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Advanced Fuel Cycle Initiative

Projected Linear Heat Generation Rate And Burnup Calculations

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ABSTRACT

This report provides physics analysis performed to determine the linear heat generation rate and burnup calculations for the Advanced Fuel Cycle Initiative tests, AFC-1D, AFC-1H, and AFC-1G. These tests will be irradiated during Advanced Test Reactor Cycle 135B.

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Advanced Fuel Cycle Initiative Projected Linear Heat Generation Rate and Burnup Calculations for ATR Cycle 135B

1. INTRODUCTION/SUMMARY

This report provides documentation of the physics analysis performed to determine the linear heat generation rate (LHGR) and burnup calculations for the Advanced Fuel Cycle Initiative (AFCI) tests, AFC-1D, AFC-1H, and AFC-1G. The AFC-1D and AFC-1H tests consists of low-fertile metallic fuel compositions and the AFC-1G test consists of non-fertile and low-fertile nitride compositions. These tests will be irradiated in the East Flux Trap (EFT) positions E1, E2, and E3, respectively, during Advanced Test Reactor (ATR) Cycle 135B.

To ensure the AFCI tests being inserted into the ATR meet reactor safety requirements, an Experiment Safety Assurance Package (ESAP) has been prepared. A key ESAP requirement is to perform thermal and physics calculations to ensure that the ESAP LHGR limit of ≤400 W/cm on any rodlet contained in the AFC-1 test assembly is met. Therefore, prior to each cycle that the AFCI experiments are scheduled to be inserted into the reactor, calculations are performed and documented in an Engineering Design File (EDF) to verify that the LHGR limit of 400 W/cm will not be exceeded during the cycle duration.

The evaluation of the AFC-1 irradiation tests was performed using the computer codes MCNP and ORIGEN2 via a coupling UNIX script, MCWO. The results demonstrate that the LHGR of the tests will remain below the ESAP limit of 400W/cm during ATR Cycle 135B.

The AFCI also has a desired programmatic upper LHGR limit of 330 W/cm, with a desired nominal value of 300 W/cm. Calculated results show that with a maximum reactor cycle power in the East lobe of 24.4 MW, the projected maximum LHGR reaches 321.4 W/cm. This is within the desired programmatic envelope for a LHGR not to exceed 330 W/cm.

2. PHYSICS EVALUATIONS FOR THE AFC-1D, -1G, AND -1H TESTS IN EFT, CYCLE 135B

The AFCI test assemblies, AFC-1D, -1G, and -1H, are scheduled to be inserted in the EFT of the ATR during Cycle 135B. The beginning of cycle material composition for the AFC–1D test is based on as-run analyses performed from previous irradiation cycles. The beginning of cycle material compositions for the AFC-1G and AFC-1H tests was provided by the fuel fabrication facility—Argonne National Laboratory.[1]

The metal fuel capsules, AFC-1D and AFC-1H, will be inserted in test positions E1 and E2; and the nitride capsule, AFC-1G, will be inserted in test position E3. The GFR-1 material capsule will be inserted in test position E4. However, because the GFR-1 material capsule does not contain any fissile material, its LHGR is low and does not affect the calculated results. Therefore it is not included in this physics analysis.

3. ASSUMPTIONS

The assumptions used for performing this analysis and the influence on the analytical results are listed and discussed briefly.

1. The three test positions in the EFT that are not being used for the AFCI irradiations, (E5, E6, and E7) will contain aluminum fillers. This configuration was determined by TRA Nuclear Safety.
2. The tests in position E1, E2, E3, and E4 will be placed in new cadmium baskets. This is an approved configuration, and results in the lowest beginning of cycle linear heat rates. Placement of AFC-1D, -1G, or -1H in a partially depleted basket would require that the LHGR analysis be re-done to simulate the change.
3. The source power in the East lobe is assumed to be 23.0 MW and is a conservative value based on the projected operational power splits for Cycle 135B of 22.2 MW. Any increase in the NE, Center, or SE lobe power levels above the projected values will require verification that the ESAP limit will be met.

4. DATA

The material composition in the AFC-1G and –1H tests are tabulated in Tables 1 and 2. The material composition for AFC-1D is based on as-run analyses performed for previous irradiation cycles and results are shown in Table 3 and Table 4.

Table 1. Experiment Fuel Composition (Isotopic G/Cm^3) For AFC-1G at the Beginning of Irradiation.

Fuel Column Constituent Densities (g/cm3)											
Rodlet	Np-237	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	N	Zr	Total Density
-1G-1	1.132	2.556	3.124	0.000	2.689	0.171	0.003	0.001	1.726	0.669	0.000	12.070
-1G-2	1.406	0.000	0.000	0.000	2.674	0.171	0.003	0.001	1.429	0.783	2.934	9.400
-1G-3	0.000	0.000	0.000	0.000	2.651	0.168	0.003	0.001	2.835	0.777	2.919	9.354
-1G-4	1.132	2.556	3.124	0.000	2.689	0.171	0.003	0.001	1.726	0.669	0.000	12.070
-1G-5	0.000	2.541	3.106	0.000	2.673	0.171	0.003	0.001	2.858	0.664	0.000	12.017
-1G-6	0.000	0.000	0.000	0.000	2.651	0.168	0.003	0.001	2.835	0.777	2.919	9.354

Table 2. Experiment Fuel Composition (Isotopic G/Cm^3) For AFC-1H at the Beginning of Irradiation.

Fuel Column Constituent Densities (g/cm^3)												
Rodlet	Np-237	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	N	Zr	Total Density
-1H-1	0.230	3.149	0.892	0.002	2.770	0.548	0.017	0.012	0.463	0.000	3.463	11.546
-1H-2	0.259	4.041	1.143	0.002	3.647	0.722	0.023	0.015	0.519	0.000	2.593	12.965
-1H-3	0.207	2.436	0.689	0.002	2.154	0.425	0.012	0.008	0.313	0.000	4.166	10.413
-1H-4	0.230	3.149	0.892	0.002	2.770	0.548	0.017	0.012	0.463	0.000	3.463	11.546
-1H-5	0.000	3.120	0.884	0.002	2.649	0.525	0.017	0.010	0.801	0.000	3.432	11.440
-1H-6	0.207	2.436	0.689	0.002	2.154	0.425	0.012	0.008	0.313	0.000	4.166	10.413

Table 3. Experiment Fuel Composition (Isotopic G/Cm^3) For AFC-1D at the Beginning of Cycle 135B.

Fuel Column Constituent Densities (g/cm3)									
Rodlet	U-235	U-238	Np-237	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
-1D-1	6.321E-5	4.165E-8	2.295E-2	5.951E-2	3.349E-0	7.137E-1	1.595E-1	4.545E-2	8.916E-1
-1D-2	6.864E-5	4.458E-8	7.945E-1	2.019E-1	2.684E-0	5.703E-1	1.752E-1	4.721E-2	7.395E-1
-1D-3	7.258E-5	4.383E-8	2.427E-5	6.556E-3	4.012E-0	8.604E-1	2.533E-1	2.068E-2	2.262E-2
-1D-4	6.395E-5	5.592E-8	1.920E-2	8.006E-2	3.193E-0	7.073E-1	2.069E-1	5.642E-2	8.099E-1
-1D-5	4.019E-5	2.489E-8	2.131E-6	2.951E-3	2.186E-0	4.539E-1	1.907E-1	1.497E-2	2.678E-3
-1D-6 Dummy	-	-	-	-	-	-	-	-	-

Table 4. Experiment Fuel Composition (Isotopic Atoms/Barn-Cm) For AFC-1D at the Beginning of Cycle 135B.

Fuel Column Constituent Densities (atoms/barn-cm)									
Rodlet	U-235	U-238	Np-237	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
-1D-1	1.620E-7	1.054E-10	5.833E-5	1.506E-4	8.438E-3	1.791E-3	3.985E-4	1.131E-4	2.228E-3
-1D-2	1.759E-7	1.128E-10	2.019E-3	5.108E-4	6.763E-3	1.431E-3	4.377E-4	1.175E-4	1.848E-3
-1D-3	1.860E-7	1.109E-10	6.167E-8	1.659E-5	1.011E-2	2.159E-3	6.330E-4	5.146E-5	5.653E-5
-1D-4	1.639E-7	1.415E-10	4.878E-5	2.026E-4	8.046E-3	1.775E-3	5.171E-4	1.404E-4	2.024E-3
-1D-5	1.030E-7	6.299E-11	5.415E-9	7.468E-6	5.509E-3	1.139E-3	4.766E-4	3.725E-5	6.691E-6
-1D-6 Dummy	-	-	-	-	-	-	-	-	-

5. COMPUTER CODES AND DATA RETENTION

The predicted physics analyses were performed using the computer code MCNP.[2] MCNP is a general Monte Carlo n-particle code written at the Los Alamos National Laboratory. Version 4B of the MCNP code, as described in LA-13709-M, Los Alamos National Laboratory (2000), was used in the evaluation. This version has been verified at the INEEL by benchmarking calculated flux magnitudes with measured flux levels for several experiments and in several test positions of the ATR core.

The code and the ATR core model have also been benchmarked for heat rate evaluations by comparison of the predicted to as-run temperatures in ATR experiments.[3,4,5,6,7] MCNP is used to provide the input for ORIGEN-2,[8] which is used to provide the depletion and transmutation for updating the MCNP model. The input and output for the two codes are transmitted via a UNIX coupling script, MCWO. The computer codes MCNP, MCWO, and ORIGEN-2 are contained in the INEEL qualified code list.

These calculations have been documented in an INEEL Engineering Design File.[9] The input and output files will be retained on the GSCMOX computer until this EDF is approved. This is contingent on operability of the computer GSCMOX. After approval of the EDF the input file and the output file will be placed on a CD and stored in Document Control with the EDF.

6. MODEL

The ATR configuration was modeled to represent the nominal power split projected for Cycle 135B as, NW-NE-C-SW-SE (18, 18, 23, 23, and 25 MW). The East flux trap source power is determined by the following calculation:

(NE+C+SE)/3.

For Cycle 135B the calculation is as follows:

(18+23+25)/3 = 22.16 MW.

For conservatism, the analyses assumed an East flux trap source power of 23 MW. The basic ATR physical model has been verified and validated by the comparison of the predicted performance to the measured performance for previous experiments irradiated in the ATR.

7. RESULTS

At the beginning of Cycle 135B, six variants of transuranic containing zirconium-based alloy fuels (AFC-1H) and six plutonium-zirconium nitride-based fuel types (AFC-1G) containing Am and Np will be inserted with AFC-1D. Each miniature fuel pin is six inches in total length, and all pins are externally identical.

The radial view of the AFC-1 test assembly arrangement in the East flux trap is shown in Figure 1. The metal assemblies AFC-1D and AFC-1H and the nitride assembly AFC-1G are located at E1, E2, and E3 positions, respectively. Each test assembly will contain six rodlets, designated as rodlet 1 to rodlet 6 as seen in the axial view in Figure 2. The AFC-1G and -1H fuel loadings for each rodlet are tabulated in Table 1 and Table 2 and the AFC-1D compositions are tabulated Table 3 and Table 4. The U-235 enrichments are specified to meet the required linear heat generation rate requirements with the 45-mils cadmium shroud being used for the tests.

The validated MCNP code was used to provide the input for ORIGEN-2. The ORIGEN-2 code is then used to provide the depletion and transmutation for updating the MCNP model. The input and output for the two codes is transmitted via a UNIX coupling script, MCWO. The MCWO-calculated burnup and fission heat rate distributions of the proposed AFC-1 rodlets for 48 Effective Full Power Days (EFPDs) of irradiation during Cycle 135B are tabulated in Table 5 and Table 6. Because of the depletion of Cd-113 during irradiation, the peak LHGR occurs in AFC-1H metal rodlet 2, which increases from 294.3 W/cm in Table 5 to 303.0 W/cm in Table 6.

The results demonstrate that the desired test conditions can be achieved in the EFT with an East lobe source power of 23 MW. The results also demonstrate that the ESAP requirement for LHGR not to exceed 400 W/cm is met with an EFT source power limit of 26.8 MW.[10] The MCNP results using an East source power of 23 MW indicate that the peak LHGR will occur at the end of Cycle 135B. The peak LHGR is 303.0 W/cm in AFC-1H metal rodlet 2.

The AFCI also has a desired programmatic upper LHGR limit of 330 W/cm, with a desired nominal value of 300 W/cm. Calculated results show that with a maximum reactor cycle power in the East lobe of 24.4 MW and using the evaluated condition of 23 MW as the East source power, the projected maximum LHGR is:

(24.4/23) x 303.0 = 321.4 W/cm.

This is within the desired programmatic envelope for a LHGR not to exceed 330 W/cm.

Table 5. Linear Fission Heat Rate and Burnup Distribution of the AFC-1 Fuel in the East Flux Trap Position at the Beginning of Cycle 135B Irradiation.

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	151.55	146.39	9.84%	4.91%	19.65%	
	Rodlet 2	166.65	172.82	12.75%	5.51%	24.79%	
	Rodlet 3	254.67	241.4	13.66%	8.00%	22.74%	
	Rodlet 4	206.11	202.16	13.97%	7.01%	26.80%	
	Rodlet 5	156.76	219.04	16.31%	9.53%	0.00%	
	Dummy	0	0	0.00%	0.00%	0.00%	
E2 AFC-1H (Metal)	Rodlet 1	201.77	138.1	0.00%	0.00%	0.00%	0.00%
	Rodlet 2	294.28	179.34	0.00%	0.00%	0.00%	0.00%
	Rodlet 3	251.9	191.15	0.00%	0.00%	0.00%	0.00%
	Rodlet 4	281.06	192.38	0.00%	0.00%	0.00%	0.00%
	Rodlet 5	251.25	173.54	0.00%	0.00%	0.00%	0.00%
	Rodlet 6	174.78	132.63	0.00%	0.00%	0.00%	0.00%
E3 AFC-1G (Nitride)	Rodlet 1	195.67	113.25	0.00%	0.00%	0.00%	0.00%
	Rodlet 2	139.27	103.48	0.00%	0.00%	0.00%	0.00%
	Rodlet 3	159.94	119.45	0.00%	0.00%	0.00%	0.00%
	Rodlet 4	288.75	167.13	0.00%	0.00%	0.00%	0.00%
	Rodlet 5	268.77	156.23	0.00%	0.00%	0.00%	0.00%
	Rodlet 6	128.85	96.23	0.00%	0.00%	0.00%	0.00%
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.							

Table 6. The Linear Fission Heat Rate and Burnup Distribution of the AFC-1 Fuel in the East Flux Trap Position at the End of Cycle 135B Irradiation (48 EFPDs).

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	Rodlet 1	158.92	154.78	12.16%	6.13%	23.58%	
AFC-1D	Rodlet 2	176.46	184.8	15.62%	6.85%	30.04%	
(Metal)	Rodlet 3	274.14	263.3	16.89%	9.99%	24.78%	
	Rodlet 4	224.12	222.38	17.13%	8.69%	32.66%	
	Rodlet 5	171.14	242.02	19.64%	11.70%	0.00%	
	Dummy	0	0	0.00%	0.00%	0.00%	
E2	Rodlet 1	211.96	146.45	1.98%	1.37%	5.36%	2.04%
AFC-1H	Rodlet 2	302.96	186.92	2.15%	1.54%	5.71%	2.24%
(Metal)	Rodlet 3	261.58	201.18	3.65%	2.27%	8.23%	3.50%
	Rodlet 4	298.93	207.33	3.11%	1.92%	7.61%	2.92%
	Rodlet 5	263.41	184.22	2.71%	1.81%	6.45%	2.71%
	Rodlet 6	183.99	140.92	2.36%	1.56%	5.76%	2.33%
E3	Rodlet 1	200.95	117.28	1.77%	0.89%	4.10%	1.90%
AFC-1G	Rodlet 2	147.09	110.04	2.85%	1.15%	5.76%	0.00%
(Nitride)	Rodlet 3	169.29	127.49	3.34%	1.41%	5.36%	0.00%
	Rodlet 4	294.44	172.5	2.57%	1.30%	5.74%	2.71%
	Rodlet 5	275.33	161.92	2.51%	1.26%	5.06%	2.59%
	Rodlet 6	134.14	100.86	2.80%	1.16%	4.26%	0.00%
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.							

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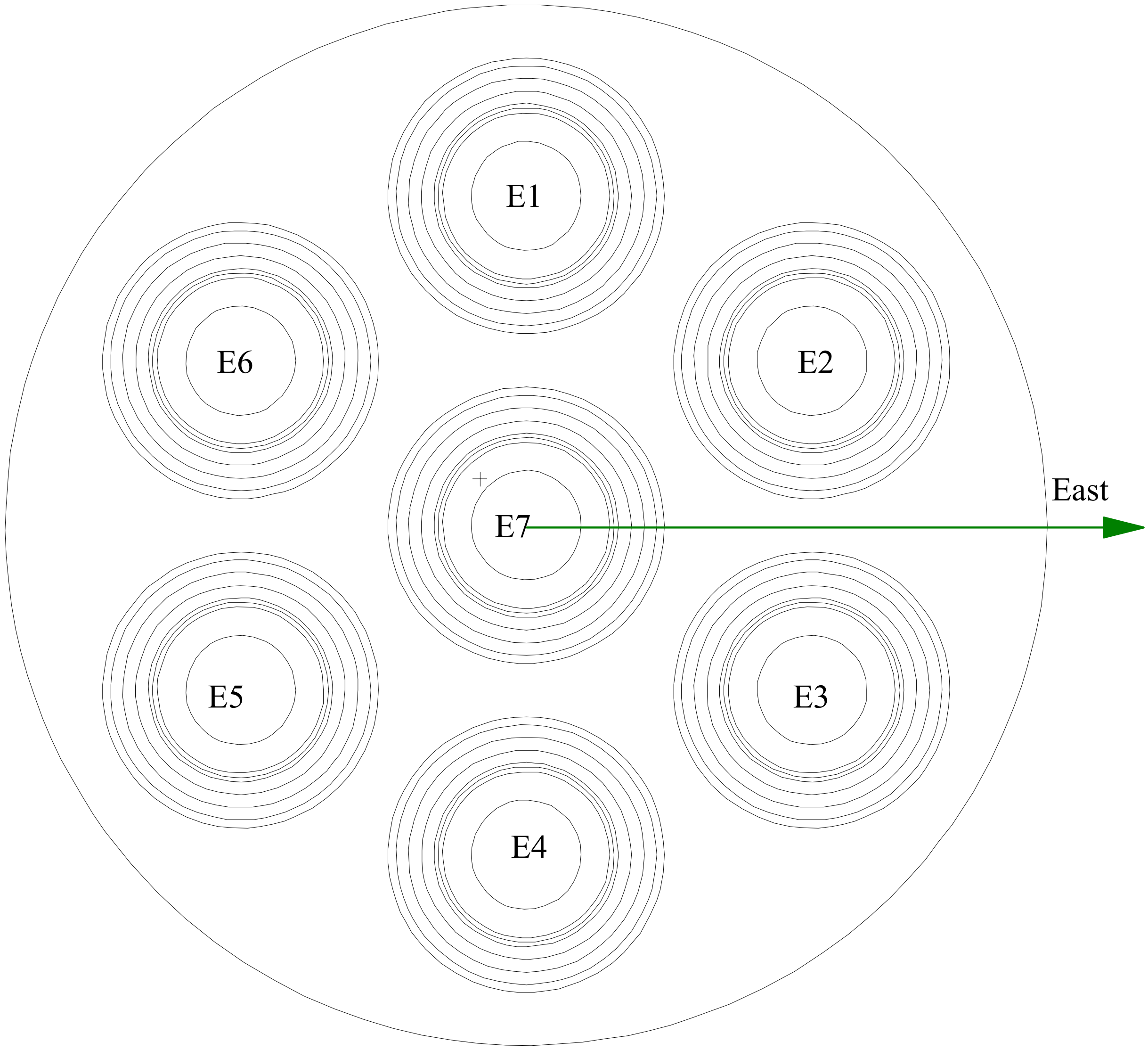

Figure 1. X-Y View of AFC-1 Test Assembly Arrangement in the East Flux Trap Position (metal capsules in E1 and E2, and nitride capsule in E3 positions).

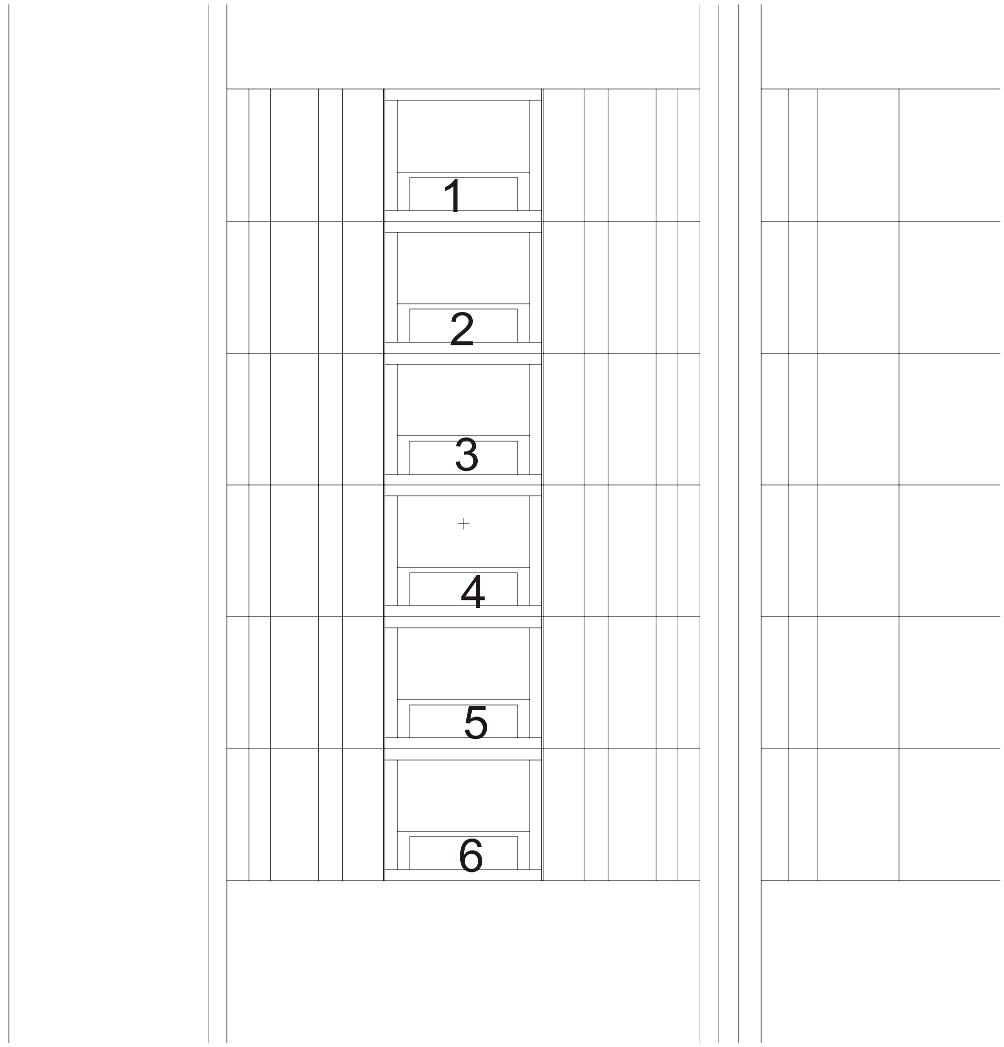

Figure 2. Axial View of AFC-1 Test Assembly Arrangement in East Flux Trap Position for Test Rodlets 1 to 6.