," February 2018.
13. ECAR-4122, "ATR Cycle 162B As-Run Analysis and Cycle 164A Bounding Physics Evaluation of Accident Tolerant Fuels ATF-1-21-6, ATF-1-23-2, and ATF-1-24-8 Basket Configurations," May 2018.
14. ECAR-4129, "Thermal Analysis for Cycle 162B-1 As-Runs and 164A-1 Projections for the ATF-1 Experiments in the ATR," May 2018.
15. ECAR-4231, "ATR Cycle 164A As-Run Analysis and Cycle 164B Bounding Physics Evaluation of Accident Tolerant Fuels ATF-1-22-1 and ATF-1-23-3 Basket Configurations," September 2018.
16. ECAR-4244, "Thermal Analysis for Cycle 164A-1 As-Runs and 164B-1 Projections for the ATF-1 Experiments in the ATR," September 2018.
17. ECAR-4582, "ATR Cycle 166A Bounding Physics Evaluation of Accident Tolerant Fuels ATF-1-22-1 and ATF-1-23-4 Basket Configurations," July 2019.
18. ECAR-4673, "Thermal Analysis of the ATF-1 Experiments for Cycle 164B-1 As-Runs and 166A-1 Projections in the ATR," August 2019.