Modern Computational Reactor Physics Methodologies and Validation Protocols for the Advanced Test Reactor

2014 Test, Research and Training Reactors Conference (TRTR)

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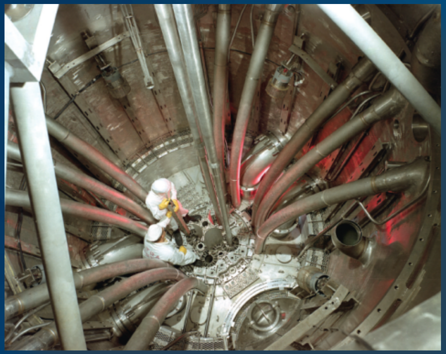
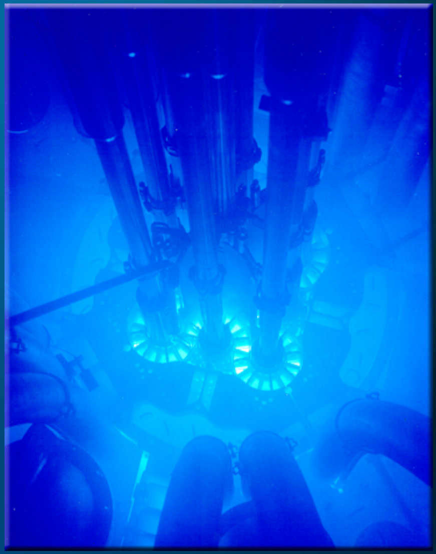
Portland Oregon, August 2014





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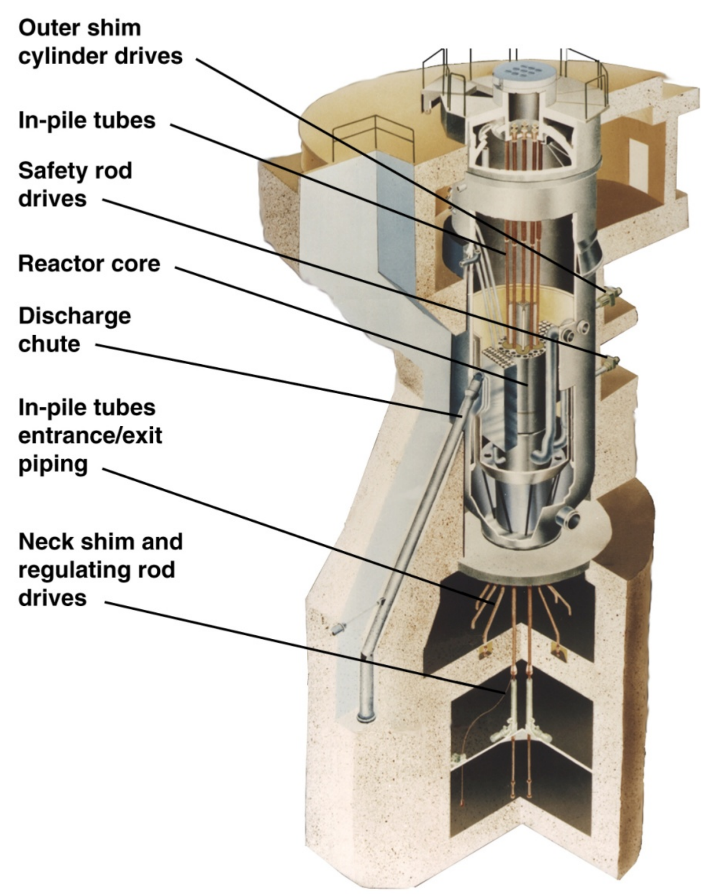
Overview

- ***How have the required neutronics and fuel cycle analyses for ATR been done historically and what are the challenges and limitations?***
- ***How are we improving the situation?***
- ***Status of the new modeling code suite***
- ***Status of validation protocols***
- ***Summary and future plans***

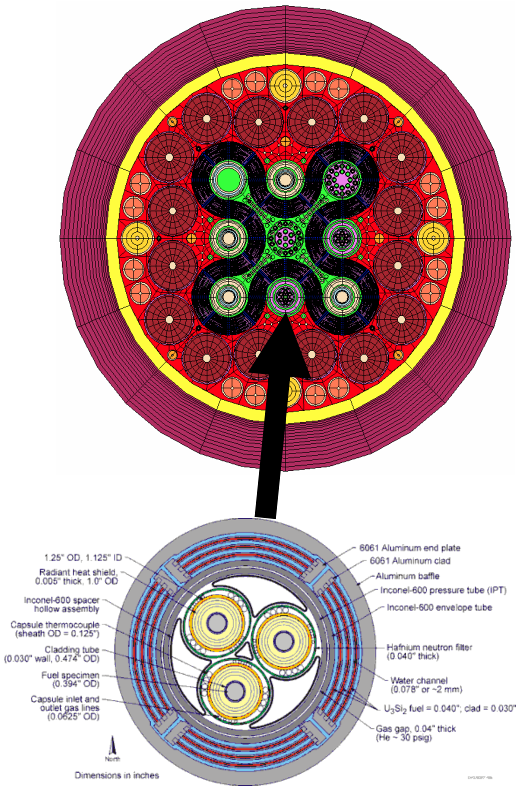


The Advanced Test Reactor

Challenges with the Current ATR Physics Modeling Methods

The ATR is a very complex, heterogeneous LWR system. Computational reactor physics modeling is used extensively to support ATR experiment design, operations and fuel cycle management, core and experiment safety analysis, and many other applications. However ..

- ***Many key ATR core physics models and protocols, based on the few-group neutron diffusion code PDQ-7, were developed as long ago as the late 1960s and early 1970s.***
- ***While certainly not unsafe when used within their limits, the legacy methods are inconsistent with modern engineering education and practice, difficult to maintain, and sometimes impossible to validate according to current standards***
- ***Overly conservative operational restrictions can sometimes be required to compensate for computational uncertainty***
- ***Some computations depend on outdated, increasingly unreliable computing hardware and are not portable to modern computers***
- ***Staff retirement and turnover, with resulting loss of legacy expertise, is of increasing concern.***



Gas Test Loop GTL-1 Fuel Plate Experiment - South Flux Trap – 2008 ….. Had to be postponed due to computational uncertainties.

New Static Computational and V&V Tools

NJOY and AMPX

MCNP

KENO

SERPENT

MC21

High-Fidelity Stochastic Neutronics Modeling

ENDF/B Version VII Basic Nuclear Data

Verification Protocols

- Direct Verification
- TSUNAMI S/U Analysis

Validation Protocols

- 1994 CIC (IRPhE)
- Previous and New ATRC Experiments
- Fuel Exposure Validation Measurements
- New ATR Full-Scale Experiments and instrumentation

NJOY and AMPX

HELIOS (2D)

•Baseline ATR Fuel and Experiment Management
•Core cycle follow

SCALE/NEWT (2D)

•Cross Section Generation
•Verification
•Uncertainty Quantification
•2D Experiment Support

ATTILA (3D)

•3D Experiment Support
•Kinetics Parameters
•Safety Analysis Support

High-Fidelity Deterministic Neutronics Modeling

Nuclear Operations and ATR Engineering Interface:

- Training Requirements
- Data Base Mgmt.
- Computational Procedures
- QA/Configuration Control
- SAR Requirements
- Safeguards/Security
- Standards from Industry

Beneficiaries:

ATR Operations and Fuel Management Support for DOE

- Core Safety Analysis (CSAP)
- ESAP for DOE Programs and WFO Customers
- Life Extension Program - Instrumentation Upgrades

ATR NSUF: Experiment Support for Academia/Industry

Verification and Validation (ANSI/ANS 19.3)

Verification: ***Ensuring that the code is mathematically correct. Comparing with other mathematical / numeric representations of the problem space ….. "Solving the equations right", not necessarily with regard to the specific engineering application under consideration for the code of interest. For ATR this is done via inter-code comparisons, standard test cases, and analytic benchmarks.***

Validation: ***Demonstrating statistical consistency of the code results with physical reality for the application of interest (i.e., measured data)……."Solving the right equations" … and rigorously quantifying the uncertainties. HELIOS, NEWT, ATTILA, KENO, MC21, Serpent, and MCNP all solve the transport equation directly for ATR in two or three dimensions, and the computed results can be directly validated against corresponding ATR and ATRC measurements according to modern standards. Some specific validation parameters of interest include:***

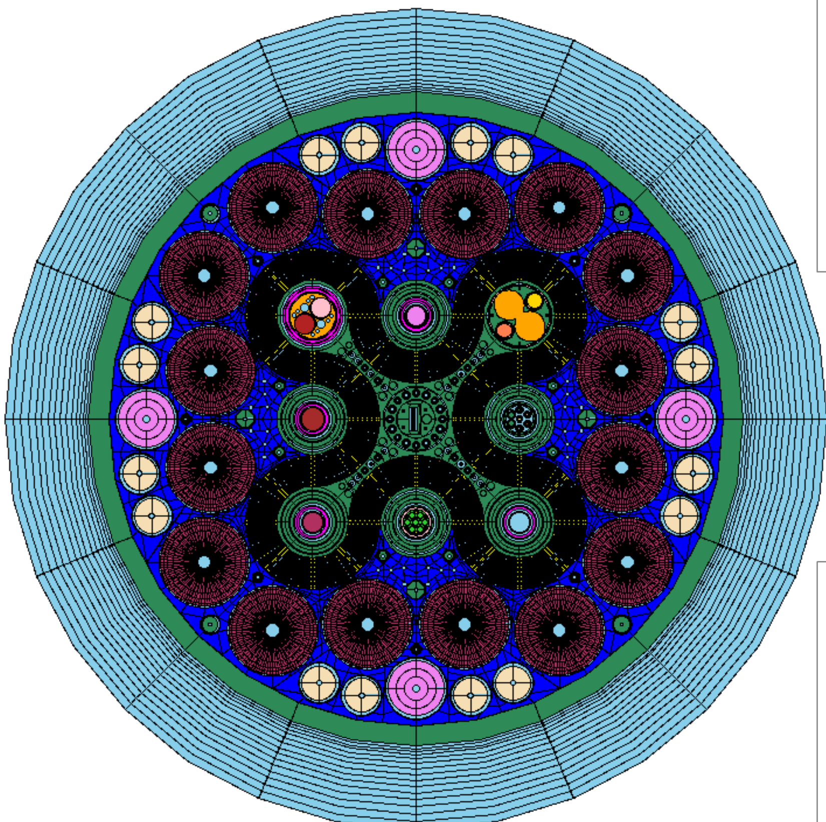
- ***Critical shim positions***
- ***Lobe powers***
- ***Element powers***
- ***Intra-Element Powers***
- ***Neutron spectra at various locations of interest***
- ***Fuel burnup***

Example ASTM standards for experimental validation of reactor physics software:

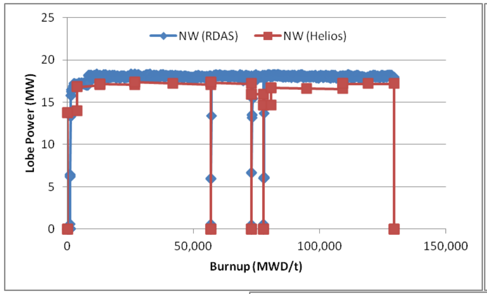
E261-10: Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E262-08: Determining Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques
E944-08: Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance

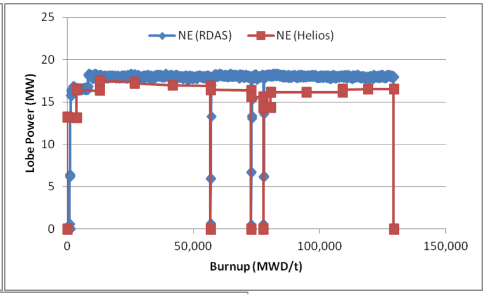
HELIOS - Cycle 145A (August 2009)

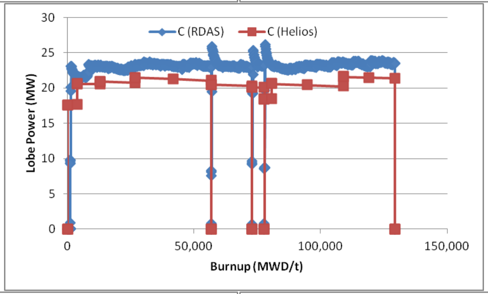
Lobe power validation began with Cycle 145A …….

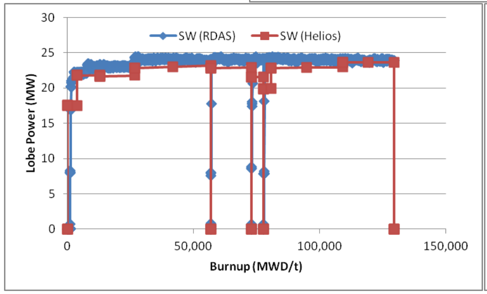


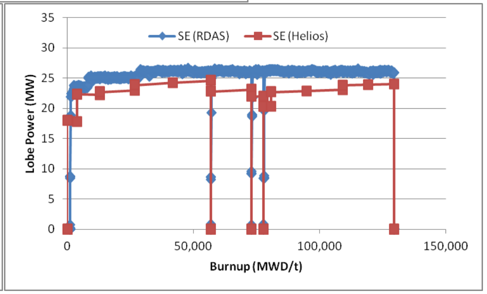
HELIOS Cycle 145A (August 2009)



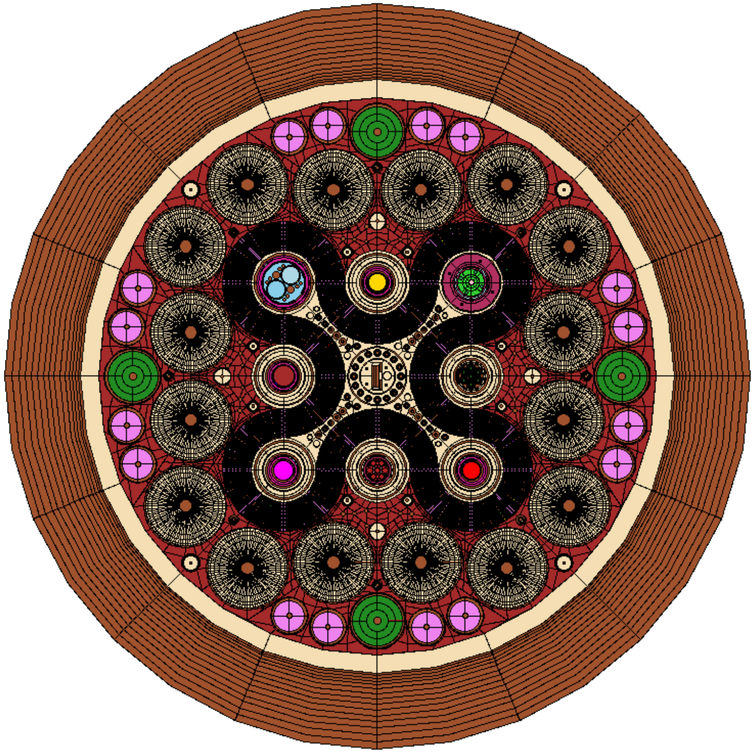




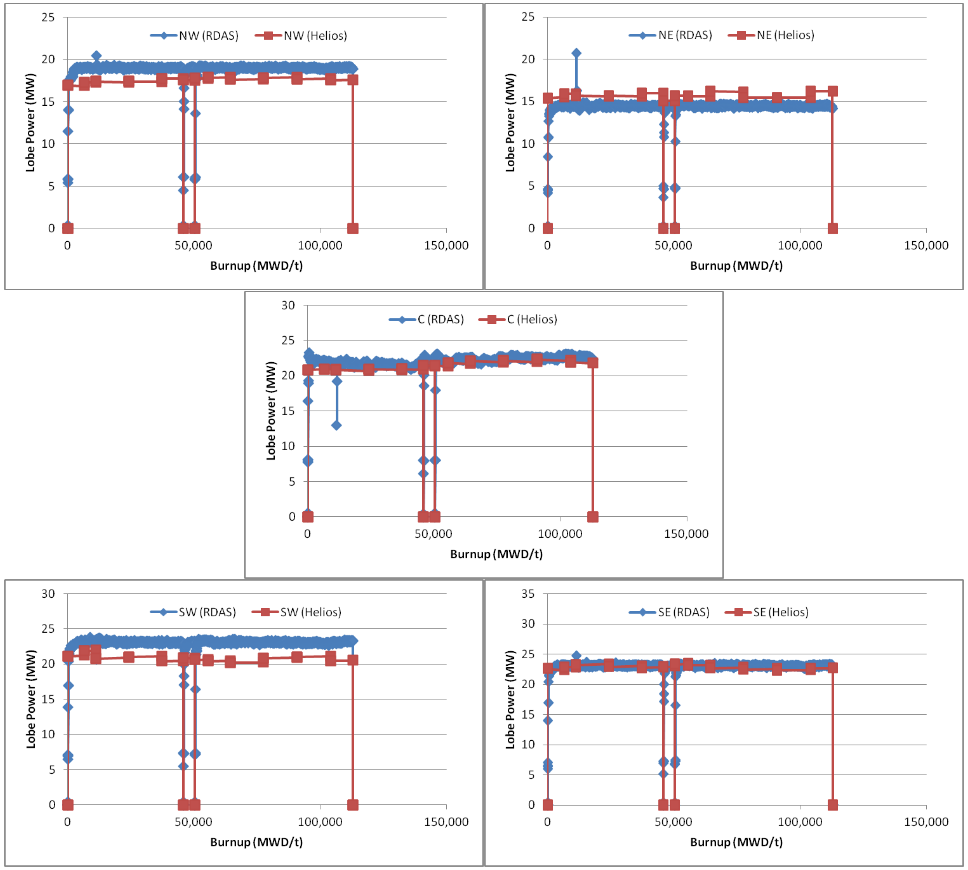




…..and now all cycles since then, through mid-2014 have been retrospectively modeled and ……..

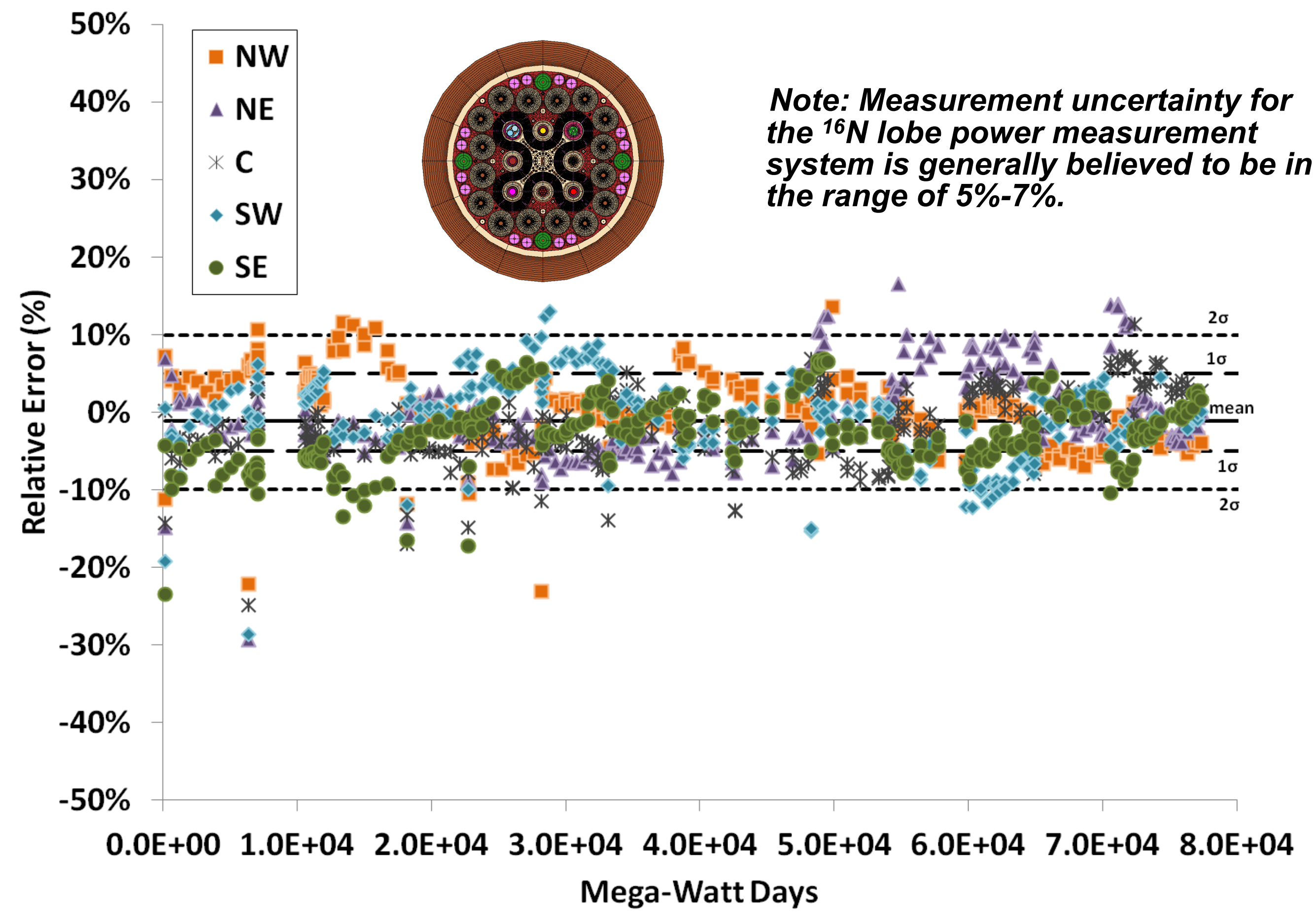


HELIOS Cycle 151B (May 2012)



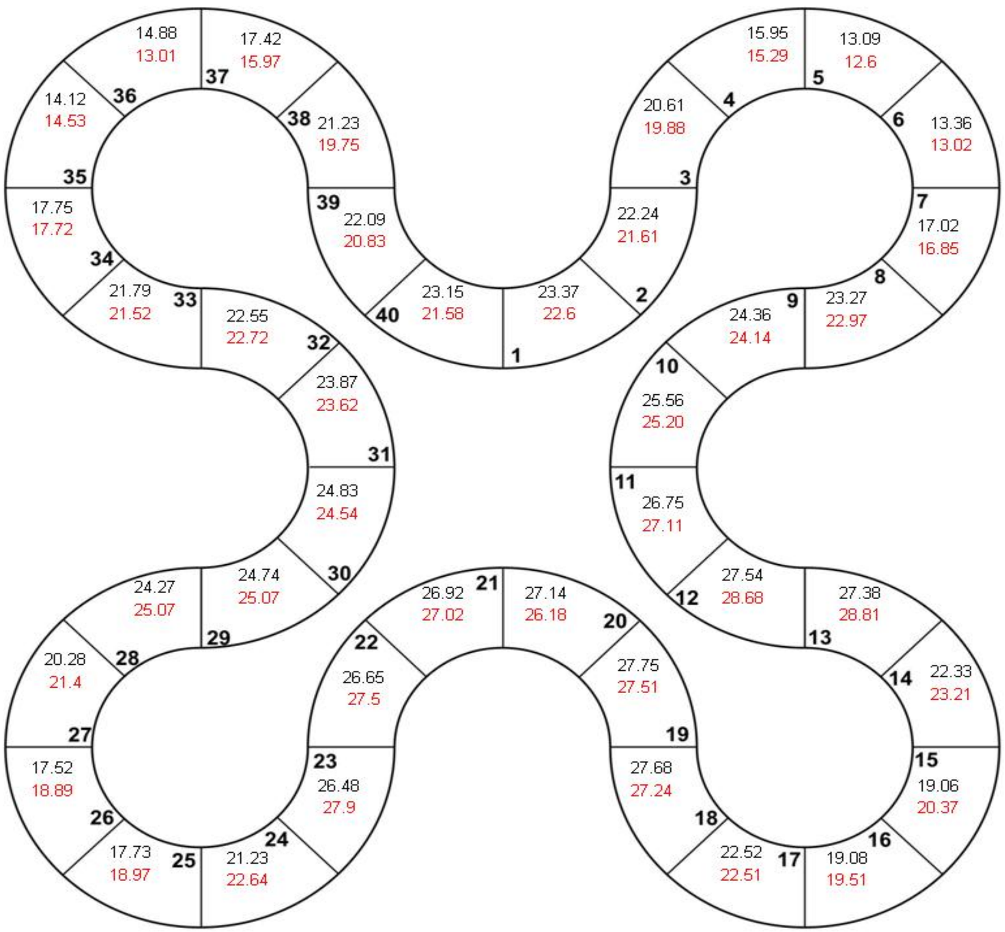
….. the first informal *prospective* HELIOS physics analysis, for cycle 157B, is now underway.

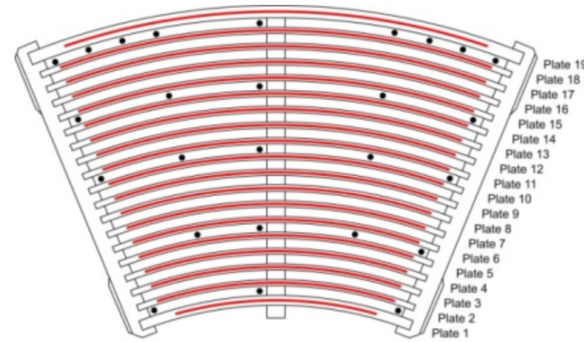
Differences Between A-Priori HELIOS and Measured Lobe Powers Since August 2009

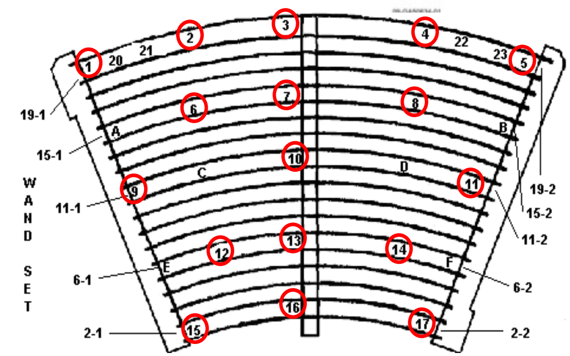


Note: Measurement uncertainty for the ^{16}N lobe power measurement system is generally believed to be in the range of 5%-7%.

In-Core Validation Experiments - MCNP A-Priori and Measured Fuel Element Powers (W) for ATRC Validation Experiment 12-5 ("Depressurized Run" 2012)



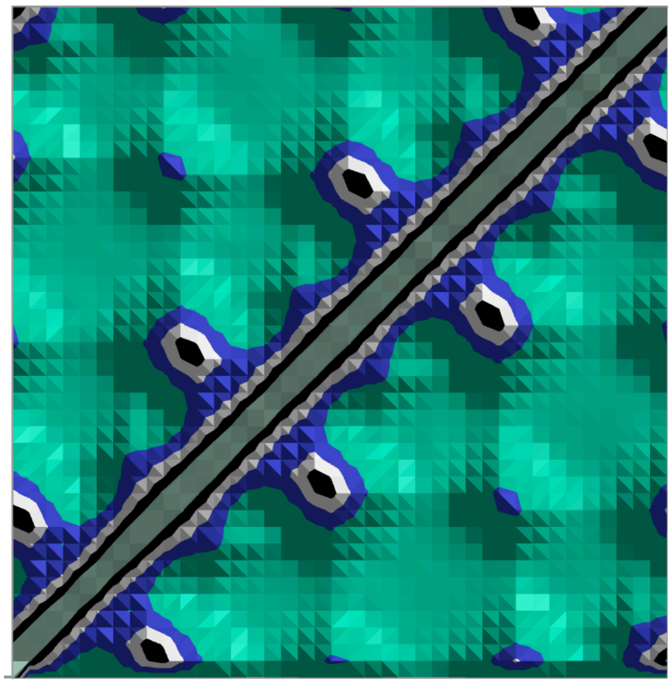




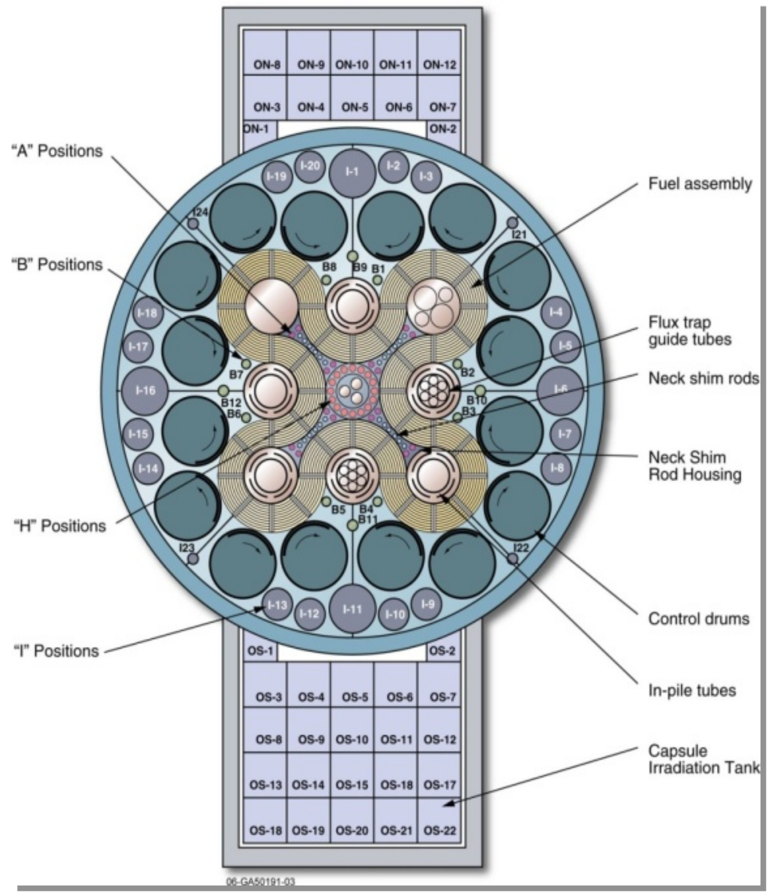
Fission wire placements for fuel element power measurement .

The same well-accepted measurement protocol (Durney and Kauffman,1967) has been used for nearly 50 years !!!

A-Priori Fission Power Correlation Matrix for ATRC

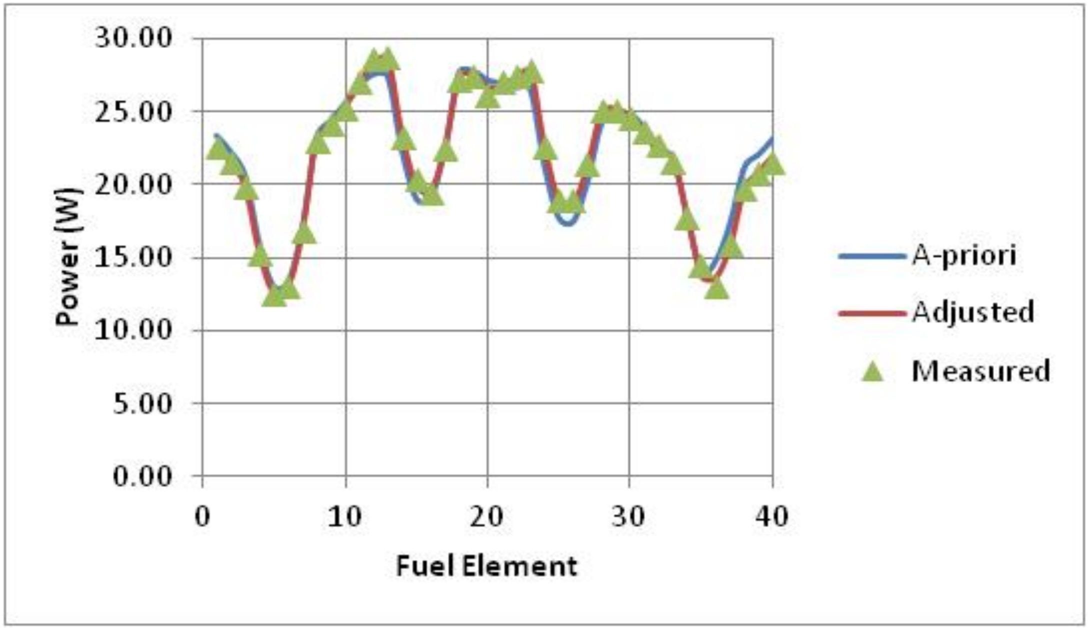


■0.00-0.20 ■0.20-0.40 ■0.40-0.60 ■0.60-0.80 ■0.80-1.00



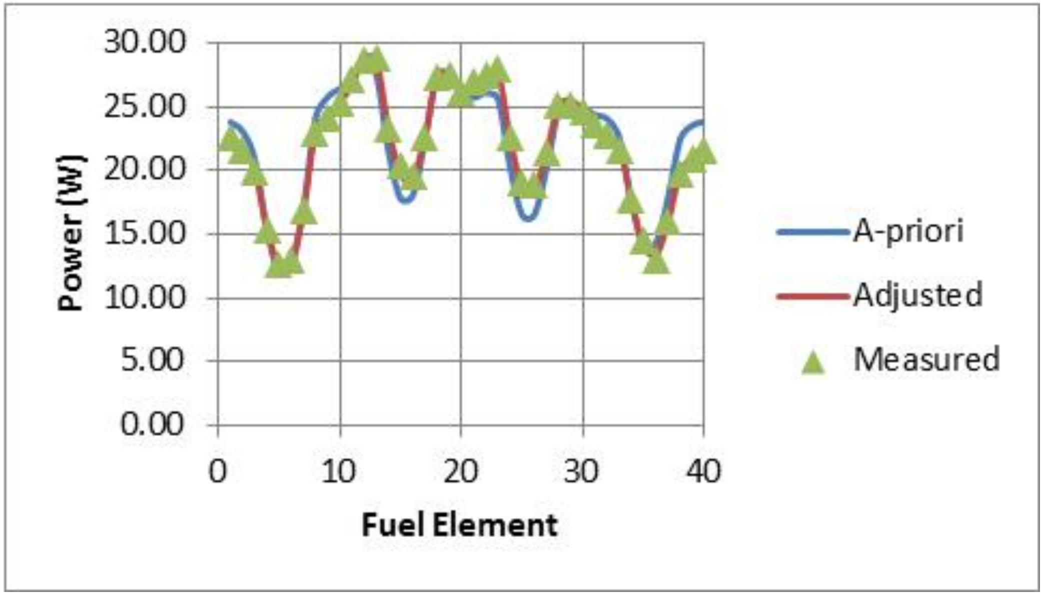
J.W. Nielsen, D.W. Nigg, A.W. LaPorta, "A Fission Matrix Based Validation Protocol for Computed Power Distributions in the Advanced Test Reactor", International Conference on Mathematics and Computational Methods Applied to Nuclear Science & Engineering (M&C 2013), Sun Valley, Idaho, USA, May 5-9, 2013

Element Power Distribution Adjustment (ATRC 12-5) MCNP-5 A-Priori



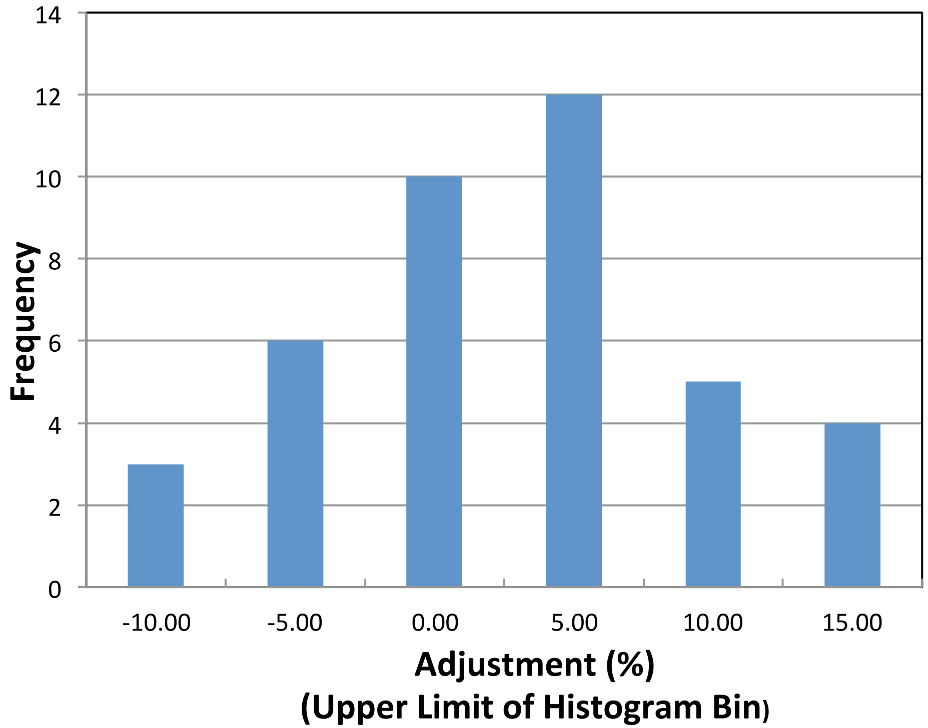
- *A priori uncertainty: 10% (1σ).*
- *Adjustment range: -9.8% (El. 37) to +6.8% (El. 25).*
- *68% of the adjustments were within ±4%.*
- *Reduced uncertainties for the adjusted powers: 3.1% - 3.7%*

Element Power Distribution Adjustment (ATRC 12-5) HELIOS A-Priori



- *A priori uncertainty: 10% (1σ).*
- *Adjustment range: -11.5% (El. 38) to +13.2% (El. 25).*
- *68% of the adjustments were within ±6.3%.*
- *Reduced uncertainties for the adjusted powers: 3.1% - 3.7%*

Element Power Distribution Adjustment (ATRC 12-5) Histogram - HELIOS A-Priori



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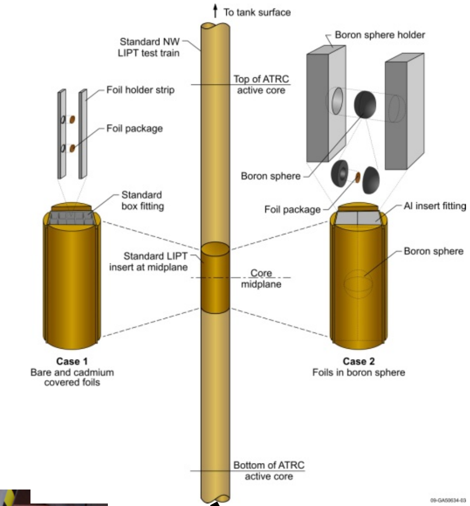
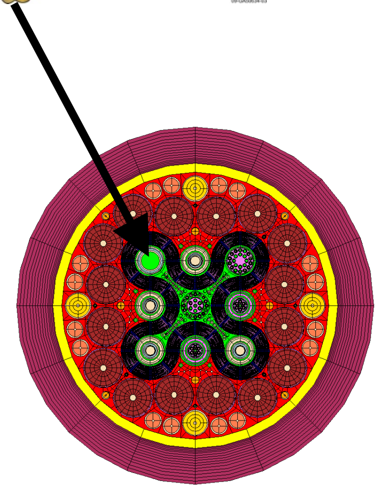
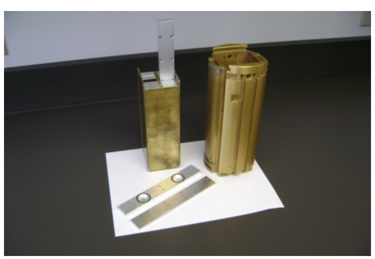
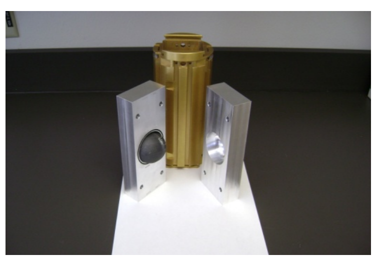
Activation Spectrometry for Neutronics Validation

NW LIPT Test Assembly and Insert Components







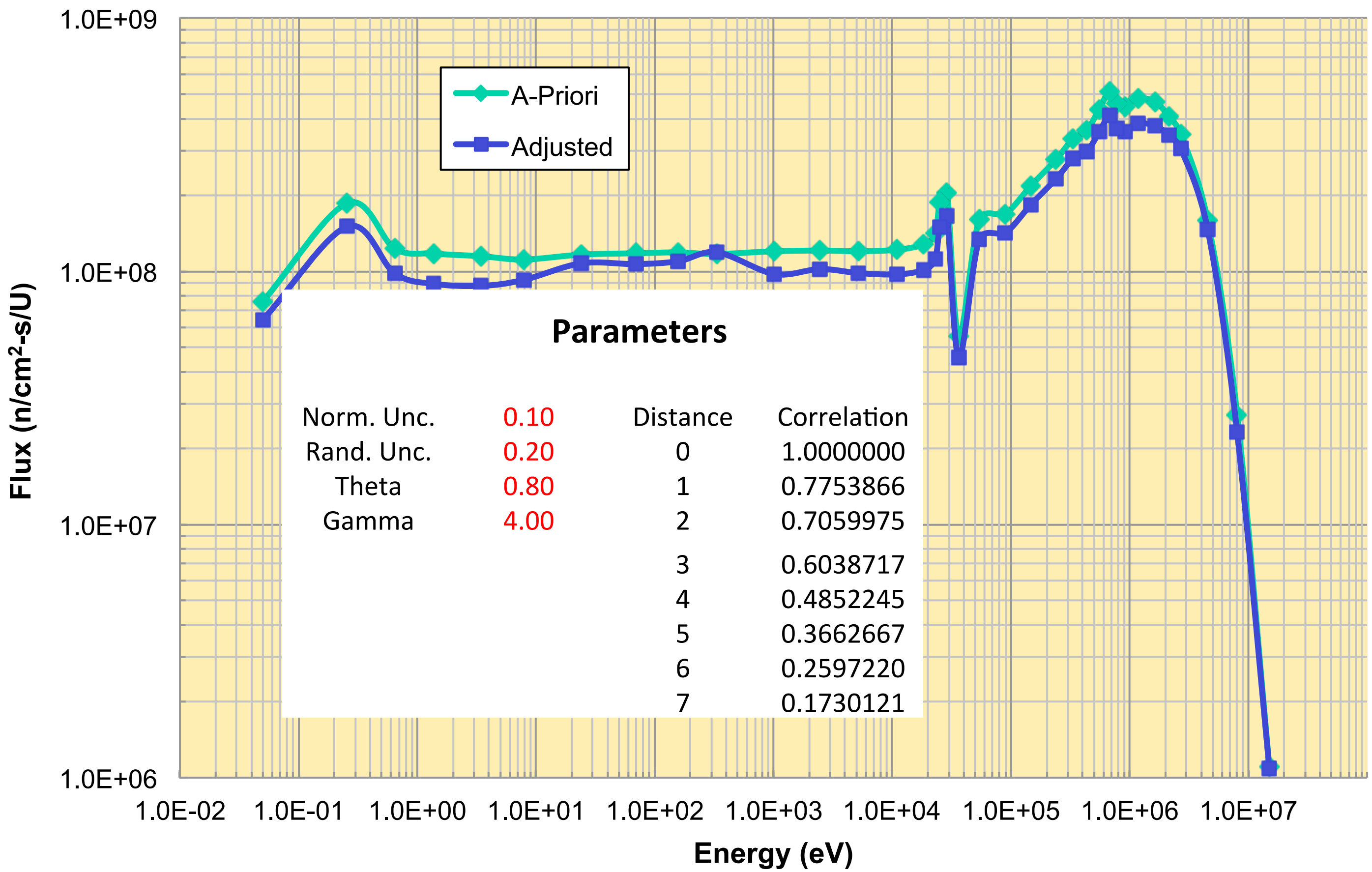


Measured Activation Rates per Atom (AFM1-AFM3)

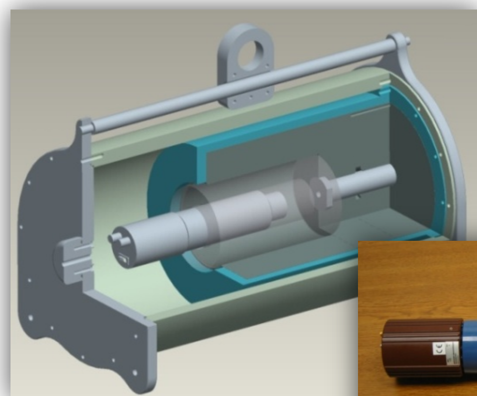
Interaction	Response	Irradiation	Spectral Modifier	Measured σΦ	% Unc.
1	Nb(n,2n)	3	Boron Sphere	2.64E-19	8.62
2	Ti-48 (n,p)	3	Boron Sphere	1.35E-19	9.46
3	Fe-56 (n,p)	3	Boron Sphere	5.12E-19	10.92
4	Ti-46 (n,p)	3	Boron Sphere	5.00E-18	12.30
5	Ti-47 (n,p)	3	Boron Sphere	1.17E-17	6.44
6	Fe-54 (n,p)	3	Boron Sphere	4.10E-17	10.90
7	Zn-502 (n,p)	3	Boron Sphere	2.05E-17	7.14
8	Ni-1004 (n,p)	3	Boron Sphere	5.72E-17	6.55
9	In-(n,n’)	3	Boron Sphere	1.30E-16	6.49
10	In(n,n’)	1	Cadmium	1.24E-16	4.04
11	In(n,n’)	1	Cadmium	1.23E-16	4.14
12	Cu(Res)	1	Cadmium	3.44E-16	4.30
13	Cu(Res)	1	Cadmium	3.54E-16	5.16
14	Mn(Res)	1	Cadmium	9.52E-16	4.57
15	Mn(Res)	1	Cadmium	1.01E-15	4.18
16	W(Res)	1	Cadmium	2.79E-14	4.10
17	W(Res)	1	Cadmium	2.86E-14	4.12
18	Au(Res)	1	Cadmium	4.90E-14	4.11
19	Au(Res)	1	Cadmium	5.09E-14	4.05
20	In(Res)	1	Cadmium	8.03E-14	4.81
21	In(Res)	1	Cadmium	8.57E-14	4.51
22	Au(Th)	1	None	1.07E-13	4.07
23	Au(Th)	1	None	1.09E-13	4.03
24	Mn(Th)	1	None	8.74E-15	4.13
25	Mn(Th)	1	None	8.26E-15	4.15

36-Group ASTM-944-Compliant LLSQ Spectral Adjustment (MCNP5 A-Priori) - ATR NW LIPT (PHYSOR 2012)

16 Linearly-Independent Dosimeter Responses

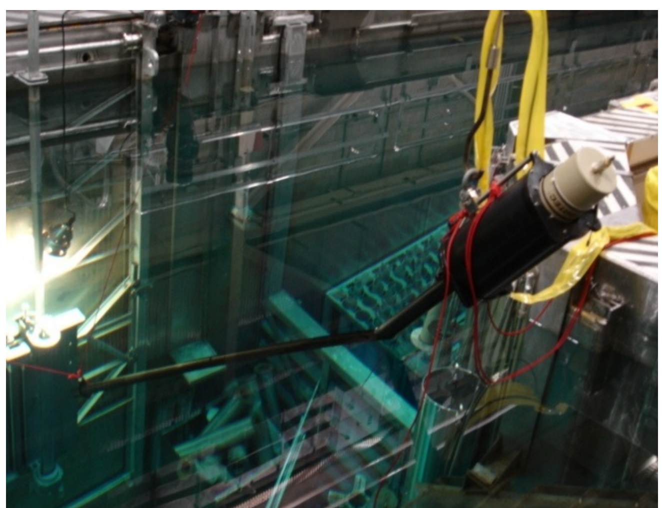


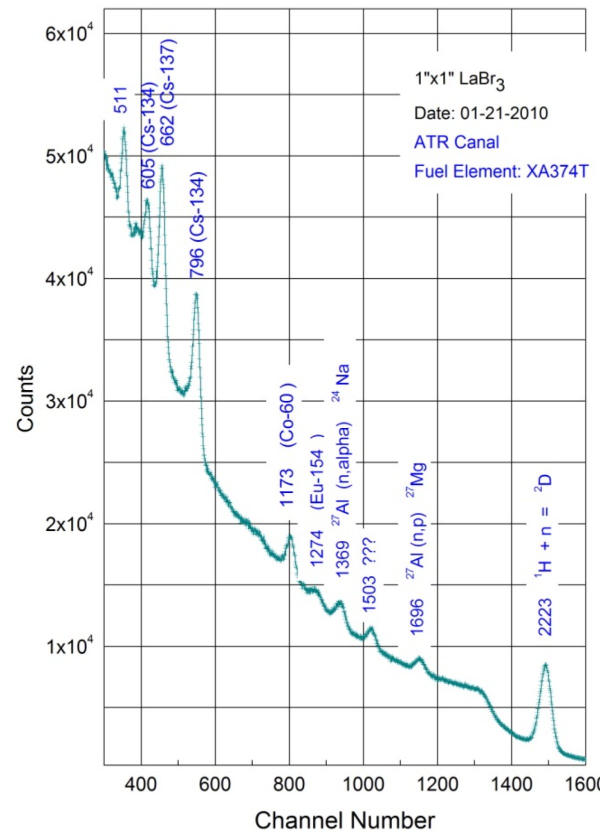
In-Canal Burnup Validation of ATR Fuel



LaBr Detector and Integrated underwater electronics package

Surface-mounted HPGe detector with integrated underwater collimator extending down to fuel element of interest





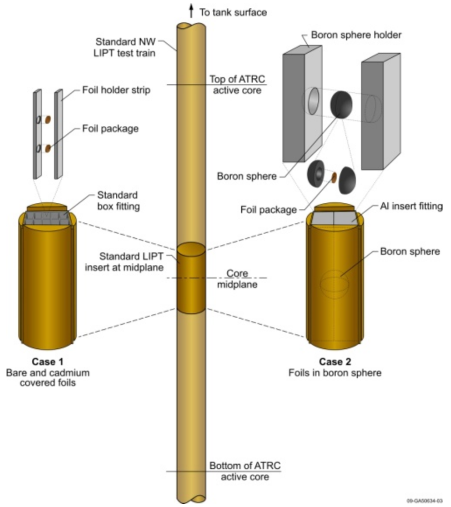
Measured gamma spectrum of depleted ATR Fuel Element

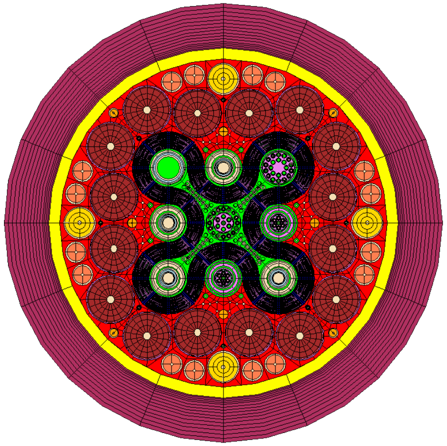
LEU Validation Strategy

•*Leveraging with current HEU validation activities.*

•*Code and cross section validation against neutronically-similar H_2O-moderated LEU and LEU-Moly plate fuel experiments from OECD Handbooks (IRPhE and ICSBEP) and other data sources.*

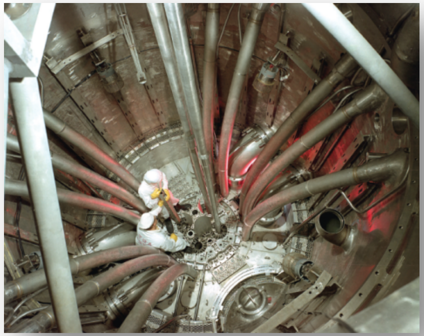
•*Direct validation against experimental data from single-plate, multi plate and full-element LEU experiments and, ultimately, hybrid HEU/ LEU cores and full LEU cores.*





Summary – Path Forward – New Challenges

- ***We are updating and integrating ATR reactor physics modeling and simulation methods, consistent with modern engineering practice, with complementary V&V protocols based on applicable industry standards***
- ***This presentation has summarized the status of the extensive validation effort in particular, including a few details for neutron spectra in core fuel and experiment positions, lobe powers, and element-to-element power distributions.***
- ***One specific ATRC power distribution benchmark experiment described here (ATRC TP 12-5, the "Depressurized Run") is an outstanding candidate for the OECD NEA International Reactor Physics Experiment (IRPhE) Benchmark Handbook***
- ***High-fidelity modeling can reduce reliance on expensive and time-consuming supporting experiments in ATRC.***
- ***But computers, no matter how powerful, will never offer a complete substitute for experimental truth and accuracy***
- ***Validation must be an ongoing part of continuous improvement in operations, especially for a constantly-changing system such as ATR***



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The authors also wish to gratefully acknowledge several useful discussions with Dr. John G. Williams, University of Arizona, on the general subject of covariance matrices and their role in this type of analysis

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