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Advanced Fuel Cycle Initiative AFC-1D, AFC-1G and AFC -1H Irradiation Report

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ABSTRACT

The U. S. Advanced Fuel Cycle Initiative (AFCI) seeks to develop and demonstrate the technologies needed to transmute the long-lived transuranic actinide isotopes contained in spent nuclear fuel into shorter-lived fission products, thereby dramatically decreasing the volume of material requiring disposition and the long-term radiotoxity and heat load of high-level waste sent to a geologic repository.

The AFC-1 irradiation experiments on transmutation fuels are expected to provide irradiation performance data on non-fertile and low-fertile fuel forms specifically, irradiation growth and swelling, helium production, fission gas release, fission product and fuel constituent migration, fuel phase equilibria, and fuel-cladding chemical interaction.

Contained in this report are the to-date physics evaluations performed on three of the AFC-1 experiments; AFC-1D, AFC-1G and AFC-1H. The AFC-1D irradiation experiment consists of metallic non-fertile fuel compositions with minor actinides for potential use in accelerator driven systems and AFC-1G and AFC-1H irradiation experiments are part of the fast neutron reactor fuel development effort. These experiments are high burnup analogs to previously irradiated experiments and are to be irradiated to ≥ 20 atom % burnup.

Results of the evaluations show that AFC-1D will remain in the ATR for approximately 100 additional effective full power days (EFPDs), and AFC-1G and AFC-1H for approximately 300 additional EFPDs in order to reach the desired programmatic burnup. The specific irradiation schedule for these tests will be determined based on future physics evaluations and all results will be documented in subsequent reports.

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Advanced Fuel Cycle Initiative AFC-1D, AFC-1G and AFC-1H Irradiation Report

1. INTRODUCTION

The irradiation of the Advanced Fuel Cycle Initiative's AFC-1 series fuel capsules and GFR-F1 material capsules is being performed in the Advanced Test Reactor (ATR) East Flux Trap (EFT) positions E1, E2, E3, and E4. There are a total of six AFC-1 fuel capsules and three GFR-F1 capsules that have been fabricated for irradiation. These tests are identified as AFC-1B, AFC-1D, AFC-1AE, AFC-1F, AFC-1G, and AFC-1H, and GFR-F1-1, GFR-F1-2, and GFR-F1-3.

The experiment safety and programmatic maximum allowable test condition specified for AFC-1AE and -1B, and -F is 5% burnup (not to exceed 10% burnup). For AFC-1D, -1G, and -1H, the maximum burnup is 20% burnup (not to exceed 25% burnup). In all cases, burnup is defined for these experiments to be percent depletion of initial Pu-239.

The first series of tests, AFC-1B and AFC-1D, consist of metallic non-fertile fuel compositions with minor actinides for potential use in accelerator driven systems. The second series, AFC-1AE and AFC-1F, consist of non-fertile and low-fertile metallic and nitride fuel compositions with minor actinides for use in fast neutron spectrum reactors or accelerator driven systems. The GFR-F1(-1, -2, -3) experiment will test fuel related refractory ceramics, nickel based 800H and MA754 (ODS) alloys, and iron based T122 and MA957 (ODS) ferritic alloys. These tests, excluding AFC-1D and GFR-F1-2 (which will be reinserted into the ATR for additional irradiation), have reached their desired burnup and/or fluence and have shipped to the Materials and Fuels Complex (MFC)[a] for Post Irradiation Examination. The irradiation history for AFC-1B, -1AE, and -1F is detailed in INEEL/EXT-04-02380.[1]

The AFC-1G and AFC-1H capsules are also part of the fast neutron spectrum fuel development effort. The AFC-1H capsule is the high burnup analog of the AFC-1F capsule and the AFC-1G capsule is the high burnup analog of the AFC-1AE nitride fuel form capsule.

This report will provide to-date irradiation history on the AFC-1D, AFC-1G, and AFC-1H test which continued irradiated in FY 2005 and will be irradiated into FY 2007.

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a. Beginning February 1, 2005, the name of the Idaho National Engineering and Environmental Laboratory (INEEL) was changed to Idaho National Laboratory (INL). Argonne National Laboratory-West was re-named the Materials and Fuels Complex (MFC).

2. ADVANCED TEST REACTOR DESCRIPTION

As the cross sectional view in Figure 1 shows, the ATR has a unique core configuration and offers 77 possible irradiation positions. The burnup level requirements led to the selection of the EFT for the irradiations. This location is magnified on the right side of Figure 1.

The irradiation environment for the AFCI test assemblies (capsules and baskets) is the ATR Primary Coolant System. ATR Primary Coolant System is clean water sampled three times per day and maintained at the slightly acidic pH of 5.0 – 5.3. Chlorides are controlled to < 0.1ppm (normal < 0.05). Normal Gross Beta-Gamma activity is < 0.16 µCi/ml. Control of pH, solids, and chlorides are maintained using ion exchange columns, filters, and chemistry control additives within the system boundaries.

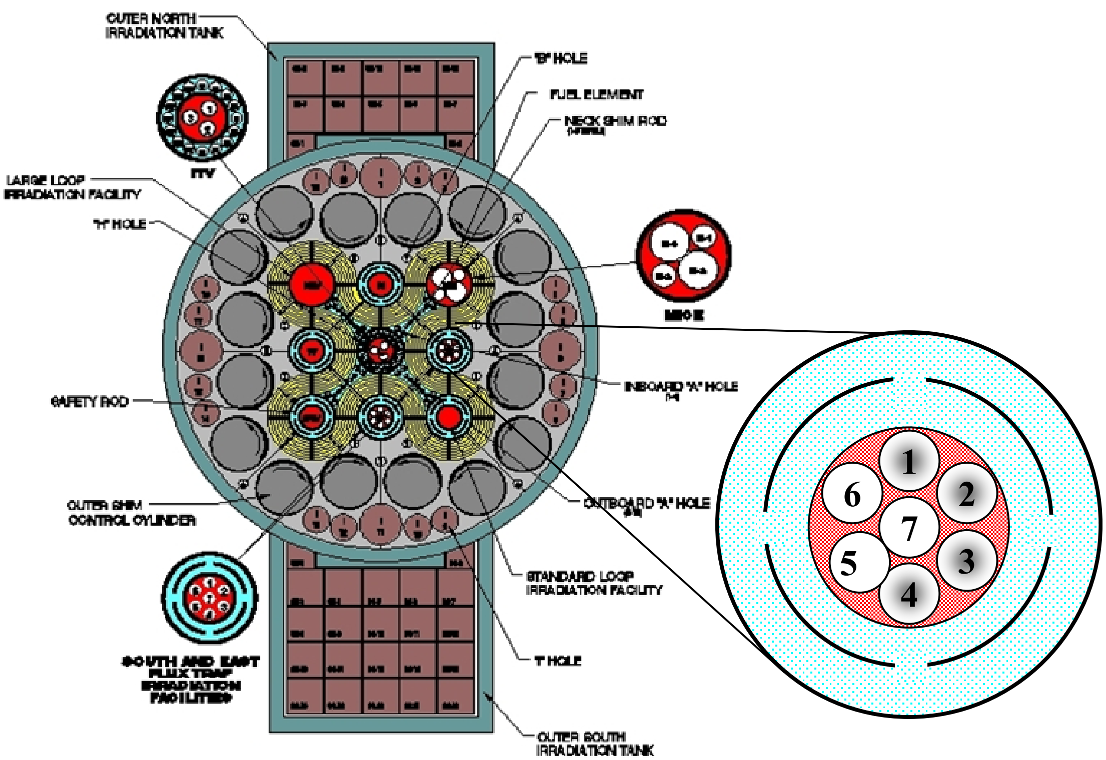


Figure 1. ATR cross section with magnified East Flux Trap.

3. IRRADIATION CONDITIONS

All test assemblies were irradiated in accordance with: INL AFCI Experiment Safety Assurance Package and controlled document W7520-0678-ES-01, "Final Experiment Description and Design and Data Package for AFC-1G and AFC-1H,"[2] and MFC controlled documents; W7520-0481-ES-02 "Final Experiment Description and Design and Data Package for AFC-1A, AFC-1B, AFC-1C and AFC-1D,"[3] and W7520-0594-ES-00 "Final Experiment Description and Design and Data Package for GFR-F1."[4]

The tests were distributed in the ATR EFT drop-in positions: E1, E2, E3 and E4. The anticipated experimental fuel powers in these positions were calculated by using the INL detailed physics code evaluation: Monte Carlo N-Particle (MCNP) full core physics model. The powers of the fuel rodlets increase with time due to depletion of the neutron absorber in the cadmium shrouded aluminum baskets. A maximum basket lifetime, to ensure the linear heat generation rate (LHGR) limits in Table 1 are not exceeded in any of the experimental fuels, has been established by analysis to be 120 full-power days of irradiation with a source power of 26 MW. For conservatism, the fuel powers used in the following analyses are those reported at basket end-of-life.

Table 1. AFCI test assembly experiment specifications.

Experiment Specifications for Irradiation in the ATR			
Performance Parameter	**AFC-1D (Metallic Fuel)**	**AFC-1G (Nitride Fuel)**	**AFC-1H (Metallic Fuel)**
Maximum Burnup	25%	25%	25%
Peak Rodlet Linear Power	400 W/cm	400 W/cm	400 W/cm
Peak Cladding Temperature			
Normal Operation	525°C	550˚C	550˚C
Off-Normal Limit	650°C	650˚C	650˚C
Fuel Temperature			
Normal Operation	900°C	1400˚C	900°C
Off-Normal Limit	1100°C	2100˚C	1100°C

The AFC-1D capsule was received at the Reactor Technology Complex (RTC), formally known as TRA,[b] in June 2003, GFR-F1 was received in February 2004, and AFC-1G and AFC-1H capsules were received in July 2005. Upon receipt, each capsule was inspected and installed in an AFC cadmium shrouded aluminum basket containing an aluminum spacer (to obtain the proper reactor axial position of the capsule). The basket assembly was then loaded into the EFT Irradiation Housing for irradiation.

Each test assembly is scheduled to remain in the EFT of the reactor for varying lengths of time depending upon the desired burnup or fluence. As necessary, the test assemblies are removed from the reactor core and transferred to the canal for temporary storage during all Powered Axial Locating Mechanism (PALM) cycles and during normal scheduled maintenance outages to replace the cadmium baskets to compensate for filter material burnup.

4. IRRADIATION HISTORY

The AFC-1D, AFC-1G, and AFC-1H test assemblies were inserted into the ATR EFT for irradiation during Cycle 135B beginning July 23, 2005. The tests were re-inserted into the ATR EFT to continue irradiation during Cycle 135C, beginning September 24 and running a total of 42 Effective Full Power Days (EFPDs), completing on November 17, 2005.

Table 2 shows the to-date irradiation details and history for each AFC-1 and GFR-F test assembly.

Table 2. AFCI test capsule east flux trap irradiation history.

ATR Operating Cycle	Cycle Start Date	EFPDs	East Flux Trap Housing Loading	Test Capsule	Basket Condition
131A	6/7/2003	48.5 Days	E1	AFC-1B	New
			E2	AFC-1D	New
			E3	Dummy	New
			E4	Dummy	New
131B	8/10/2003	13.8 Day PALM	All tests removed for high power Palm Cycle		
132A	12/07/2003	43.5 Days	E1	AFC-1B	New
			E2	AFC-1F	New
			E3	AFC-1D	New
			E4	AFC-1Æ	New
132B	2/21/2004	1.6 Day PALM	All tests removed for high power Palm Cycle		
132C	2/29/2004	50.3 Days	E1	AFC-1D	New
			E2	AFC-1F	New
			E3	AFC-1Æ	New
			E4	GFR-F1-1, -2, -3	Depleted*
133A	5/2/2004	13 Day PALM	All tests removed for high power Palm Cycle		
133B	5/30/2004	60.9 Days	E1	Dummy	Depleted*
			E2	AFC-1D	Depleted*
			E3	Dummy	Depleted*
			E4	GFR-F1-1, -2, -3	Depleted*
CIC		250 Days	All tests removed for Core Internal Changout		
134AB-2	04/14/05	46.6 Days	Backup test		
135A	06/26/05	13 Day PALM	All tests removed for high power Palm Cycle		
135B-1 and -2	07/23/05	48.5 Days	E1	AFC-1D	New
			E2	AFC-1H	New
			E3	AFC-1G	New
			E4	GFR-F1-2	New
* Depleted = ~50 EFPD of Irradiation					

5. PROJECTED PHYSICS ANALYSES EXPERIMENT DATA

Prior to each cycle, projected physics analysis is performed using the computer code MCNP. MCNP is a general purpose Monte Carlo N-Particle code written by the Los Alamos National Laboratory. MCNP version 4C, as described in, LA-13709-M, Los Alamos National Laboratory (2000),[5] was used for this AFCI evaluation. The computer code was used to predict the neutron fission heating tally, which then was converted to LHGR, for this analysis. The depletion methodology used to evaluate the AFCI experiments, requires coupling the Monte-Carlo code, MCNP, with the isotope depletion code, ORIGEN2.[6] This depletion methodology is accomplished using a BASH shell script titled MCNP Coupled With ORIGEN2 (MCWO). MCWO has been verified at the INL by benchmarking calculated flux magnitudes with measured flux levels for several experiments in several test positions for the ATR core. Additionally, MCWO and the ATR core model have been benchmarked for heat rate evaluations by comparing the measured temperatures to predicted temperatures in various ATR experiments.

All three computer codes MCNP, MCWO, and ORIGEN2 are listed as verified and validated software in the INL Enterprise Architecture Repository and are accepted as qualified scientific and engineering analysis software.

The planned EFPDs documented in the ATR Test Plan are used in the analysis to perform the projected calculations. However, the EFPDs of any cycle may change due to unexpected difficulties and the need for an unplanned outage of the ATR . Therefore, the actual EFPDs may vary from the projected EFPDs.

Cycle 135B began on July 23, 2005, and ran for 25.5 EFPDs, prior to being shut down on August 19 for six days due to difficulties encountered with a Nuclear Reactor Programs irradiation test located in the South East flux trap. On August 25, the ATR was restarted to complete an additional 23 EFPDs for a total of 48.5 EFPDs. On September 17, 2005, at the end of Cycle 135B-2, the ATR was shut down for a planned maintenance outage of seven days.

Table 3 shows the total projected and actual EFPDs of irradiation and East Lobe power for each test.

Table 3. Projected EFPDs and East Lobe power vs. actual EFPDs and East Lobe power.

Test	Projected EFPDs	Predicted East Lobe Power	Total Actual EFPDs	Actual East Lobe Power
Cycle 135B-1and -2	51	23 MW	48.5	24.3 MW

Table 4 shows the results from the heat rates and burnup distribution calculations for each rodlet in the AFC-1D, AFC-1G, and AFC-1H capsules at the beginning of Cycle 135B of Cycle 135B.

Table 4. Projected linear fission heat rate and burnup distribution of the AFC-1 series fuel experiments in the East Flux Trap position at the beginning of Irradiation Cycle 135B.

ID		Linear Heat Rate (W/cm)	Fission Heat Rate (W/g)	^{239}Pu Depletion (atom%)	Heavy Metals Depletion (atom%)	Am Depletion (atom%)	^{235}U Depletion (atom%)
E1 AFC-1D (Metal)	Rodlet 1	153.06	132.71	9.84%	4.91%	19.65%	--
	Rodlet 2	167.32	147.05	12.75%	5.51%	24.79%	--
	Rodlet 3	256.37	228.07	13.66%	8.00%	22.74%	--
	Rodlet 4	205.44	181.27	13.97%	7.01%	26.80%	--
	Rodlet 5	153.71	159.96	16.31%	9.53%	--	--
	Dummy	--	--	--	--	--	--
E2 AFC-1H (Metal)	Rodlet 1	196.75	136.76	0.00%	0.00%	0.00%	0.00%
	Rodlet 2	217.85	135.22	0.00%	0.00%	0.00%	0.00%
	Rodlet 3	269.91	204.83	0.00%	0.00%	0.00%	0.00%
	Rodlet 4	276.40	190.63	0.00%	0.00%	0.00%	0.00%
	Rodlet 5	276.91	193.18	0.00%	0.00%	0.00%	0.00%
	Rodlet 6	184.93	141.84	0.00%	0.00%	0.00%	0.00%
E3 AFC-1G (Nitride)	Rodlet 1	134.28	113.67	0.00%	0.00%	--	--
	Dummy	--	--	--	--	--	--
	Rodlet 3	272.05	177.73	0.00%	0.00%	0.00%	0.00%
	Rodlet 4	213.09	179.03	0.00%	0.00%	0.00%	0.00%
	Dummy	--	--	--	--	--	--
	Dummy	--	--	--	--	--	--

Note: *All the MCNP tallies are normalized to a total core power of 109.8 MW, which represents an E-lobe source power of 23 MW.*

At the end of 25.5 EFPDs of irradiation during ATR Cycle 135B, as-run calculations were performed and are noted in Table 5. Based on these as-run calculations, the projected linear and fission heat rates and burnup distributions were calculated through the end of Cycle 135B, for a total of 48.5 EFPDs. Using 48.5 EFPDs, the maximum LHGR is seen in the AFC-1H metal fuel rodlet 4, reaching 288.20, as noted in Table 6.

The projected linear and fission heat rates and burnup distributions were then projected for the AFC-1 rodlets for 42 EFPDs of irradiation during Cycle 135C. The maximum LHGR is seen in the AFC-1H metal fuel rodlet 4, reaching 294.88 W/cm as noted in Table 7. This maximum LHGR is under the ESAP LHGR safety limit of 400 W/cm and therefore will remain in the EFT through the end of Cycle 135C.

The desired LHGR programmatic upper value is 330 W/cm. Based on the evaluated condition of 22.3 MW as the East source power, and by using the maximum advertised East source power of 24.5 MW for Cycle 135C, calculations show the tests remain within the programmatic LHGR limit [(24.5/22.3) x 294.88 = 323.97 W/cm].

Table 5. As-run linear and fission heat rates and burnup distribution of the AFC-1 fuel in the East Flux Trap position at the end of 25.5 EFPDs during Cycle 135B irradiation.

Test Position and ID		Linear Heat Rate (W/Cm)	Fission Heat Rate (W/G)	^{239}Pu Depletion (Atom%)	Heavy Metals Depletion (Atom%)	Am Depletion (Atom%)	^{235}U Depletion (Atom%)
E-1 AFC-1D (Metal)	Rodlet 1	141.87	123.42	10.88%	5.48%	21.67%	--
	Rodlet 2	145.65	128.50	13.99%	6.12%	27.43%	--
	Rodlet 3	223.67	200.12	15.09%	8.94%	23.68%	--
	Rodlet 4	199.26	176.69	15.39%	7.82%	29.55%	--
	Rodlet 5	147.03	153.67	17.92%	10.57%	0.00%	--
	Dummy	0.00	0.00	0.00%	0.00%	0.00%	--
E-2 AFC-1H (Metal)	Rodlet 1	207.63	145.05	1.16%	0.74%	2.86%	1.05%
	Rodlet 2	238.59	148.86	1.28%	0.66%	3.60%	1.47%
	Rodlet 3	268.14	204.97	1.79%	1.23%	4.48%	1.59%
	Rodlet 4	288.10	200.12	1.60%	1.04%	3.95%	1.51%
	Rodlet 5	277.30	194.86	1.53%	1.05%	3.57%	1.39%
	Rodlet 6	206.72	159.44	1.40%	0.96%	3.78%	1.23%
E-3 AFC-1G (nitride)	Rodlet 1	132.69	112.68	1.10%	0.58%	--	--
	Dummy	0.00	0.00	0.00%	0.00%	--	--
	Rodlet 3	260.02	170.98	1.23%	0.71%	3.21%	1.38%
	Rodlet 4	189.74	160.16	1.64%	0.86%	--	--
	Dummy	--	--	--	--	--	--
	Dummy	--	--	--	--	--	--

Note: *All the MCNP tallies are normalized to a E-lobe source power of 22.3 MW.*

Table 6. Projected linear and fission heat rates and burnup distribution of the AFC-1 fuel rodlets in the EFT at the end of Cycle 135B irradiation (48.5 EFPD).

Test Position and ID		Linear heat rate (W/cm)	Fission heat rate (W/g)	^{239}Pu depletion (atom%)	Heavy metals depletion (atom%)	Am depletion (atom%)	^{235}U depletion (atom%)
E-1 AFC-1D (Metal)	Rodlet 1	143.77	125.51	11.90%	6.05%	23.58%	--
	Rodlet 2	145.72	129.02	15.15%	6.69%	29.51%	--
	Rodlet 3	225.50	202.77	16.27%	9.72%	24.22%	--
	Rodlet 4	200.90	179.01	16.74%	8.59%	31.90%	--
	Rodlet 5	149.90	157.26	19.32%	11.49%	0.00%	--
	Dummy	0.00	0.00	0.00%	0.00%	0.00%	--
E-2 AFC-1H (Metal)	Rodlet 1	207.05	145.31	2.24%	1.41%	5.35%	2.03%
	Rodlet 2	239.20	149.91	2.44%	1.23%	6.73%	2.76%
	Rodlet 3	267.66	205.98	3.42%	2.37%	8.05%	3.12%
	Rodlet 4	288.20	201.51	3.04%	1.98%	7.25%	2.93%
	Rodlet 5	282.04	199.44	2.81%	1.96%	6.68%	2.59%
	Rodlet 6	211.02	163.60	2.69%	1.83%	6.93%	2.37%
E-3 AFC-1G (nitride)	Rodlet 1	134.14	114.22	2.02%	1.02%	--	--
	Dummy	0.00	0.00	0.00%	0.00%	0.00%	--
	Rodlet 3	261.36	172.82	2.36%	1.31%	6.14%	2.63%
	Rodlet 4	194.40	164.75	3.00%	1.56%	--	--
	Dummy	--	--	--	--	--	--
	Dummy	--	--	--	--	--	--

Note: *All the MCNP tallies are normalized to a E-lobe source power of 22.3 MW.*

Table 7. Projected linear and fission heat rates and burnup distribution of the AFC-1 rodlets in the EFT at the end of Cycle 135C irradiation (42 EFPD).

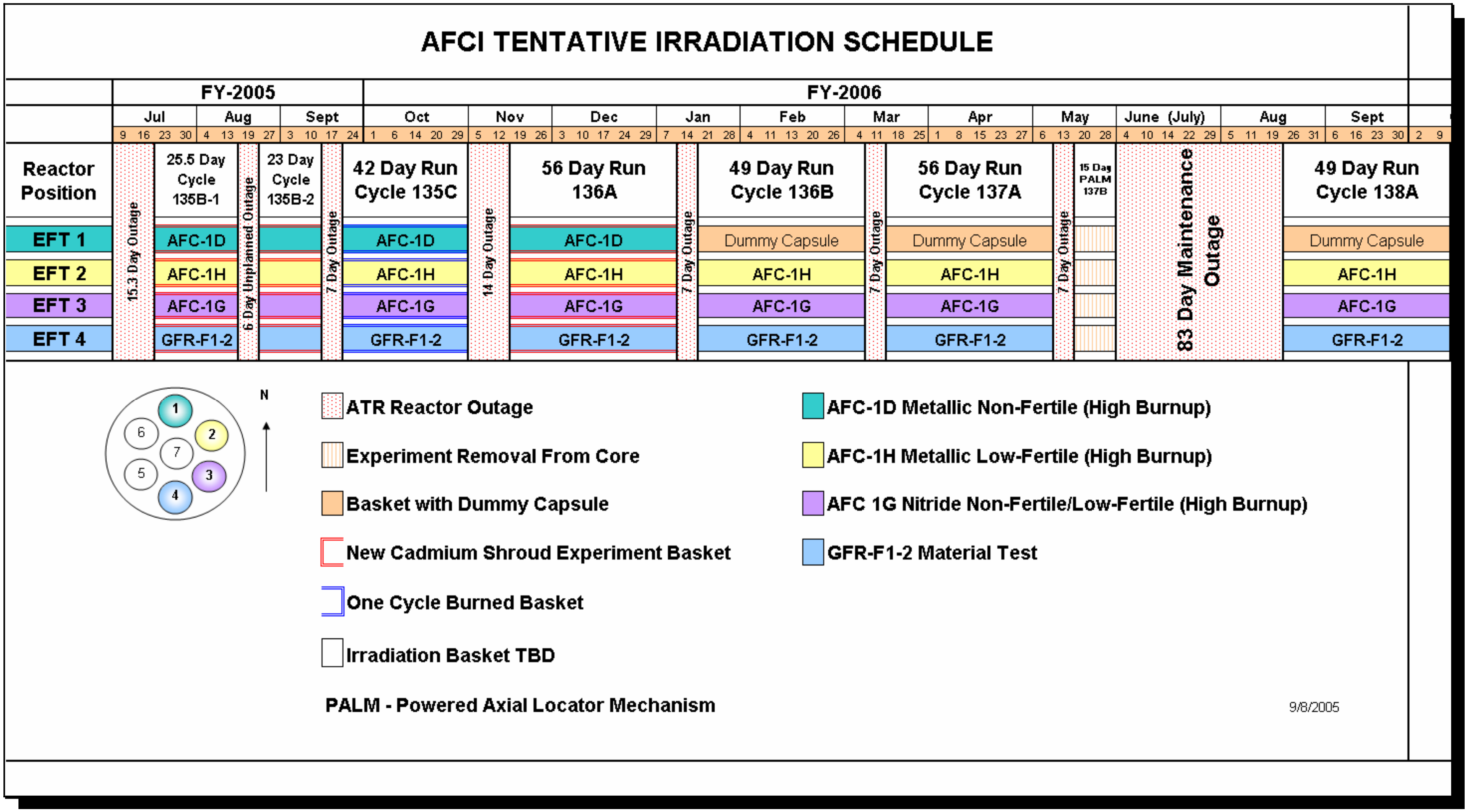
Test Position and ID		Linear Heat Rate (W/cm)	Fission Heat Rate (W/g)	^{239}Pu Depletion (Atom%)	Heavy Metals Depletion Atom%)	Am Depletion (Atom%)	^{235}U Depletion (Atom%)
E-1 AFC-1D (Metal)	Rodlet 1	147.59	129.65	13.71%	7.06%	27.01%	--
	Rodlet 2	148.83	132.63	17.17%	7.74%	33.21%	--
	Rodlet 3	232.16	210.71	18.48%	11.21%	24.87%	--
	Rodlet 4	207.45	186.49	19.19%	10.01%	36.17%	--
	Rodlet 5	156.79	165.69	21.97%	13.26%	0.00%	--
	Dummy	0.00	0.00	0.00%	0.00%	0.00%	--
E-2 AFC-1H (Metal)	Rodlet 1	213.01	150.76	4.13%	2.62%	10.00%	3.82%
	Rodlet 2	241.22	152.38	4.39%	2.23%	12.27%	5.08%
	Rodlet 3	271.79	211.70	6.33%	4.37%	14.39%	5.75%
	Rodlet 4	294.88	208.59	5.62%	3.66%	13.29%	5.41%
	Rodlet 5	293.71	210.22	5.26%	3.70%	12.34%	4.88%
	Rodlet 6	219.82	172.04	5.16%	3.43%	12.59%	4.42%
E-3 AFC-1G (nitride)	Rodlet 1	138.41	118.47	3.77%	1.90%	--	--
	Dummy	0.00	0.00	0.00%	0.00%	0.00%	--
	Rodlet 3	263.99	176.41	4.39%	2.43%	11.44%	4.86%
	Rodlet 4	204.36	174.51	5.55%	2.89%	--	--
	Dummy	--	--	--	--	--	--
	Dummy	--	--	--	--	--	--

Note: *All the MCNP tallies are normalized to a E-lobe source power of 22.3 MW.*

6. FUTURE AFC-1 IRRADIATIONS

The high burnup AFC-1D test assembly is expected to complete irradiation in January 2006 at the end of ATR operating Cycle 136A and the high burnup AFC-1G and AFC-1H tests in December 2006 at the end of ATR operating Cycle 138B. Table 8 shows the tentative irradiation schedule through FY 2006. A final irradiation report will be prepared at the end of each fiscal year and at the completion of irradiation.

Table 8. AFCI Irradiation Schedule.



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