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Advanced Test Reactor Neutron Dosimetry Report

Analytical Laboratories Radiation Measurements Department (U440)

Results of Neutron Dosimetry Measurements for the Advanced Test Reactor Cycle 172A-1

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SUMMARY

Results of neutron dosimetry measurements in ATR for cycle 172A-1 are presented. Cobalt and nickel wires were installed in numerous irradiation locations for the duration of the cycle. The specific activity of these wire segments can be used in conjunction with the presented cycle history information to determine the thermal- and fast-neutron fluence rates for each irradiation position during the cycle using the referenced standard test methods.

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ACRONYMS

ATR	Advanced Test Reactor
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy-Idaho Operations Office
INL	Idaho National Laboratory
OSCC	Outer Shim Control Cylinder
FMWH	Fluence Monitor Wire holder
SR	Safety Rod
FMWS	Fluence Monitor Wire Scanner
HPGe	High Purity Germanium
N	North
S	South
E	East
W	West
NW	North-West
NE	North-East
SE	South-East
SW	South-West

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1. ATR REACTOR DOSIMETRY MOTIVATION

The Advanced Test Reactor (ATR) is a versatile nuclear research reactor located at the Idaho National Laboratory (INL) in eastern Idaho, United States. It is one of the most powerful and flexible research reactors in the world and is primarily used for materials testing, isotope production, and basic nuclear science research. The ATR is a light-water-cooled, beryllium-moderated reactor with a nominal thermal power capacity of 250 MW utilizing specially designed fuel, arranged in a serpentine pattern to create 9 flux traps, illustrated in Fig. 1. The special design of ATR allows for the neutron flux in flux traps to be controlled locally by 16 outer shim control cylinders (OSCCs), providing flexibility for experiment programs, and allowing experiments with different dose requirements to be irradiated concurrently. The expected neutron flux in most experiments in ATR is determined by simulation and modelling of the anticipated reactor conditions. Experiments placed in ATR provide their sponsors with insights into the physical response of materials and fuels to very high neutron fluences. The high neutron flux and long cycles that these materials are exposed to during irradiation at ATR is only available at this one-of-a-kind facility. This provides experiment sponsors with the ability to extrapolate experiment performance data, dramatically speeding up test programs that would not be possible without the high-flux environment at ATR. It is critical to measure the neutron fluence in ATR because of the heterogenous nature of the core and variations in the rector configuration between each ATR cycle. Simulations and models include numerous assumptions and often do not account for the complicated arrangement of experiments and components in the reactor. It is common for many experiments to be installed simultaneously in the ATR core, and frequently the various experiment programs do not have access to the full design parameters of the other experiments that are installed concurrently. The measurements obtained using fluence monitor dosimeter wires provide a critical validation of the assumptions that drive simulation and modelling efforts. These methods must therefore be validated using measured results from concurrent dosimetry measurements.

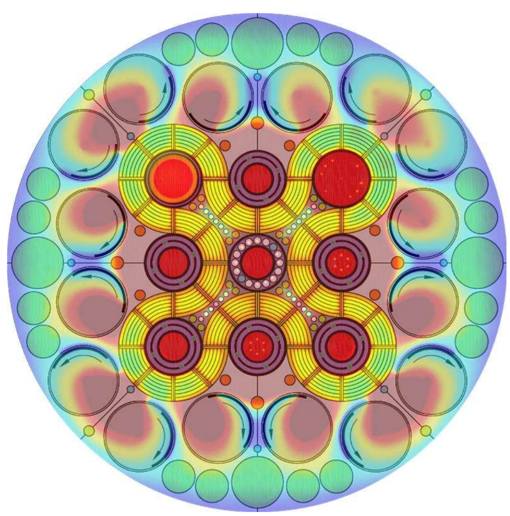

Figure 1. This heat-map of the neutron population in a typical ATR cycle illustrates the dramatic variations throughout the reactor and reflector due to the heterogeneous nature of the core (adapted from [1]).

Fluence Monitor Wire Holders (FMWHs) are assembled for each cycle such that the dosimeter wires are situated to span the fueled region of the reactor. The length of the dosimeter wires varies to ensure proper positioning after installation for each FWMH depending on the method and location of insertion into the reactor core. Each FMWH is assembled with care given to the type and length of each dosimeter wire, shown in Figure 2. Some FMWHs are attached directly to the safety rod drives (SR holders) such that the dosimeter wires are positioned in the reactor when the safety rods are fully withdrawn. These SR holders are typically situated in the N, S, E, W, SE, and SW flux traps [1] depicted in Figure 1. Other FMWHs are installed into drop-in positions or are integrated into experiment test-trains directly. Drop-in dosimetry is more common in the experiment positions in the beryllium reflector. The nominal dosimetry loading of each FMWH is either 0.1% or 0.5% Co/Al wire with a 97% nickel wire described in Table I.

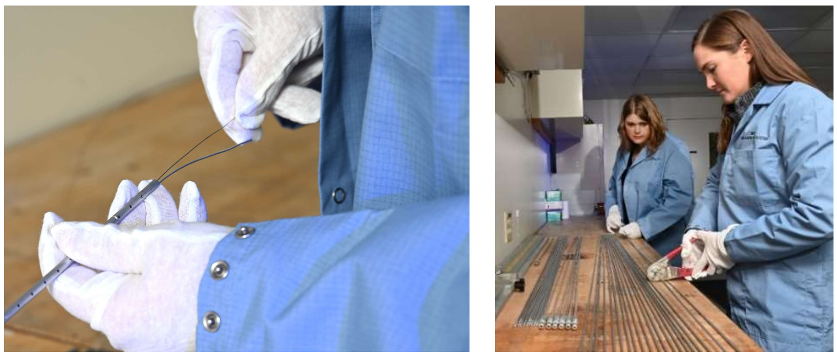

Figure 2. The FMWHs are assembled by hand at RML for each irradiation cycle, the Ni and Co/Al wires are cut to the appropriate length (LEFT) and held in place by crimping the FMWH so that their final position will span the fueled region of the reactor core (RIGHT).

Table 1. Description of typical dosimeter wire properties.

Wire Material	Nominal Purity	Diameter	Purpose
Cobalt / Aluminum	0.1% or 0.5% Co	0.8 mm	Thermal Neutrons
Nickel	97%	0.5 mm	> 1 MeV Neutrons

These dosimeter wires, which were selected to correspond with ASTM standards E481 [2] and E264 [3] respectively, activate predictably when exposed to a neutron flux. Following each irradiation cycle, the radioactivity of the wires is measured and can be used to determine the average neutron fluence rate, both fast and thermal [4], in that region of the reactor for that cycle. The neutron absorption cross-sections for the reactions of interest are shown in Figure 3.

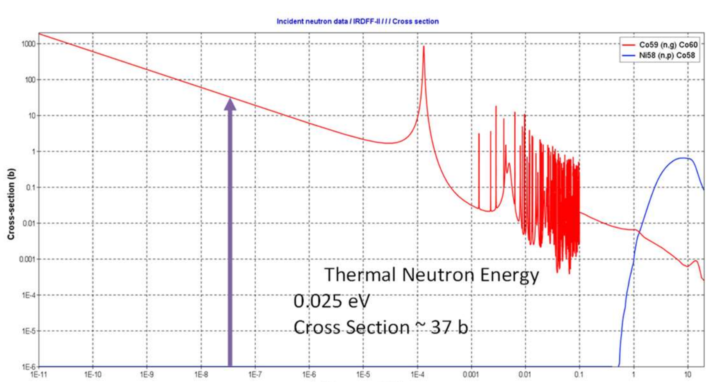

Figure 3. Neutron absorption cross-sections for the reactions of interest [5] [6]

These cross-sections show that cobalt is predominantly sensitive to thermal neutrons, however a large resonance for epithermal neutrons exists. If a 2200 m/s thermal cross-section is used to calculate fluence rate, a cadmium correction factor must be used to correct for epithermal neutron absorption in the cobalt wires. Alternatively, the energy-dependent cross section and a-priori flux may be used without a cadmium correction [2]. The amount of correction that is applied for epithermal neutron absorption depends on the location of the FMWH and is therefore not a constant but rather a function of position. During the irradiation of Cycle 152A, additional measurements were performed using cadmium covered as well as bare neutron monitors in the Southwest, Southeast, and H positions of the Center lobe to determine the division in neutron energy between epithermal and thermal neutrons summarized in Table 2 [7]. Nickel has a threshold energy near 1 MeV for neutron absorption and is commonly used for measurement of >1-MeV neutrons. Using the energy-dependent activation cross-section along with an a-priori neutron energy profile accounts for this difference. However, if the ^{235}U thermal fission spectrum averaged cross section of 92 mb is used, a fast-fission factor must be calculated to account for the number of fission neutrons born below 1-MeV which contribute to nickel activation. Calculated fast-fission correction factors for historical dosimetry measurements at ATR are summarized in Table 3. Finally, a correction for the burnup of ^{58}Co in nickel dosimetry wires under high thermal neutron flux irradiation conditions must be made [3].

Table 2. Resonance Corrections for Co-60 Measurements in ATR [7].

Holder Location	Resonance Correction
SW1 – SW4	0.78
W1, 2, 4	0.76
W3	0.81
N1, N2, N3	0.76
N4	0.81
E1	0.81
E2, E3, E4	0.76
S1, S3, S4	0.76
S2	0.81
SE1 - SE4	0.78
NW1 - NW4	0.78
NE1 - NE4	0.78
A1 - A8	0.76
A9 - A16	0.75
All B Positions	0.84
All I Positions	0.98

Table 3. Fast flux correction factors used in historical dosimetry measurements at ATR.

Experiment	Scaling Factor
SR	1.0
MP	1.0
IR (Generic)	1.0
BR (Generic)	1.0
NEFT	1.0
IRT3	1.167
EPRI	1.03
AGR	1.00
ATF	1.167
AFC	1.167
NuScale	1.0

2. REACTOR DOSIMETRY MEASUREMENTS

Following the irradiation cycle, the dosimeter wires are far too radioactive to be removed from the ATR canal and measured by conventional techniques. Therefore, an in-canal Fluence Monitor Wire Scanner (FMWS) was developed to measure the activity of the activated dosimeter wires. The original FMWS had been in service since 1958 where it served the Engineering Test Reactor (ETR) and Materials Test Reactor (MTR) for 13 years before being moved to the ATR Canal in 1971. The FMWS was historically used to measure the axial distribution of neutron flux in ATR but ceased to function in 2024. It is still used to obtain a segment of wire from the FMWH who's specific activity is reported herein.

The vertical position associated with the neutron dosimeter measurement are relative to the 80 ft. elevation (nominal core center-plane) of the ATR core. The elevation values are in inches and negative values are below the 80 ft. elevation. Using the dimensions of the dosimeter holders, the location of the dosimeter wire in the holder, and the length of the wire an elevation value the wire segment can be determined with the tolerances listed in Table 4.

Table 4. Dosimeter wire snippet tolerance stack-up.

Known Values	**Tolerance (in.)**
Holder Fabrication	+ 0.11
Cutting the Monitor Wire to Length	+ 0.10
Wire Alignment in the Holder	+ 0.13
Mounting the Wire to the Scanner	+ 0.13
Scanning Control	+ 0.01
Scanner Home Positioning	+ 0.06
Estimated Values	
4.25” Wire Scanner Fixture Offset	+ 0.25
Stack-up of the Experiment Components	± 0.33
Position of the Experiment Relative to 80 ft. during Operation	± 0.75
Total Tolerance	**+ 1.87 / - 1.08**

All wire segments were removed from position 1200 (24-in.) position of the dosimeter wire unless otherwise specified, corresponding to the dosimetry location relative to the core center plane in Table 5 for common holders at ATR. After removal from the ATR canal, each wire segment was returned to RML and weighted using a Meitler Toledo XP105 DeltaRange balance with a mass uncertainty of ± 0.00009 g and the gamma-ray activity of each isotope of interest is measured using HPGe detectors, shown in Figure 4.

Table 5. Summary of dosimetry wire snippet cut locations for FMWHs at ATR.

Experiment	Dosimeter Location (in.)
SR	0.75
MP-2	5.25
IR (Generic)	-6.75
BR (Generic)	-6.50
NEFT	9.00
IRT3	-2.00
EPRI[a]	12.63
AGR	3.00
ATF	7.20
AFC	7.20
NuScale	0.50

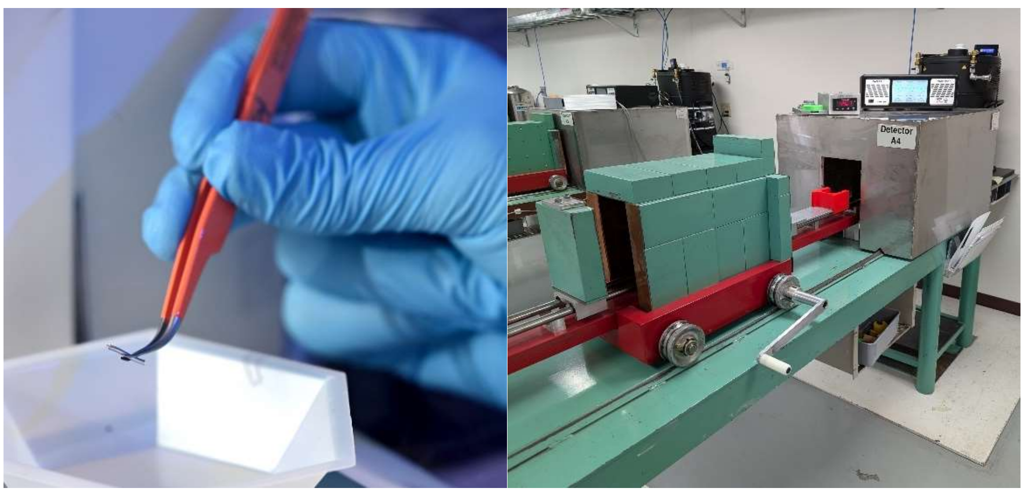

Figure 4. Each wire segment (LEFT) is weighed and measured using High Purity Germanium (HPGe) detectors (RIGHT).

2.1. MEASUREMENT RESULTS

The FMWH position, associated experiment, holder ID number, wire composition, wire weight, and associated nuclide activities were recorded for each cobalt and nickel wire segment recovered from FMWHs for the cycle. The measured activities were averaged across 4 HPGe detectors and the standard deviation of these 4 measurements are listed along with other relevant information in Table 6. The wire activity reported is decay corrected to the reactor shutdown date and time, March 20th, 2024 03:00 [8]. The measured wire concentrations are presented in **Error! Reference source not found.**.

[a] EPRI Holders are too short to cut at the 1200 position and are typically cut at position 950, nearest the core center plane.

Table 6. Summary of reactor dosimetry measurements for the ATR cycle.

Position	Experiment	Holder	Material	Wire Mass (mg)	Nuclide	Activity (Bq/g)	St. Dev. (Bq/g)	St. Dev. (%)
SE-4	2B-SE	**SR-404**	0.5% Co	6.6	Co-60	2.14E+09	1.13E+08	5.28%
			97% Ni	5.3	Co-58	9.78E+09	6.19E+08	6.32%
SE-3	2B-SE	**SR-403**	0.5% Co	7.5	Co-60	2.07E+09	1.14E+08	5.50%
			97% Ni	5.3	Co-58	9.94E+09	7.85E+08	7.90%
SE-2	2B-SE	**SR-402**	0.5% Co	5.8	Co-60	1.95E+09	1.64E+08	8.44%
			97% Ni	4.5	Co-58	9.11E+09	5.86E+08	6.43%
SE-1	2B-SE	**SR-401**	0.5% Co	5.5	Co-60	2.16E+09	1.12E+08	5.17%
			97% Ni	6.3	Co-58	9.63E+09	5.14E+08	5.34%
SW-4	2D-SW	**SR-400**	0.5% Co	6.9	Co-60	2.01E+09	1.35E+08	6.75%
			97% Ni	6.0	Co-58	9.99E+09	6.59E+08	6.60%
SW-3	2D-SW	**SR-399**	0.5% Co	7.0	Co-60	1.90E+09	1.10E+08	5.80%
			97% Ni	6.3	Co-58	8.90E+09	5.62E+08	6.31%
SW-2	2D-SW	**SR-398**	0.5% Co	7.0	Co-60	2.00E+09	7.32E+07	3.67%
			97% Ni	4.0	Co-58	9.17E+09	6.18E+08	6.75%
SW-1	2D-SW	**SR-397**	0.5% Co	6.9	Co-60	2.06E+09	1.19E+08	5.75%
			97% Ni	5.6	Co-58	9.30E+09	6.11E+08	6.57%
W-4	1C-W	**SR-396**	0.5% Co	6.9	Co-60	2.04E+09	1.09E+08	5.31%
			97% Ni	5.5	Co-58	5.52E+09	3.25E+08	5.88%
W-3	1C-W	**SR-395**	0.5% Co	6.6	Co-60	2.27E+09	1.23E+08	5.42%
			97% Ni	6.0	Co-58	4.27E+09	2.85E+08	6.67%
W-2	1C-W	**SR-394**	0.5% Co	5.4	Co-60	2.06E+09	1.14E+08	5.54%
			97% Ni	5.8	Co-58	9.31E+09	5.92E+08	6.37%
W-1	1C-W	**SR-393**	0.5% Co	5.7	Co-60	2.34E+09	1.32E+08	5.63%
			97% Ni	6.0	Co-58	8.87E+09	5.30E+08	5.97%
N-4	1D-N	**SR-392**	0.5% Co	6.6	Co-60	1.67E+09	9.86E+07	5.91%
			97% Ni	5.6	Co-58	3.37E+09	2.30E+08	6.82%
N-3	1D-N	**SR-391**	0.5% Co	6.9	Co-60	1.76E+09	1.03E+08	5.88%
			97% Ni	5.5	Co-58	7.19E+09	2.70E+08	3.76%
N-2	1D-N	**SR-390**	0.5% Co	6.2	Co-60	1.75E+09	9.94E+07	5.67%
			97% Ni	5.6	Co-58	8.05E+09	5.25E+08	6.53%
N-1	1D-N	**SR-389**	0.5% Co	5.3	Co-60	1.88E+09	1.07E+08	5.70%
			97% Ni	5.6	Co-58	5.59E+09	4.07E+08	7.28%
I-19	NuScale-A	**IR-67**	0.5% Co	4.1	Co-60	1.23E+08	9.16E+06	7.43%
			97% Ni	6.1	Co-58	1.17E+08	1.16E+07	9.96%
I-3	NuScale-D	**IR-66**	0.5% Co	6.5	Co-60	1.18E+08	9.52E+06	8.07%
			97% Ni	11.5	Co-58	1.34E+08	9.89E+06	7.41%
I-2	NuScale-C	**IR-65**	0.5% Co	4.5	Co-60	8.87E+07	6.24E+06	7.03%
			97% Ni	6.1	Co-58	7.82E+07	7.10E+06	9.08%

Table 7: Measured wire concentrations.

Wire Material	Nominal Purity	Measured Purity	Standard Deviation
Cobalt / Aluminum	0.50%	0.4842%	1.26%
Nickel	97%	98.67%	2.69%

2.2. CYCLE HISTORY

To calculate average fluence-rate from the specific activities provided in Table 6, the as-run cycle history must be approximated [9]. The stepwise approximation listed in Table 8 and depicted in Figure 5 represent the best integral fit of power provided by ATR Reactor Engineering for the cycle [8]. The total exposure for each lobe in ATR is summarized in Table 9 [8]. These values can be used to correct for the relative power distribution in the reactor core throughout the cycle. It is typical to use an average of the 3 adjacent lobes when determining exposures for off-lobe positions (i.e. N, S, E, & W). Likewise, exposures for positions in the reactor that are not situated directly in the in-pile tube locations must be approximated. It is typical to use the nearest lobe position as described in Table 10. Experiment positions in the reflector, beyond the OSCCs are not accurately represented by individual lobes and therefore cannot be similarly approximated.

Table 8. Stepwise approximation of total core power for the ATR cycle [8]

Duration (days)	Power (MWth)	Power Factor
3.27	24.9	0.15
2.83	32.9	0.19
0.35	113.1	0.66
0.90	171.8	1.00
3.12	112.7	0.66
3.22	0.1	0.00
0.27	46.9	0.27
3.93	113.3	0.66

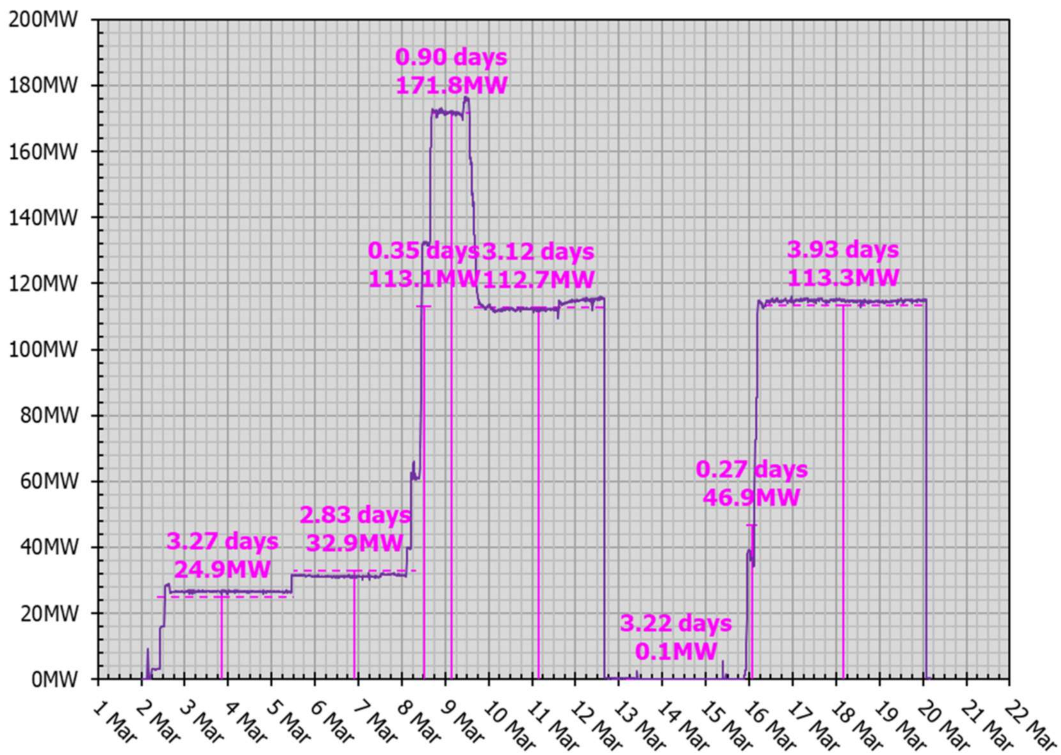

Figure 5. Stepwise approximation of total core power for the ATR cycle [8]

Table 9. Lobe exposure distribution for the ATR cycle [8]

Lobe	NW	NE	C	SW	SE
Exposure (MWd)	199.7	215.6	234.2	264.1	265.7
Effective Power (MW_{th})	13.6~~205~~	14.7~~232~~	16.0~~277~~	18.0~~292~~	18.1~~313~~

Table 10. Lobe power approximations for each experiment position in ATR.

Experiment Position	Lobe
A1 – A8	C
A9, B1, B2, I21	NE
A10, B3, B4, I22	SE
A11, B5, B6, I23	SW
A12, B7, B8, I24	NW
B9	N
B10	E
B11	S
B12	W

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