Analysis of the Cycle to Cycle Neutron Fluence Profiles in the Advanced Test Reactor

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TRTR 2016

M. K. Morrison Biography

- B. S. in Nuclear Engineering

  from Missouri's University of Science & Technology
- Minors in Mathematics and Material Science

- Started working at the Advanced Test Reactor in 2009
- Technical Lead in ATR Reactor Engineering

- ATR / INL Representative to TRTR Community since 2011
- Chair of ANS Standard 15.2

  Quality Control for Plate-Type Uranium-Aluminum Fuel Elements

Objective

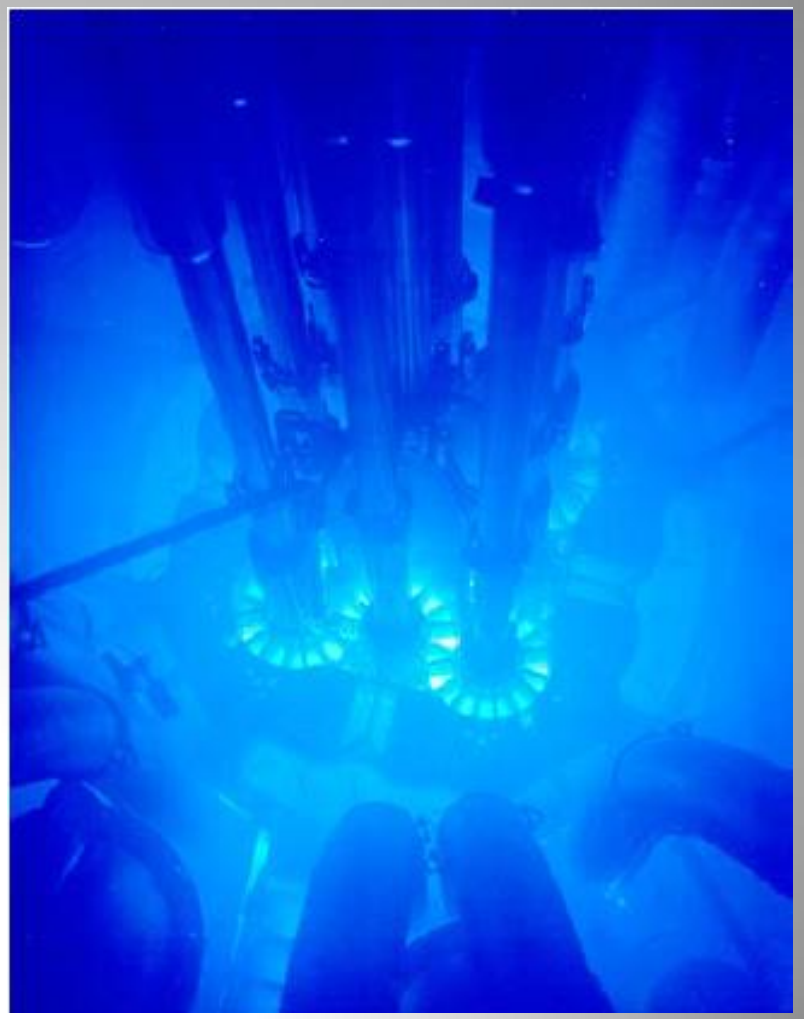
- Confirm that the ATR thermal and fast axial flux profiles have not changed over the last three core change evolutions.

Motivation

- Since the initial startup of ATR in 1967 there has been routine neutron fluence monitoring of the thermal and fast spectrums during every irradiation cycle.
- Each cycle is highly documented and monitored, providing a wealth of knowledge of reactor operation, performance, and experiment versatility.

The Advanced Test Reactor

Thermal Power (Maximum Design Power)	250 MW_{th}
Maximum Thermal Neutron Flux	$1.0 \times 10^{+15}$ n/cm^2-sec
Maximum Fast Neutron Flux	$5.0 \times 10^{+14}$ n/cm^2-sec
Flux Traps	9
In-Core Experiment Positions	68
Out-of-Core Experiment Positions	34
Fuel Elements	40
Active Core Length	4 ft (1.2 m)
Reactivity Control Drums/Rods	Hafnium
Coolant	Light Water
Reflector	Beryllium



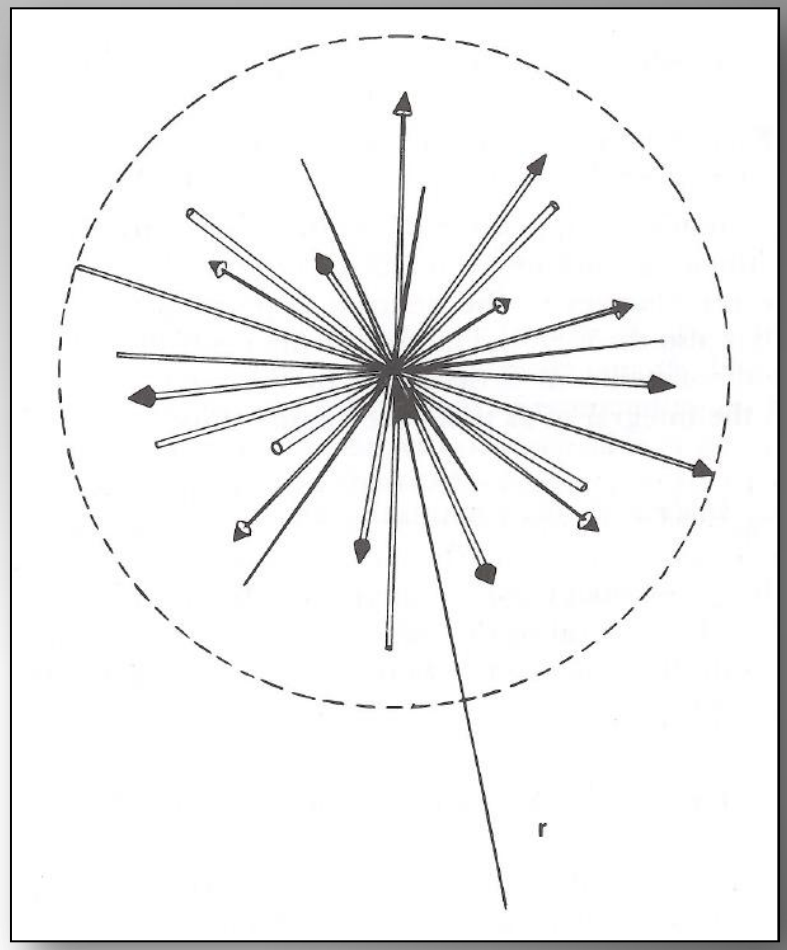
What is Flux and Fluence?

Flux

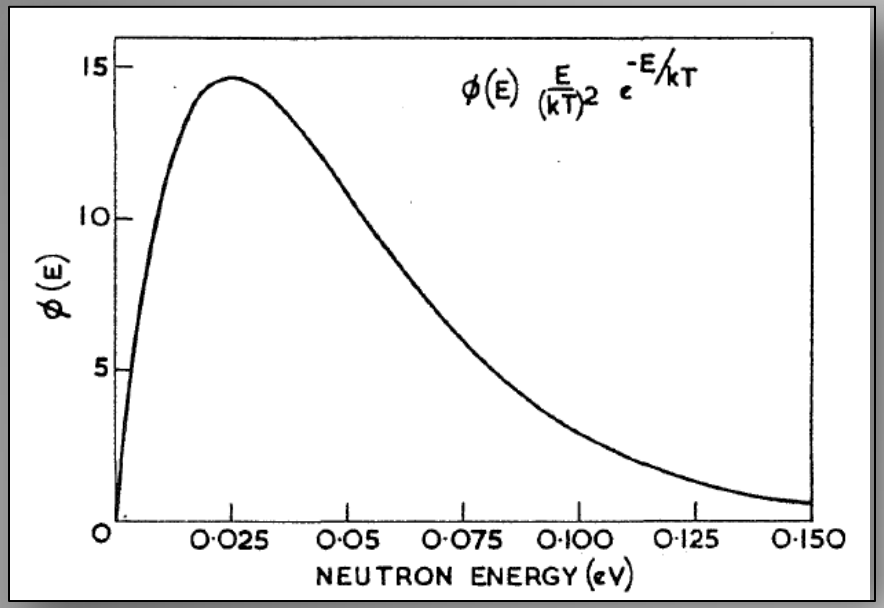
$$\phi(r,E) = \upsilon(E)n(r,E) = neutrons \Big/ \left(cm^2 \Big/ \text{sec}\right)$$

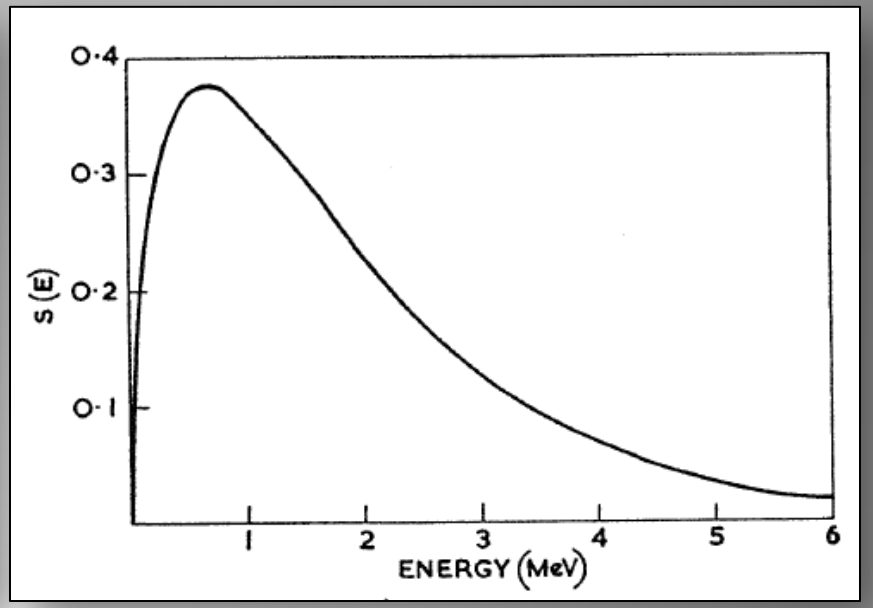
Fluence

$$\Phi(t) = \int_0^t \phi(t')dt$$



Neutron Energies





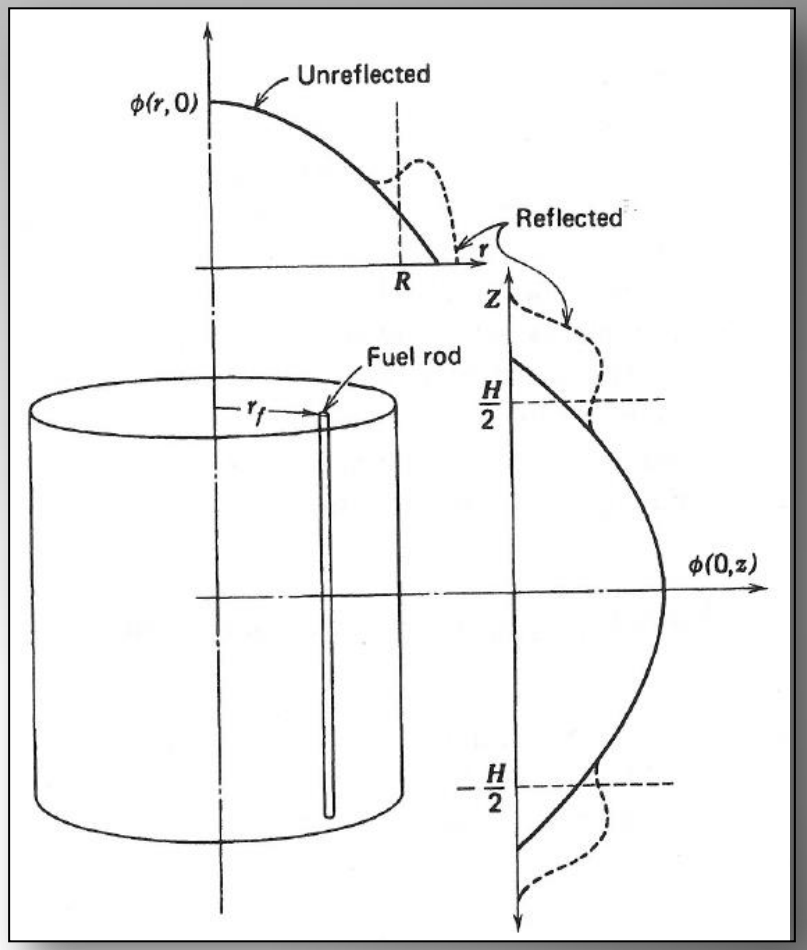
- Thermal neutron flux (0.025 eV)
- Measured by Co-59 (n,γ) Co-60
- Fast neutron flux (> 1 Mev)
- Measured by Ni-58 (n,p) Co-58

A Finite Reflected Cylindrical Core

$$\phi(r) = J_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{z\pi}{H}\right)$$

Bare Cylinder Equation

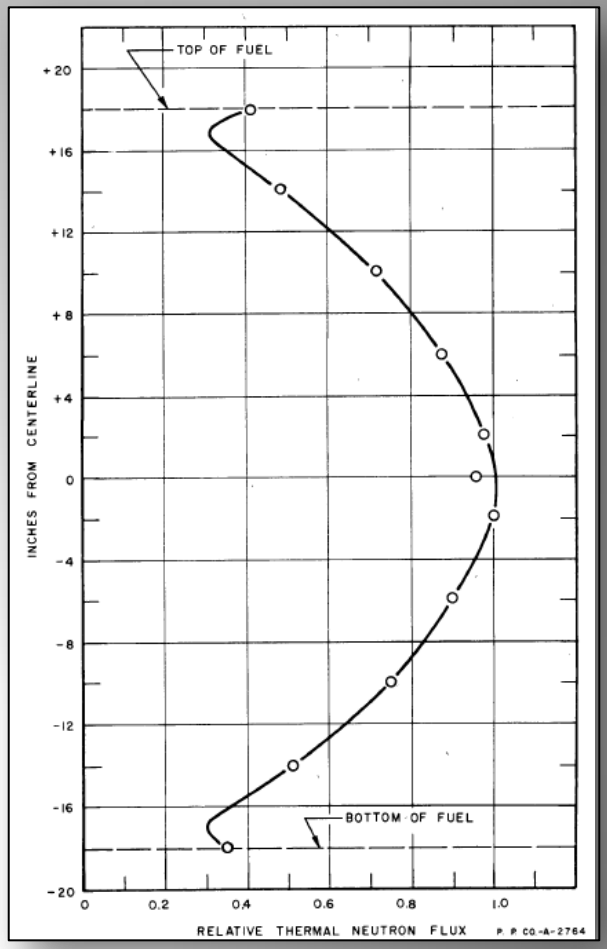
- Homogeneous fissile material
- Uniform flux profile
- Reflector helps to flatten flux profile
- Even irradiation of experiments, fuel, and core structures



Typical Normalized ATR Flux Profile

- Established during design development of ATR in the 1950's

- **Have the ATR flux profiles changed during the last three core change evolutions?**



Cycles of Interest

1994 CIC Cycles		2004 CIC Cycles		2012 Reconfiguration Cycles	
99B-1	103B-1	130B-1	134B-1/2	149A-1	152B-1
100A-1	104A-1	131A-1	135B-1/2	149B-1	154A-1
101B-1	104B-1	132A-1/2	135C-1	150B-1	154B-1
102A-1	105A-1	132B/C-1	136A-1	151A-1	155A-1
102B-1	105B-1	133B-1	136B-1	151B-1	155B-1

- ATR Cycle: interval of time reactor is critical and at power
- Every Cycle is uniquely identified
- Starts and Ends at SCRAM
- Analyzed data from 5 Cycles before and after core change evolution
- ATR has continuously operated since 1967

Cycles of Interest

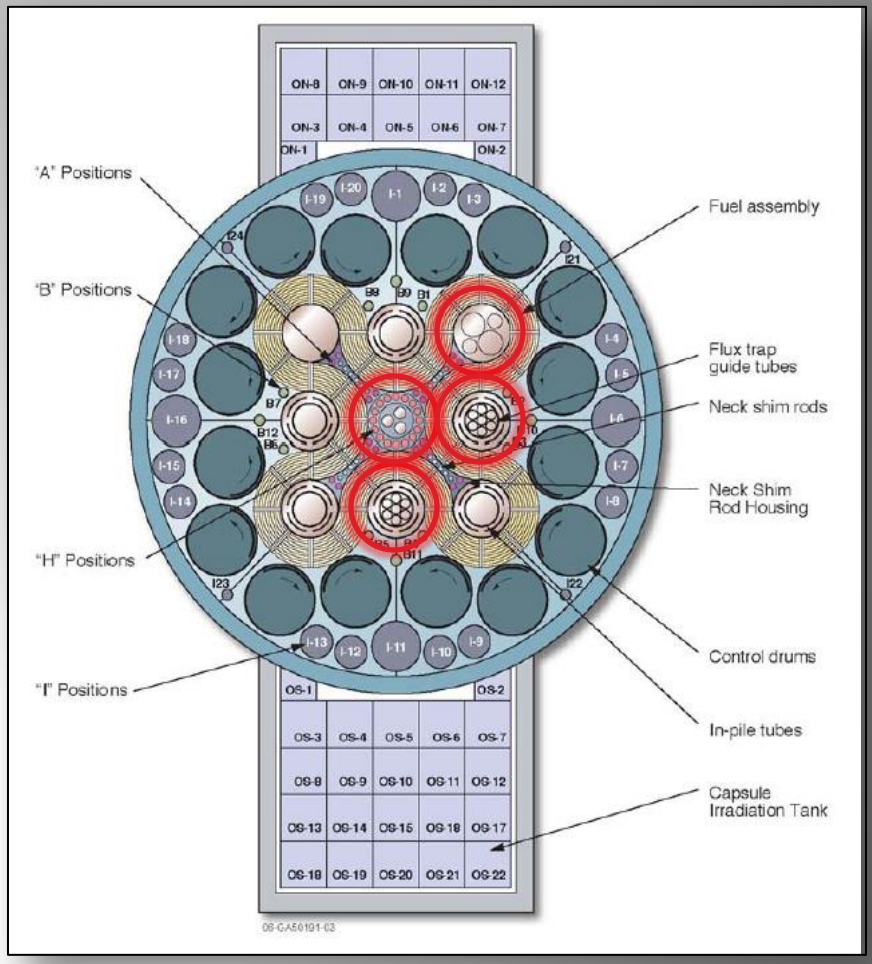
Cycle	EFPD	Cycle	EFPD	Cycle	EFPD
99B-1	33.7	130B-1	44.5	149A-1	36.8
100A-1	20.6	131A-1	48.5	149B-1	53.6
101B-1	35.0	132A-1/2	44.1	150B-1	41.9
102A-1	41.8	132B/C-1	50.3	151A-1	56.1
102B-1	34.9	133B-1	61.4	151B-1	51.3
103B-1	39.5	134B-1/2	46.5	152B-1	51.0
104A-1	43.4	135B-1/2	48.0	154A-1	52.3
104B-1	45.5	135C-1	40.6	154B-1	53.4
105A-1	43.7	136A-1	50.9	155A-1	55.1
105B-1	42.1	136B-1	39.0	155B-1	49.9

- Routine neutron fluence monitoring during every Cycle

$$EFPD = \int_0^t CF(t)dt = CF \times t$$

What is a Core Change Evolution

- Core Internals Change out (CIC)
- Replacement of Reflector and core structures
- Occurs roughly every 10 years
- Based on aggregate EFPD
- Experiment position reconfigurations
- These evolutions could alter the neutron flux profile



How Flux is Measured

- Thermal flux uses CoAl wire
- Co-59 (n,γ) Co-60 reaction
- Fast flux uses Ni wire
- Ni-58 (n,p) Co-58 reaction

- Wires are contained in Flux Monitor Holders
- Each holder is uniquely identified
- Safety Rod flux monitors are 56 inches long
- New Flux monitors are made for every cycle
- Process called Neutron Activation Analysis

Measurement Instrumentation

- Wire Scanner – an the inorganic scintillator NaI(Tl) detection system
- Located in ATR Canal area

- GIC - high pressure gamma ionization chamber
- Counts a 0.25 inch section of the flux monitor wires from where the highest flux was located
- Located in ATR Radiation Measurements Laboratory

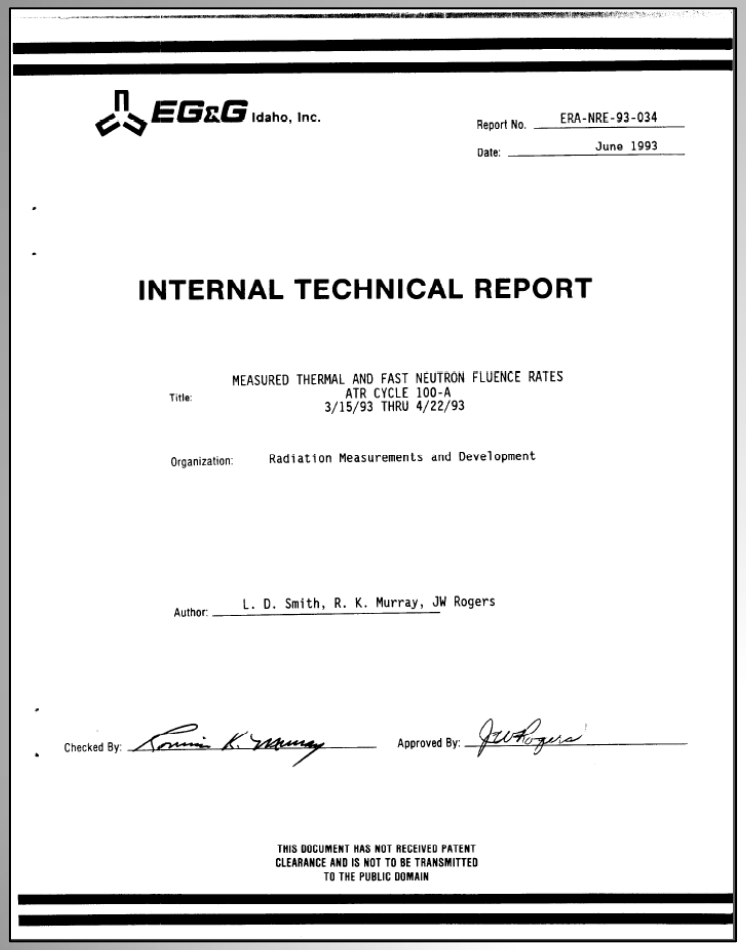
From Counts to Flux

$$A = N\sigma\phi(1 - e^{-\lambda t_i}) \qquad A = e^{-\lambda t_d}$$

- A = induced specific activity measured by the GIC
- N = number of atoms of the nuclide being activated in the wire per unit mass
- σ = averaged cross section for activation of the nuclide of interest
  - considers material specific factors such as epithermal adjustment and burnout correction
- λ= ln(2) / $t_{1/2}$ for the activated nuclide
- t_i = irradiation time (EFPD)
- t_d = decay time from SCRAM
- ϕ = neutron flux for the energy spectrum

$$\phi = \frac{A}{N\sigma\left(1 - e^{-\lambda t_i}\right)}$$

Measured Neutron Fluence Rate Reports



EG&G Idaho, Inc.

Report No. ERA-NRE-93-034

Date: June 1993

INTERNAL TECHNICAL REPORT

Title: MEASURED THERMAL AND FAST NEUTRON FLUENCE RATES
ATR CYCLE 100-A
3/15/93 THRU 4/22/93

Organization: Radiation Measurements and Development

Author: L. D. Smith, R. K. Murray, JW Rogers

Checked By: Louis K. Murray Approved By: J.W. Rogers

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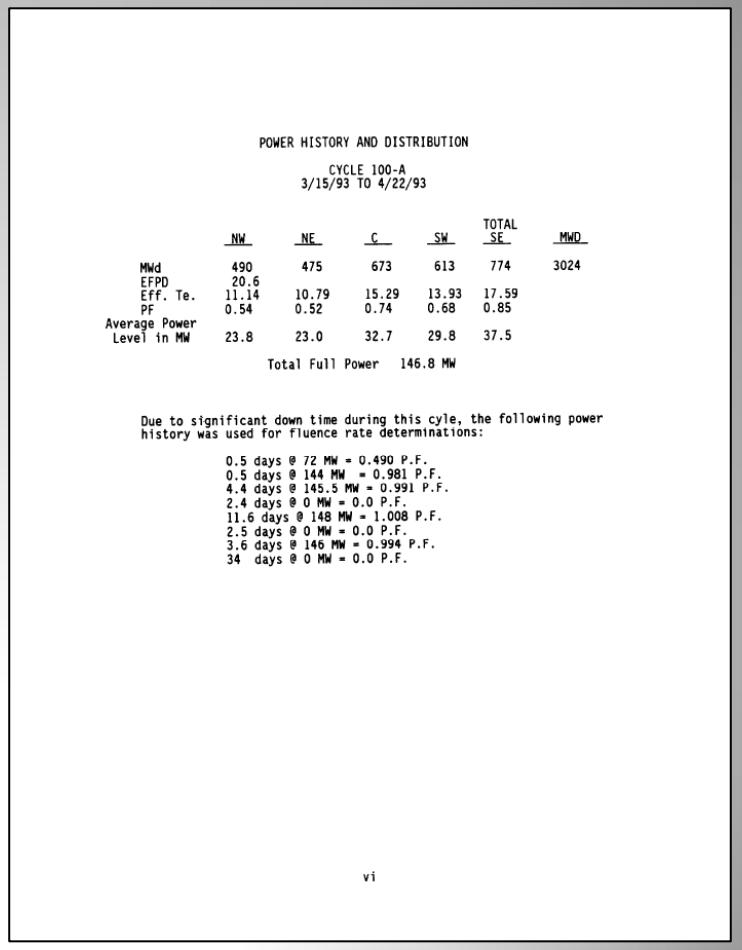

POWER HISTORY AND DISTRIBUTION

CYCLE 100-A
3/15/93 TO 4/22/93

	NW	NE	C	SW	TOTAL SE	MWD
MWd	490	475	673	613	774	3024
EFPD	20.6					
Eff. Te.	11.14	10.79	15.29	13.93	17.59	
PF	0.54	0.52	0.74	0.68	0.85	
Average Power Level in MW	23.8	23.0	32.7	29.8	37.5	

Total Full Power 146.8 MW

Due to significant down time during this cyle, the following power history was used for fluence rate determinations:

0.5 days @ 72 MW = 0.490 P.F.
0.5 days @ 144 MW = 0.981 P.F.
4.4 days @ 145.5 MW = 0.991 P.F.
2.4 days @ 0 MW = 0.0 P.F.
11.6 days @ 148 MW = 1.008 P.F.
2.5 days @ 0 MW = 0.0 P.F.
3.6 days @ 146 MW = 0.994 P.F.
34 days @ 0 MW = 0.0 P.F.

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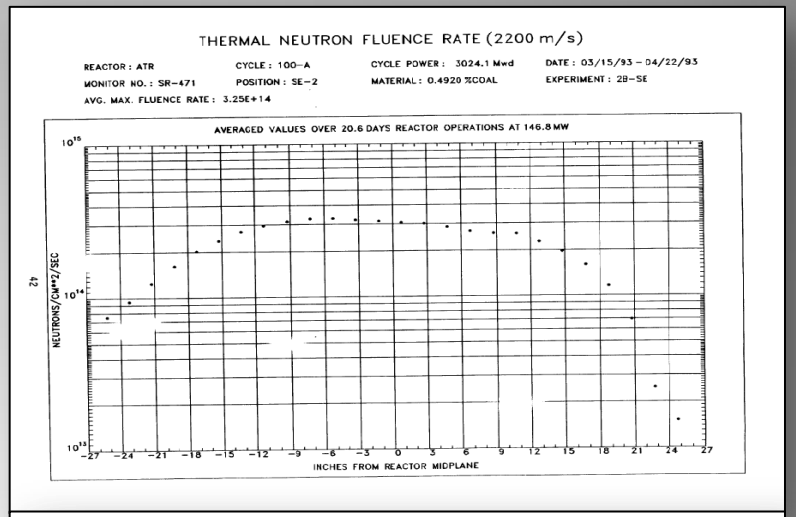
Report Data

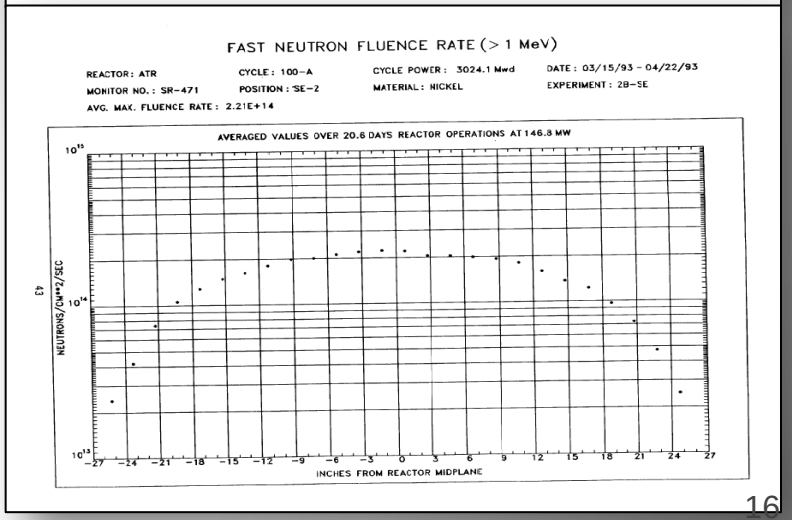
ATR NEUTRON MONITOR RESULTS PAGE: 9

CYCLE: 100-A POSITION: SE-2 MONITOR ID: SR-471
EFPD: 20.6 AVERAGE MW: 37.5 DATE: 03/15/93 to 04/22/93

ELEVATION from core CL (inches)	"THERMAL" 2200 m/s CO (n/cm**2/sec)	"FAST" >1 MeV NI (n/cm**2/sec)
24.73	1.52E+13	2.48E+13
22.75	2.49E+13	4.72E+13
20.75	6.98E+13	7.31E+13
18.75	1.16E+14	9.67E+13
16.75	1.60E+14	1.23E+14
14.75	1.96E+14	1.37E+14
12.75	2.27E+14	1.59E+14
10.75	2.57E+14	1.81E+14
8.75	2.59E+14	1.93E+14
6.75	2.68E+14	1.99E+14
4.75	2.86E+14	2.03E+14
2.75	3.01E+14	2.05E+14
0.75	3.07E+14	2.20E+14
-1.25	3.13E+14	2.22E+14
-3.25	3.19E+14	2.19E+14
-5.25	3.28E+14	2.12E+14
-7.25	3.26E+14	2.00E+14
-9.25	3.13E+14	1.98E+14
-11.25	2.95E+14	1.80E+14
-13.25	2.70E+14	1.63E+14
-15.25	2.36E+14	1.49E+14
-17.25	2.02E+14	1.28E+14
-19.25	1.61E+14	1.06E+14
-21.25	1.24E+14	7.41E+13
-23.25	9.46E+13	4.20E+13
-25.25	7.52E+13	2.40E+13

CENTER LINE FLU. RATE	3.07E+14	2.20E+14
AVG. MAX. FLU. RATE	3.25E+14	2.21E+14
MAX. FLU. RATE/MW (AVG.)	8.66E+12	5.88E+12
K FACTOR	288.41	3415.04
RESONANCE CORRECTION	0.76	NA
C/L. BURNOUT CORRECTION	1.001	1.956
BACKGROUND (COUNTS/SEC.)	1.52	1.52
CHECK SOURCE (COUNTS/SEC.) 05/14/93 08:51	1757.	1757.





Analysis Method

$$A = \begin{bmatrix} \\ \\ \end{bmatrix}$$

Normalization to 1

$$Max\ of\ A = B$$

$$\frac{A}{B} = \begin{bmatrix} \\ \\ \end{bmatrix} = C$$

Scaling to 20 MW

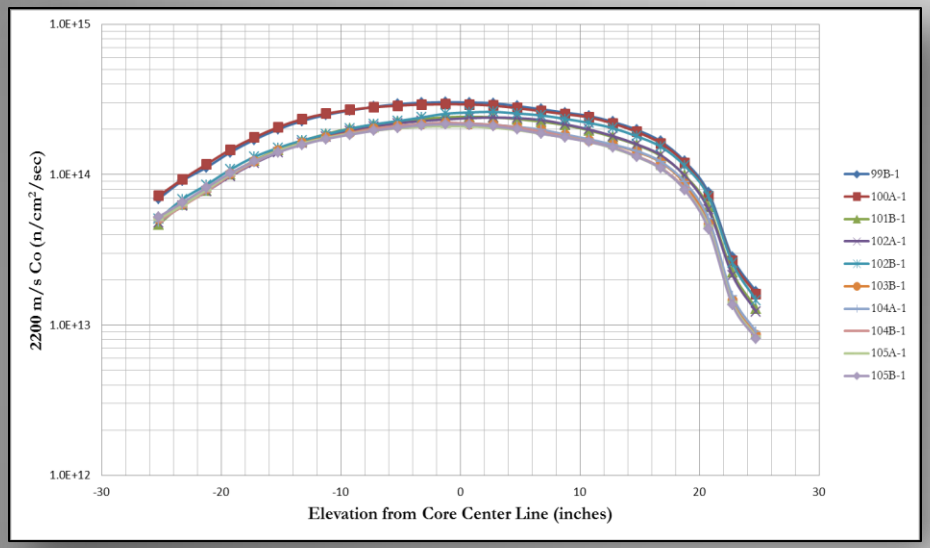
$$\frac{Power\ of\ A}{20\ MW} = Y$$

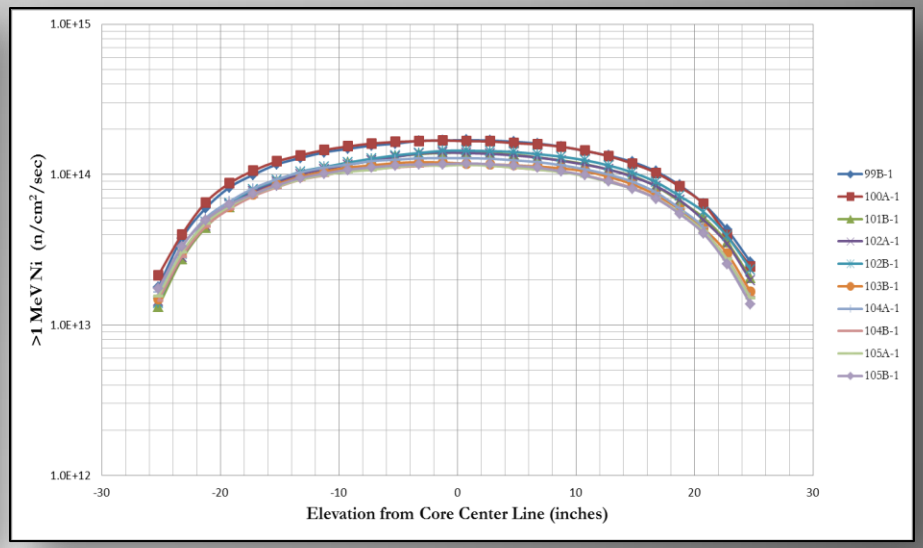
$$C \times Y = \begin{bmatrix} \\ \\ \end{bmatrix}$$

Average Cycle Thermal Neutron Flux

Elevation From Core CL (inches)	N-1	N-3	N-4	E-1	E-2	E-3	E-4	SW-1	SW-2	SW-3	SW-4	S-1	S-2	S-3	S-4	SE-1	SE-2	SE-3	SE-4	Average
24.73	1.49E+13	1.71E+13	1.38E+13	1.46E+13	1.84E+13	1.88E+13	1.72E+13	1.56E+13	1.40E+13	1.26E+13	1.52E+13	1.86E+13	1.45E+13	1.52E+13	2.18E+13	1.44E+13	1.52E+13	1.58E+13	1.69E+13	1.603E+13
22.75	2.52E+13	2.73E+13	2.53E+13	2.70E+13	3.12E+13	3.09E+13	2.75E+13	2.53E+13	2.44E+13	2.11E+13	2.46E+13	2.82E+13	2.67E+13	2.53E+13	3.62E+13	2.52E+13	2.49E+13	2.48E+13	2.75E+13	2.677E+13
20.75	6.69E+13	6.92E+13	7.06E+13	7.65E+13	8.05E+13	7.81E+13	6.98E+13	6.37E+13	6.37E+13	5.56E+13	6.56E+13	7.01E+13	8.12E+13	7.31E+13	9.35E+13	7.00E+13	6.98E+13	7.07E+13	7.36E+13	7.169E+13
18.75	1.12E+14	1.14E+14	1.17E+14	1.27E+14	1.30E+14	1.26E+14	1.12E+14	1.10E+14	1.06E+14	9.50E+13	1.07E+14	1.24E+14	1.37E+14	1.29E+14	1.44E+14	1.17E+14	1.16E+14	1.23E+14	1.24E+14	1.195E+14
16.75	1.48E+14	1.54E+14	1.55E+14	1.74E+14	1.72E+14	1.71E+14	1.52E+14	1.52E+14	1.43E+14	1.29E+14	1.45E+14	1.72E+14	1.90E+14	1.68E+14	1.89E+14	1.58E+14	1.60E+14	1.67E+14	1.66E+14	1.613E+14
14.75	1.70E+14	1.78E+14	1.79E+14	2.01E+14	2.08E+14	2.02E+14	1.79E+14	1.77E+14	1.70E+14	1.53E+14	1.70E+14	2.10E+14	2.36E+14	2.14E+14	2.26E+14	1.83E+14	1.96E+14	2.01E+14	2.00E+14	1.923E+14
12.75	1.91E+14	2.00E+14	2.02E+14	2.35E+14	2.33E+14	2.23E+14	2.05E+14	2.07E+14	2.00E+14	1.73E+14	1.90E+14	2.39E+14	2.64E+14	2.36E+14	2.52E+14	2.20E+14	2.27E+14	2.30E+14	2.29E+14	2.187E+14
10.75	2.11E+14	2.14E+14	2.22E+14	2.54E+14	2.54E+14	2.43E+14	2.21E+14	2.26E+14	2.17E+14	1.98E+14	2.16E+14	2.60E+14	2.84E+14	2.52E+14	2.73E+14	2.47E+14	2.57E+14	2.60E+14	2.56E+14	2.403E+14
8.75	2.25E+14	2.19E+14	2.29E+14	2.72E+14	2.70E+14	2.61E+14	2.34E+14	2.40E+14	2.28E+14	2.16E+14	2.29E+14	2.78E+14	2.96E+14	2.68E+14	2.88E+14	2.51E+14	2.59E+14	2.69E+14	2.60E+14	2.522E+14
6.75	2.33E+14	2.31E+14	2.37E+14	2.85E+14	2.81E+14	2.66E+14	2.43E+14	2.59E+14	2.47E+14	2.33E+14	2.52E+14	2.93E+14	3.08E+14	2.89E+14	2.95E+14	2.61E+14	2.68E+14	2.77E+14	2.67E+14	2.645E+14
4.75	2.40E+14	2.37E+14	2.44E+14	2.90E+14	2.90E+14	2.80E+14	2.54E+14	2.76E+14	2.70E+14	2.52E+14	2.73E+14	3.00E+14	3.24E+14	2.98E+14	3.06E+14	2.70E+14	2.86E+14	2.91E+14	2.74E+14	2.766E+14
2.75	2.46E+14	2.40E+14	2.49E+14	2.99E+14	2.98E+14	2.90E+14	2.59E+14	2.96E+14	2.89E+14	2.67E+14	2.83E+14	3.10E+14	3.35E+14	3.09E+14	3.17E+14	2.88E+14	3.01E+14	3.05E+14	2.83E+14	2.876E+14
0.75	2.46E+14	2.40E+14	2.51E+14	3.03E+14	2.98E+14	2.94E+14	2.61E+14	3.03E+14	2.91E+14	2.75E+14	2.87E+14	3.19E+14	3.49E+14	3.12E+14	3.22E+14	2.97E+14	3.07E+14	3.11E+14	2.93E+14	2.926E+14
-1.25	2.47E+14	2.41E+14	2.49E+14	3.03E+14	3.01E+14	2.90E+14	2.65E+14	3.00E+14	2.91E+14	2.77E+14	2.90E+14	3.24E+14	3.50E+14	3.08E+14	3.17E+14	2.97E+14	3.13E+14	3.16E+14	3.01E+14	2.937E+14
-3.25	2.40E+14	2.39E+14	2.49E+14	2.99E+14	2.98E+14	2.89E+14	2.57E+14	2.97E+14	2.87E+14	2.68E+14	2.83E+14	3.20E+14	3.45E+14	3.11E+14	3.19E+14	3.06E+14	3.19E+14	3.20E+14	3.06E+14	2.922E+14
-5.25	2.37E+14	2.32E+14	2.42E+14	2.90E+14	2.86E+14	2.81E+14	2.48E+14	2.81E+14	2.66E+14	2.52E+14	2.62E+14	3.20E+14	3.43E+14	3.10E+14	3.20E+14	3.18E+14	3.28E+14	3.31E+14	3.11E+14	2.873E+14
-7.25	2.28E+14	2.27E+14	2.31E+14	2.82E+14	2.82E+14	2.70E+14	2.39E+14	2.57E+14	2.46E+14	2.31E+14	2.41E+14	3.26E+14	3.49E+14	3.15E+14	3.22E+14	3.10E+14	3.26E+14	3.32E+14	3.15E+14	2.805E+14
-9.25	2.21E+14	2.17E+14	2.29E+14	2.65E+14	2.61E+14	2.58E+14	2.28E+14	2.46E+14	2.32E+14	2.13E+14	2.31E+14	3.16E+14	3.42E+14	3.05E+14	3.10E+14	3.01E+14	3.13E+14	3.19E+14	3.06E+14	2.691E+14
-11.25	2.10E+14	2.07E+14	2.12E+14	2.51E+14	2.52E+14	2.45E+14	2.14E+14	2.36E+14	2.21E+14	2.05E+14	2.15E+14	2.99E+14	3.20E+14	2.83E+14	2.91E+14	2.83E+14	2.95E+14	3.02E+14	2.85E+14	2.540E+14
-13.25	1.85E+14	1.84E+14	1.90E+14	2.30E+14	2.25E+14	2.21E+14	1.97E+14	2.25E+14	2.10E+14	1.96E+14	2.07E+14	2.78E+14	2.99E+14	2.63E+14	2.66E+14	2.58E+14	2.70E+14	2.76E+14	2.64E+14	2.339E+14
-15.25	1.66E+14	1.64E+14	1.72E+14	1.96E+14	2.03E+14	1.98E+14	1.69E+14	2.10E+14	1.88E+14	1.74E+14	1.86E+14	2.45E+14	2.64E+14	2.27E+14	2.31E+14	2.28E+14	2.36E+14	2.43E+14	2.32E+14	2.069E+14
-17.25	1.44E+14	1.43E+14	1.52E+14	1.70E+14	1.71E+14	1.65E+14	1.45E+14	1.77E+14	1.66E+14	1.53E+14	1.63E+14	2.08E+14	2.22E+14	1.84E+14	1.87E+14	1.85E+14	2.02E+14	2.12E+14	2.01E+14	1.763E+14
-19.25	1.18E+14	1.18E+14	1.25E+14	1.44E+14	1.44E+14	1.39E+14	1.24E+14	1.57E+14	1.40E+14	1.32E+14	1.41E+14	1.68E+14	1.81E+14	1.56E+14	1.56E+14	1.55E+14	1.61E+14	1.67E+14	1.60E+14	1.466E+14
-21.25	9.48E+13	9.52E+13	9.57E+13	1.14E+14	1.16E+14	1.13E+14	9.87E+13	1.27E+14	1.10E+14	1.03E+14	1.13E+14	1.37E+14	1.44E+14	1.28E+14	1.27E+14	1.20E+14	1.24E+14	1.33E+14	1.30E+14	1.170E+14
-23.25	7.38E+13	7.88E+13	7.11E+13	8.30E+13	9.14E+13	9.41E+13	8.02E+13	1.05E+14	8.89E+13	8.15E+13	9.20E+13	1.15E+14	1.13E+14	1.02E+14	1.11E+14	9.01E+13	9.46E+13	1.02E+14	1.05E+14	9.329E+13
-25.25	5.28E+13	6.26E+13	4.80E+13	5.52E+13	6.60E+13	7.54E+13	6.38E+13	8.48E+13	6.89E+13	6.46E+13	7.26E+13	9.80E+13	7.52E+13	7.77E+13	8.94E+13	7.21E+13	7.52E+13	8.58E+13	8.35E+13	7.219E+13

Average Cycle Neutron Flux





- Thermal neutron flux (0.025 eV)
- Fast neutron flux (> 1 Mev)

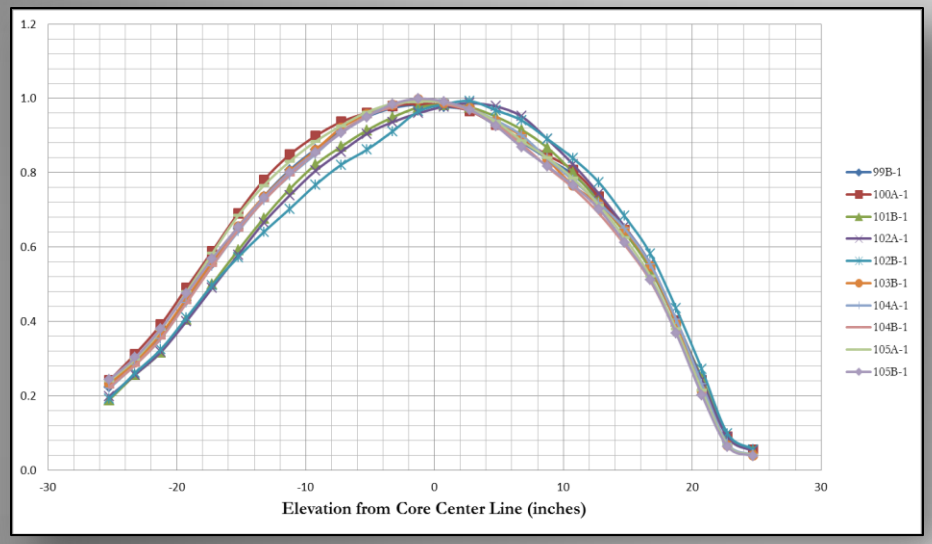
Normalized Cycle Neutron Flux

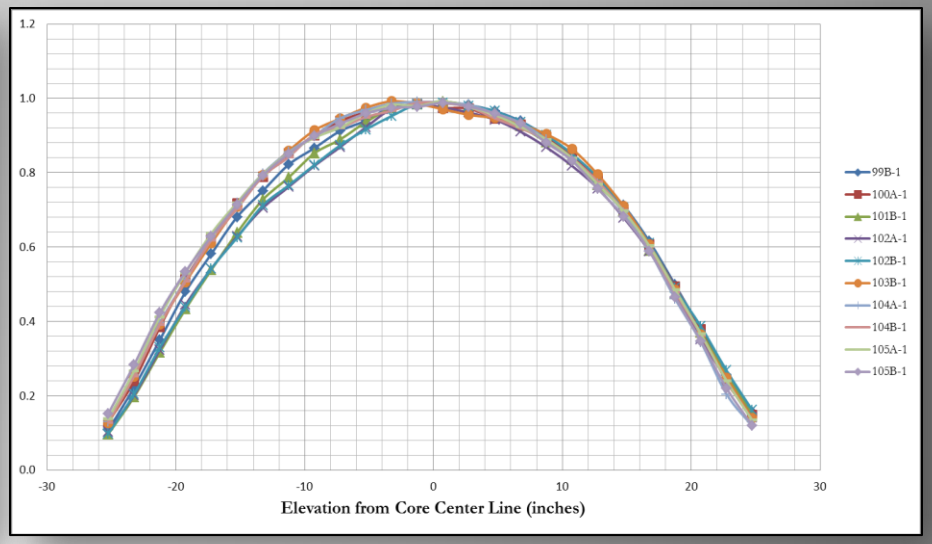
Max	N-1	N-3	N-4	E-1	E-2	E-3	E-4	SW-1	SW-2	SW-3	SW-4	S-1	S-2	S-3	S-4	SE-1	SE-2	SE-3	SE-4
Fluence	2.47E+14	2.41E+14	2.51E+14	3.03E+14	3.01E+14	2.94E+14	2.65E+14	3.03E+14	2.91E+14	2.77E+14	2.90E+14	3.26E+14	3.50E+14	3.15E+14	3.22E+14	3.18E+14	3.28E+14	3.32E+14	3.15E+14

Normalized to 1

(inches)	N-1	N-3	N-4	E-1	E-2	E-3	E-4	SW-1	SW-2	SW-3	SW-4	S-1	S-2	S-3	S-4	SE-1	SE-2	SE-3	SE-4	Average
24.73	0.0603	0.0710	0.0550	0.0482	0.0611	0.0639	0.0649	0.0515	0.0481	0.0455	0.0524	0.0571	0.0414	0.0483	0.0677	0.0453	0.0463	0.0476	0.0537	0.0542
22.75	0.1020	0.1133	0.1008	0.0891	0.1037	0.1051	0.1038	0.0835	0.0838	0.0762	0.0848	0.0865	0.0763	0.0803	0.1124	0.0792	0.0759	0.0747	0.0873	0.0905
20.75	0.2709	0.2871	0.2813	0.2525	0.2674	0.2656	0.2634	0.2102	0.2189	0.2007	0.2262	0.2150	0.2320	0.2321	0.2904	0.2201	0.2128	0.2130	0.2337	0.2418
18.75	0.4534	0.4730	0.4661	0.4191	0.4319	0.4286	0.4226	0.3630	0.3643	0.3430	0.3690	0.3804	0.3914	0.4095	0.4472	0.3679	0.3537	0.3705	0.3937	0.4025
16.75	0.5992	0.6390	0.6175	0.5743	0.5714	0.5816	0.5736	0.5017	0.4914	0.4657	0.5000	0.5276	0.5429	0.5333	0.5870	0.4969	0.4878	0.5030	0.5270	0.5432
14.75	0.6883	0.7386	0.7131	0.6634	0.6910	0.6871	0.6755	0.5842	0.5842	0.5523	0.5862	0.6442	0.6743	0.6794	0.7019	0.5755	0.5976	0.6054	0.6349	0.6462
12.75	0.7733	0.8299	0.8048	0.7756	0.7741	0.7585	0.7736	0.6832	0.6873	0.6245	0.6552	0.7331	0.7543	0.7492	0.7826	0.6918	0.6921	0.6928	0.7270	0.7349
10.75	0.8543	0.8880	0.8845	0.8383	0.8439	0.8265	0.8340	0.7459	0.7457	0.7148	0.7448	0.7975	0.8114	0.8000	0.8478	0.7767	0.7835	0.7831	0.8127	0.8070
8.75	0.9109	0.9087	0.9124	0.8977	0.8970	0.8878	0.8830	0.7921	0.7835	0.7798	0.7897	0.8528	0.8457	0.8508	0.8944	0.7893	0.7896	0.8102	0.8254	0.8474
6.75	0.9433	0.9585	0.9442	0.9406	0.9336	0.9048	0.9170	0.8548	0.8488	0.8412	0.8690	0.8988	0.8800	0.9175	0.9161	0.8208	0.8171	0.8343	0.8476	0.8888
4.75	0.9717	0.9834	0.9721	0.9571	0.9635	0.9524	0.9585	0.9109	0.9278	0.9097	0.9414	0.9202	0.9257	0.9460	0.9503	0.8491	0.8720	0.8765	0.8698	0.9294
2.75	0.9960	0.9959	0.9920	0.9868	0.9900	0.9864	0.9774	0.9769	0.9931	0.9639	0.9759	0.9509	0.9571	0.9810	0.9845	0.9057	0.9177	0.9187	0.8984	0.9657
0.75	0.9960	0.9959	1.0000	1.0000	0.9900	1.0000	0.9849	1.0000	1.0000	0.9928	0.9897	0.9785	0.9971	0.9905	1.0000	0.9340	0.9360	0.9367	0.9302	0.9817
-1.25	1.0000	1.0000	0.9920	1.0000	1.0000	0.9864	1.0000	0.9901	1.0000	1.0000	1.0000	0.9939	1.0000	0.9778	0.9845	0.9340	0.9543	0.9518	0.9556	0.9853
-3.25	0.9717	0.9917	0.9920	0.9868	0.9900	0.9830	0.9698	0.9802	0.9863	0.9675	0.9759	0.9816	0.9857	0.9873	0.9907	0.9623	0.9726	0.9639	0.9714	0.9795
-5.25	0.9595	0.9627	0.9641	0.9571	0.9502	0.9558	0.9358	0.9274	0.9141	0.9097	0.9034	0.9816	0.9800	0.9841	0.9938	1.0000	1.0000	0.9970	0.9873	0.9612
-7.25	0.9231	0.9419	0.9203	0.9307	0.9369	0.9184	0.9019	0.8482	0.8454	0.8339	0.8310	1.0000	0.9971	1.0000	1.0000	0.9748	0.9939	1.0000	1.0000	0.9367
-9.25	0.8947	0.9004	0.9124	0.8746	0.8671	0.8776	0.8604	0.8119	0.7973	0.7690	0.7966	0.9693	0.9771	0.9683	0.9627	0.9465	0.9543	0.9608	0.9714	0.8985
-11.25	0.8502	0.8589	0.8446	0.8284	0.8372	0.8333	0.8075	0.7789	0.7595	0.7401	0.7414	0.9172	0.9143	0.8984	0.9037	0.8899	0.8994	0.9096	0.9048	0.8483
-13.25	0.7490	0.7635	0.7570	0.7591	0.7475	0.7517	0.7434	0.7426	0.7216	0.7076	0.7138	0.8528	0.8543	0.8349	0.8261	0.8113	0.8232	0.8313	0.8381	0.7805
-15.25	0.6721	0.6805	0.6853	0.6469	0.6744	0.6735	0.6377	0.6931	0.6460	0.6282	0.6414	0.7515	0.7543	0.7206	0.7174	0.7170	0.7195	0.7319	0.7365	0.6909
-17.25	0.5830	0.5934	0.6056	0.5611	0.5681	0.5612	0.5472	0.5842	0.5704	0.5523	0.5621	0.6380	0.6343	0.5841	0.5807	0.5818	0.6159	0.6386	0.6381	0.5895
-19.25	0.4777	0.4896	0.4980	0.4752	0.4784	0.4728	0.4679	0.5182	0.4811	0.4765	0.4862	0.5153	0.5171	0.4952	0.4845	0.4874	0.4909	0.5030	0.5079	0.4907
-21.25	0.3838	0.3950	0.3813	0.3762	0.3854	0.3844	0.3725	0.4191	0.3780	0.3718	0.3897	0.4202	0.4114	0.4063	0.3944	0.3774	0.3780	0.4006	0.4127	0.3915
-23.25	0.2988	0.3270	0.2833	0.2739	0.3037	0.3201	0.3026	0.3465	0.3055	0.2942	0.3172	0.3528	0.3229	0.3238	0.3447	0.2833	0.2884	0.3072	0.3333	0.3121
-25.25	0.2138	0.2598	0.1912	0.1822	0.2193	0.2565	0.2408	0.2799	0.2368	0.2332	0.2503	0.3006	0.2149	0.2467	0.2776	0.2267	0.2293	0.2584	0.2651	0.2412

Normalized Cycle Neutron Flux





- Thermal neutron flux (0.025 eV)
- Fast neutron flux (> 1 Mev)

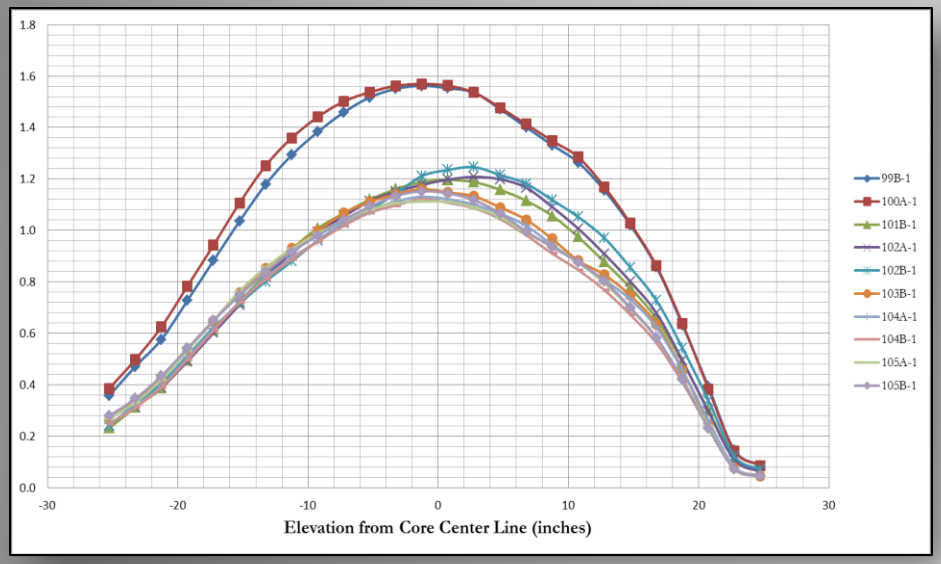
Cycle Neutron Flux Scaled to 20 MW

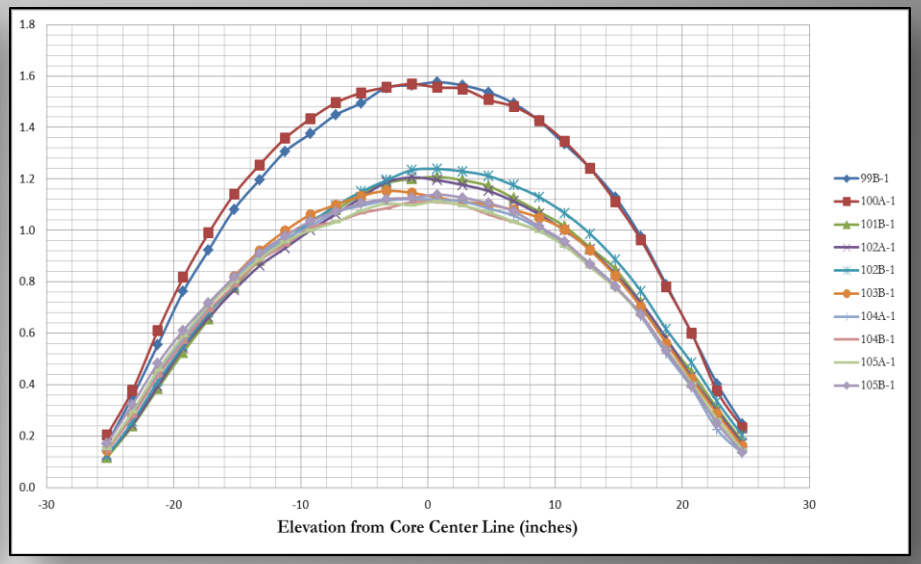
	N-1	N-3	N-4	E-1	E-2	E-3	E-4	SW-1	SW-2	SW-3	SW-4	S-1	S-2	S-3	S-4	SE-1	SE-2	SE-3	SE-4
Cycle Power	26.5	26.5	26.5	31.1	31.1	31.1	31.1	29.8	29.8	29.8	29.8	33.3	33.3	33.3	33.3	37.5	37.5	37.5	37.5
Scaled to 20 MW	1.325	1.325	1.325	1.555	1.555	1.555	1.555	1.49	1.49	1.49	1.49	1.665	1.665	1.665	1.665	1.875	1.875	1.875	1.875

Scaled to 20 MW

(inches)	N-1	N-3	N-4	E-1	E-2	E-3	E-4	SW-1	SW-2	SW-3	SW-4	S-1	S-2	S-3	S-4	SE-1	SE-2	SE-3	SE-4	Average
24.73	0.0799	0.0940	0.0728	0.0749	0.0951	0.0994	0.1009	0.0767	0.0717	0.0678	0.0781	0.0950	0.0690	0.0803	0.1127	0.0849	0.0869	0.0892	0.1006	0.0858
22.75	0.1352	0.1501	0.1336	0.1386	0.1612	0.1634	0.1614	0.1244	0.1249	0.1135	0.1264	0.1440	0.1270	0.1337	0.1872	0.1486	0.1423	0.1401	0.1637	0.1431
20.75	0.3589	0.3805	0.3727	0.3926	0.4159	0.4131	0.4096	0.3132	0.3262	0.2991	0.3370	0.3580	0.3863	0.3864	0.4835	0.4127	0.3990	0.3993	0.4381	0.3833
18.75	0.6008	0.6268	0.6176	0.6518	0.6716	0.6664	0.6572	0.5409	0.5427	0.5110	0.5498	0.6333	0.6517	0.6819	0.7446	0.6899	0.6631	0.6947	0.7381	0.6386
16.75	0.7939	0.8467	0.8182	0.8930	0.8886	0.9044	0.8919	0.7475	0.7322	0.6939	0.7450	0.8785	0.9039	0.8880	0.9773	0.9316	0.9146	0.9431	0.9881	0.8621
14.75	0.9119	0.9786	0.9449	1.0315	1.0746	1.0684	1.0504	0.8704	0.8704	0.8230	0.8734	1.0725	1.1227	1.1311	1.1686	1.0790	1.1204	1.1352	1.1905	1.0272
12.75	1.0246	1.0996	1.0663	1.2060	1.2037	1.1795	1.2029	1.0179	1.0241	0.9306	0.9762	1.2207	1.2559	1.2474	1.3030	1.2972	1.2976	1.2989	1.3631	1.1692
10.75	1.1319	1.1766	1.1719	1.3035	1.3122	1.2853	1.2968	1.1114	1.1111	1.0651	1.1098	1.3279	1.3510	1.3320	1.4116	1.4564	1.4691	1.4684	1.5238	1.2850
8.75	1.2070	1.2040	1.2089	1.3959	1.3949	1.3805	1.3731	1.1802	1.1674	1.1619	1.1766	1.4198	1.4081	1.4166	1.4892	1.4800	1.4806	1.5192	1.5476	1.3480
6.75	1.2499	1.2700	1.2511	1.4626	1.4517	1.4069	1.4259	1.2736	1.2647	1.2533	1.2948	1.4965	1.4652	1.5276	1.5254	1.5389	1.5320	1.5644	1.5893	1.4128
4.75	1.2874	1.3030	1.2880	1.4883	1.4982	1.4810	1.4905	1.3572	1.3825	1.3555	1.4027	1.5322	1.5413	1.5751	1.5823	1.5920	1.6349	1.6434	1.6310	1.4772
2.75	1.3196	1.3195	1.3144	1.5345	1.5395	1.5338	1.5198	1.4556	1.4798	1.4362	1.4540	1.5833	1.5936	1.6333	1.6391	1.6981	1.7207	1.7225	1.6845	1.5359
0.75	1.3196	1.3195	1.3250	1.5550	1.5395	1.5550	1.5315	1.4900	1.4900	1.4792	1.4746	1.6292	1.6602	1.6491	1.6650	1.7512	1.7550	1.7564	1.7440	1.5626
-1.25	1.3250	1.3250	1.3144	1.5550	1.5550	1.5338	1.5550	1.4752	1.4900	1.4900	1.4900	1.6548	1.6650	1.6280	1.6391	1.7512	1.7893	1.7846	1.7917	1.5691
-3.25	1.2874	1.3140	1.3144	1.5345	1.5395	1.5286	1.5081	1.4605	1.4695	1.4416	1.4540	1.6344	1.6412	1.6439	1.6495	1.8042	1.8236	1.8072	1.8214	1.5620
-5.25	1.2714	1.2755	1.2775	1.4883	1.4775	1.4862	1.4552	1.3818	1.3620	1.3555	1.3461	1.6344	1.6317	1.6386	1.6547	1.8750	1.8750	1.8694	1.8512	1.5372
-7.25	1.2231	1.2480	1.2194	1.4472	1.4568	1.4281	1.4024	1.2638	1.2596	1.2426	1.2382	1.6650	1.6602	1.6650	1.6650	1.8278	1.8636	1.8750	1.8750	1.5014
-9.25	1.1855	1.1930	1.2089	1.3600	1.3484	1.3646	1.3379	1.2097	1.1879	1.1457	1.1869	1.6139	1.6269	1.6121	1.6030	1.7748	1.7893	1.8016	1.8214	1.4406
-11.25	1.1265	1.1381	1.1191	1.2881	1.3019	1.2958	1.2557	1.1605	1.1316	1.1027	1.1047	1.5271	1.5223	1.4959	1.5047	1.6686	1.6864	1.7056	1.6964	1.3596
-13.25	0.9924	1.0116	1.0030	1.1804	1.1624	1.1689	1.1560	1.1064	1.0753	1.0543	1.0636	1.4198	1.4224	1.3901	1.3754	1.5212	1.5434	1.5587	1.5714	1.2514
-15.25	0.8905	0.9017	0.9080	1.0059	1.0487	1.0472	0.9917	1.0327	0.9626	0.9360	0.9557	1.2513	1.2559	1.1999	1.1945	1.3443	1.3491	1.3724	1.3810	1.1068
-17.25	0.7725	0.7862	0.8024	0.8724	0.8834	0.8727	0.8508	0.8704	0.8500	0.8230	0.8375	1.0623	1.0561	0.9726	0.9669	1.0908	1.1547	1.1973	1.1964	0.9431
-19.25	0.6330	0.6488	0.6599	0.7390	0.7439	0.7352	0.7276	0.7720	0.7168	0.7100	0.7244	0.8580	0.8610	0.8246	0.8066	0.9139	0.9204	0.9431	0.9524	0.7837
-21.25	0.5085	0.5234	0.5052	0.5850	0.5993	0.5977	0.5792	0.6245	0.5632	0.5540	0.5806	0.6997	0.6850	0.6766	0.6567	0.7075	0.7088	0.7511	0.7738	0.6253
-23.25	0.3959	0.4332	0.3753	0.4260	0.4722	0.4977	0.4706	0.5163	0.4552	0.4384	0.4727	0.5873	0.5376	0.5391	0.5740	0.5313	0.5408	0.5761	0.6250	0.4981
-25.25	0.2832	0.3442	0.2534	0.2833	0.3410	0.3988	0.3744	0.4170	0.3528	0.3475	0.3730	0.5005	0.3577	0.4107	0.4623	0.4251	0.4299	0.4846	0.4970	0.3861

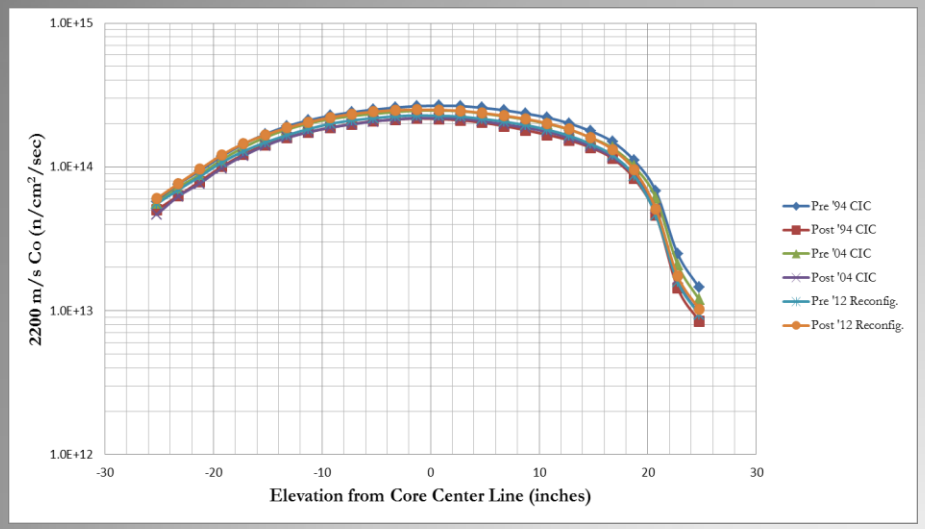
Cycle Neutron Flux Scaled to 20 MW

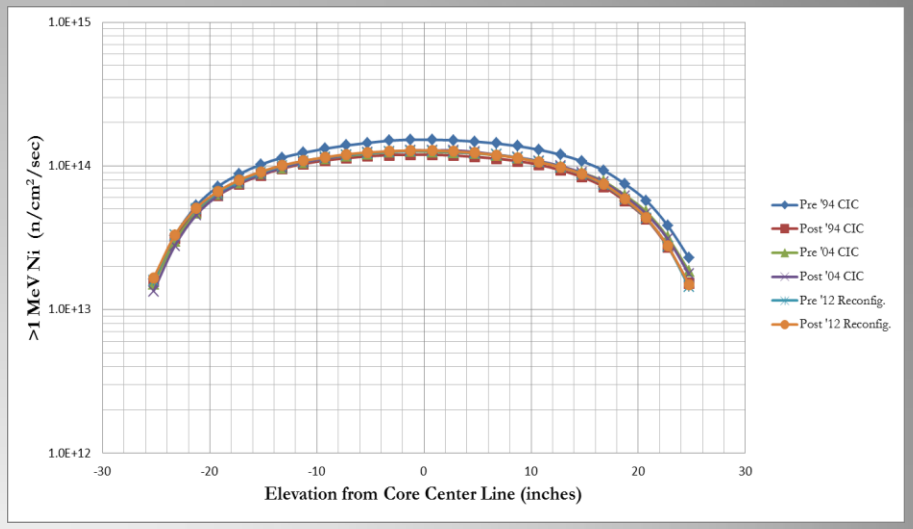




- Thermal neutron flux (0.025 eV)
- Fast neutron flux (> 1 Mev)

Final Results





- Tightly grouped profiles

- **No noticeable deviation of the ATR neutron flux profile, thermal or fast, away from expected cosine distribution**

Future Analysis Possibilities

- Expand the analysis to cover lifetime of a reflector
- Use the center line fluence rate and average maximum fluence rates to evaluate cycle to cycle behavior of the 9 flux trap positions

Questions?

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U-235 Fission Cross Section Energy