ARCADIA® Code System Pre-submittal Meeting

AREVA/NRC Meeting
Rockville, MD
5/19/2015

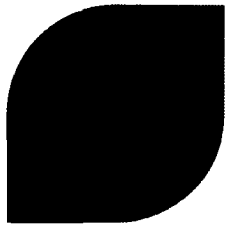
AREVA

Opening Remarks

Tony Attard
Regulatory Engineer

AREVA

Agenda



▶ Safety and Operational Excellence	- A. Attard
▶ Objectives	- A. Attard
▶ Introduction	- K. Segard
▶ Range of Applicability	- K. Segard
▶ APOLLO2-A Enhancements	- R. Rubilar
▶ APOLLO2-A Validation	- R. Rubilar
▶ ARTEMIS™ Enhancements	- R. Rubilar
▶ ARCADIA® Validation	- M. Guzzardo
▶ ARCADIA® Transient Validation	- M. Guzzardo
▶ ARCADIA® Uncertainty Analysis	- M. Guzzardo
▶ Change Process	- K. Segard
▶ Conclusions	- K. Segard
▶ Next Steps	- A. Attard

Objective

- Provide a status update on ARCADIA® Code System development
- Provide an overview of AREVA's Advanced PWR Methodologies
- Provide an overview of the enhancements made to the ARCADIA® Code System
- Show comparisons against measurements for APOLLO-2A and ARTEMIS™
- Show comparisons against measurements highlighting the ARCADIA® transient capability
- Summary (Obtain NRC feedback)
- Next Steps

▶Introduction

Kevin Segard
Supervisor, Methods and Licensing

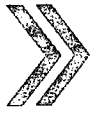
Background

- In 2002 AREVA began the development of a new set of advanced PWR codes
  - APOLLO2-A Lattice Code
  - ARTEMIS™ 3D Core Simulator
  - COBRA-FLX™ 3D Thermal-Hydraulics Code
- These and other auxiliary codes makeup the ARCADIA® code system
- ARCADIA® and COBRA-FLX™ Topicals Reports were submitted in March 2010
- Both have received NRC approval

Planned Schedule

- Pre-submittal meeting
- Topical submittal to NRC
- Post-submittal meeting
- Additional meetings/technical audits as needed
- Requested NRC approval

[ ]



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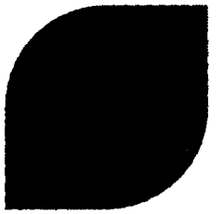
Requirements

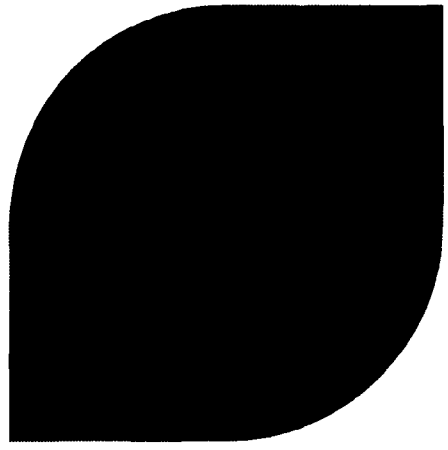
- The ARCADIA® Code System Supports Topical Reports
  - AREA – AREVA's Rod Ejection Analysis
  - ARITA – ARTEMIS™ / RELAP Integrated Transient Analysis Methodology
  - ARABOW – AREVA's Bow Methodology
- Submittal Schedule
  - AREA
  - ARITA
  - ARABOW

[ ]

Start of Proprietary Information



- Proprietary meeting will begin with next slide



Range of Applicability

Presenter: Kevin Segard
Position: Supervisor, Methods and Licensing

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Applicability (1/3)

- PWR designs
  - W 157, W 193, B&W 177, S 177, S 193, CE 217
  - Core heights vary from 136.7" to 144"
- PWR Assembly types with a lattice array of 14X14 to 18X18
  - Small and large guide tube configurations are included
- Fuel materials include UO_2 and Enriched Reprocessed Uranium (ERU)
- Control rod absorber materials
  - Ag-In-Cd, B4C, and Hf

Applicability (2/3)

▶Burnable absorbers

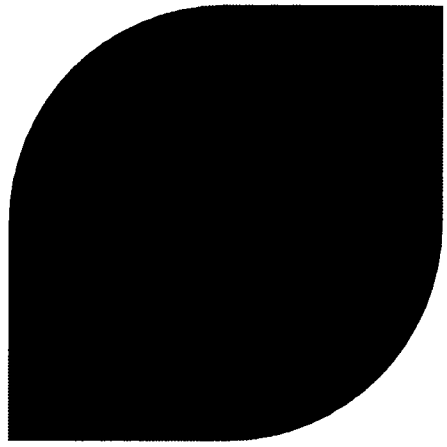
- Discrete boron rods that are inserted into guide tube locations
- Fuel pellet burnable absorber coating (ZrB_2)
- Gadolinia bearing fuel rods up to 10 wt% Gd_2O_3

Range of applicability can be extended by performing additional benchmarks and showing that the specified criteria are met.

Applicability (3/3)

- **Incore Detectors**
  - Incore movable fission detectors
  - Fixed Rhodium detectors
  - Aeroball Measurement System
- **Reconstruction methods include**
  - INPAX-W from ANP-10297P-A
  - INPAX-C from ANP-10297P-A
  - MEDIAN ANP-10297P Supplement 1

Applicability to other detector types requires reanalysis and NRC approval



ARCADIA® Updates: APOLLO2-A Enhancements

Roberto Rubilar
Advisory Engineer
Methods and Licensing
Neutronics – Lynchburg

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APOLLO Developments

▶Main improvements

◈ Code modifications

- e.g., improved tracking, code modifications

◈ Functionalities

- e.g., new kernel, custom or automatic cross section library modifications, memory management

◈ Model changes

- e.g., explicit reflector scheme, improved self-shielding

Motivation

- **While performing comparisons to cores containing MOX fuel assemblies, AREVA identified:**

[ ]

- **Enhance the ARCADIA® topical report to include Doppler effect**

CEA was receptive to working with AREVA on these issues

Enhancements are expected to benefit both MOX and UO_2 cores

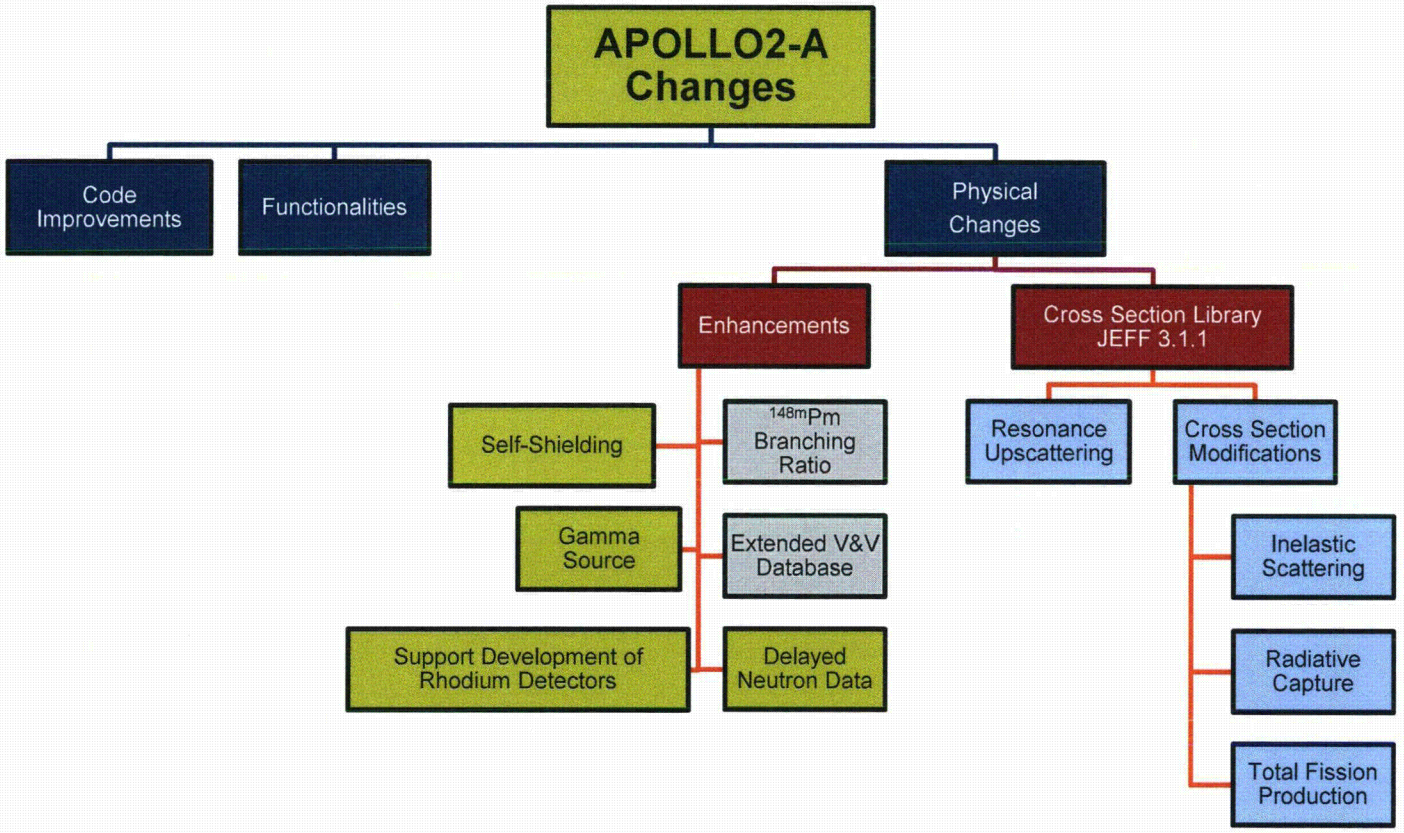
Developments

▶Objectives

[ ]

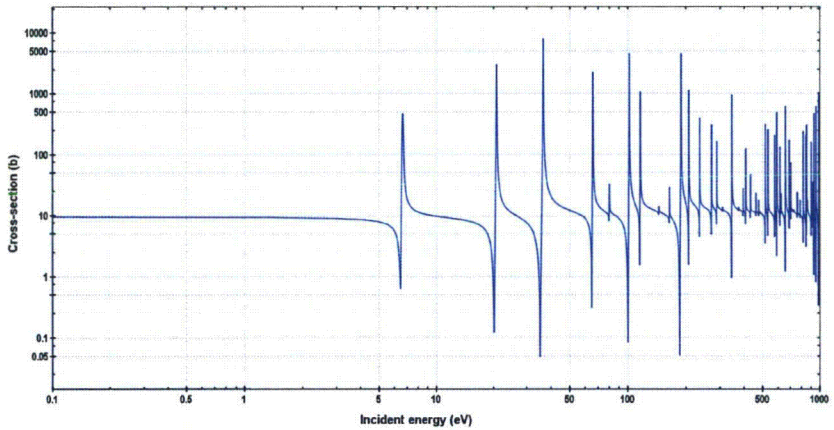
- **Validation and verification:**
  - To be within the measured uncertainties
  - To gain CEA concurrence with the proposed changes

APOLLO2-A Developments



APOLLO2-A Developments
Resonance Upscattering Model

- **Implementation**
  - **New neutron transport library takes into account:**
    - Resonant upscattering of [ ]
      - Increase the number of energy groups to describe a more detailed treatment of the [ ] resonances



    - Higher upscattering threshold for [ ]

Improved Doppler predictions

APOLLO2-A Developments
Cross Section Adjustments

▶Uncertainty vs adjustments comparison

[ ]

Enhancements:

1) **Improve core reactivity predictions**
2) **Bring these cross sections closer to the ENDF-B/VII library values while remaining within the uncertainty of the JEFF 3.1.1 library**

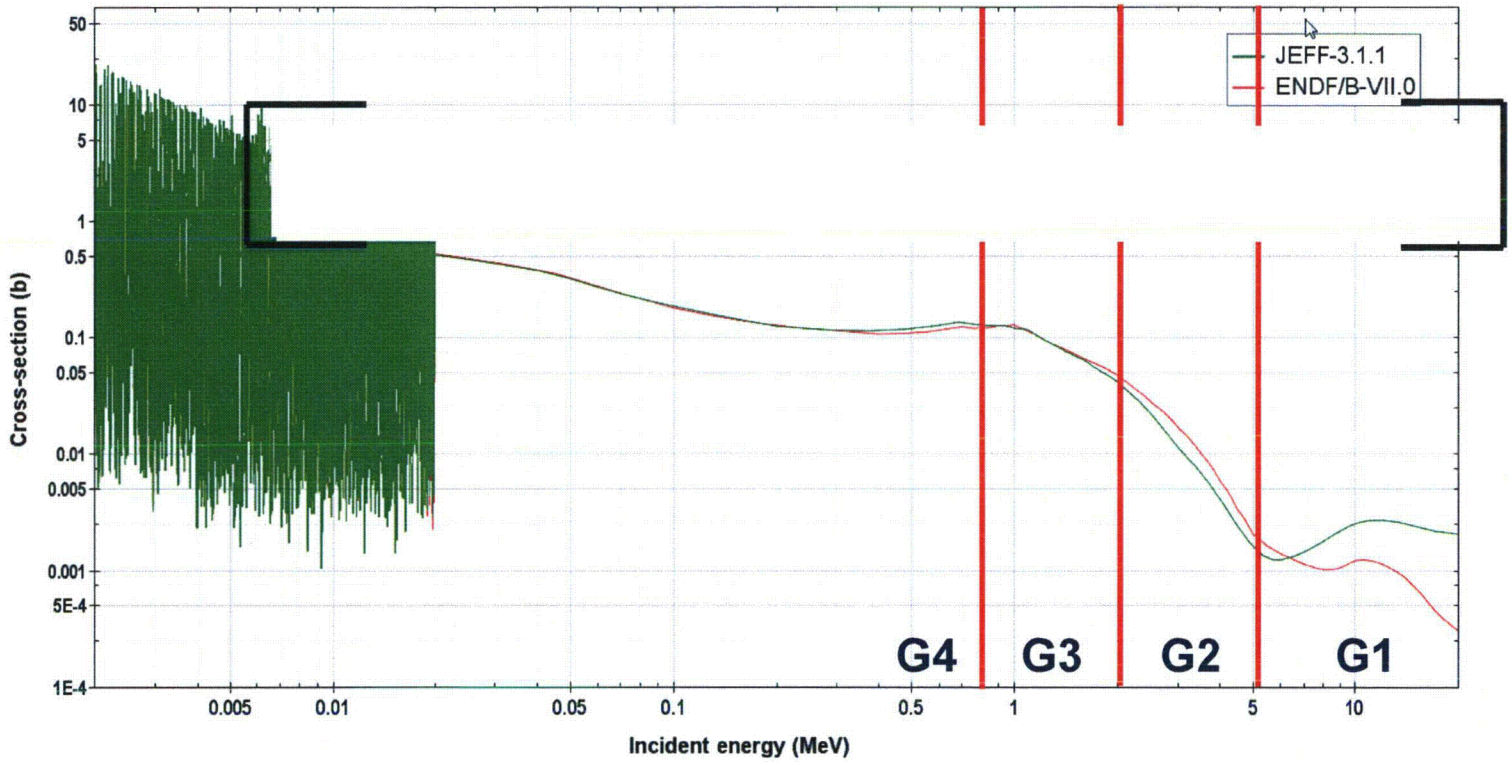
APOLLO2-A Developments
Cross Section Adjustments

- Justification: [ ] Inelastic Cross Sections

- Make adjustments to cross sections
- Adjustments remain with the uncertainty of the measurements

APOLLO2-A Developments
Cross Section Adjustments

- **Justification: [ ] Radiative Capture (n,γ)**

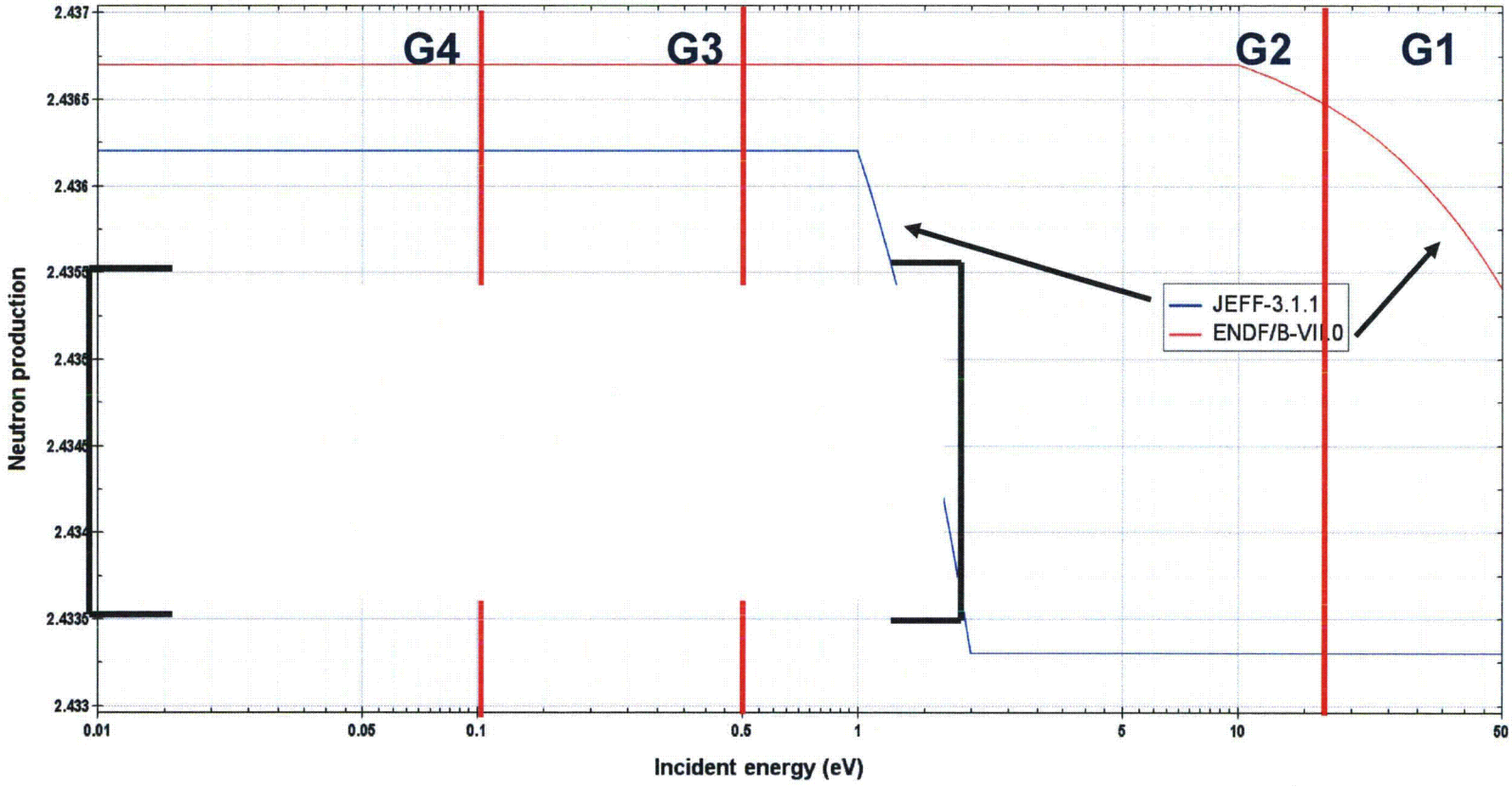


- Uncertainty in measurements is > 1% for experiments
- The dispersion of the data can accommodate a change of 0.4%

Back

APOLLO2-A Developments
Cross Section Adjustments

- Justification: [^{235}U] Neutron Multiplication

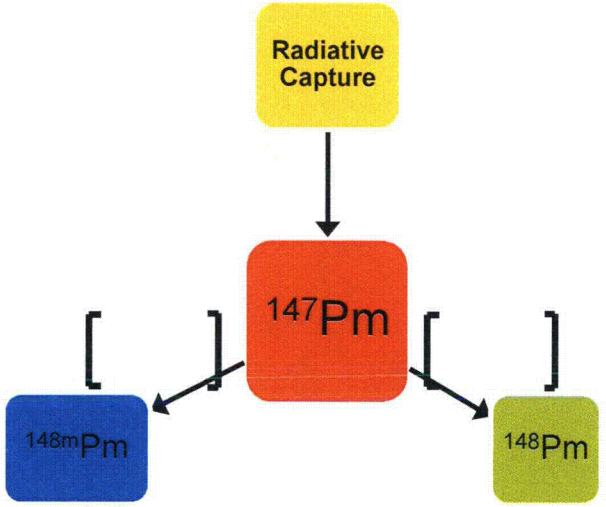


- A modification of 0.1% would be below 1σ for all evaluations

Back

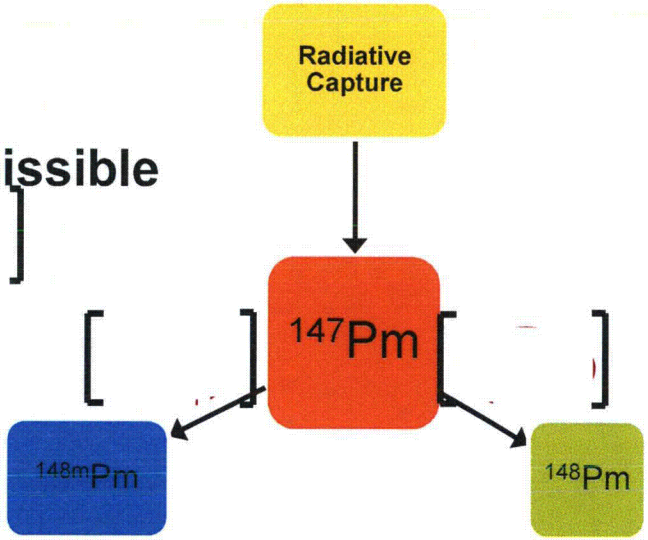
APOLLO2-A Developments
Additional Enhancements

- Changes to:
  - ^{148m}Pm branching ratio
- Motivation
  - Reactivity loss with exposure was seen against cycle measurements
  - CEA reviewed the possible fission products that may have a significant effect on the reactivity
  - CEA decided to investigate ^{148m}Pm



APOLLO2-A Developments
Additional Enhancements

- **Justification for change:**
  - Literature review showed that the current value is inconsistent with modern experiments
  - CEA recommends [ ]
  - APOLLO2-A uses the lowest admissible value to maximize the effect: [ ]

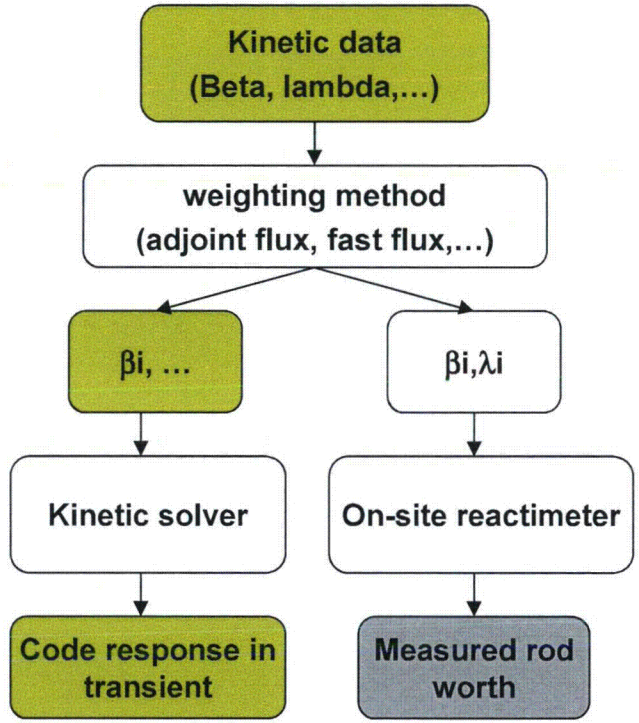


Improvement to core reactivity predictions at EOC and affect the startup critical boron concentration

APOLLO2-A Developments
Additional Enhancements

Delayed Neutron Data

- Eight precursor groups are set by default for nuclides incurring fission (previously condensation included six precursor groups)
- Transfer of the original 8 groups from JEFF3.1.1 library through the chain AP2-A – HERMES – ARTEMIS



Enhancements improve core response in transients

APOLLO2-A Developments
Additional Enhancements

- **Support for Rhodium Detectors**
  - **Self-shielding of ^{103}Rh has been included in APOLLO2-A calculations**
  - **Detector response is affected but not the system reactivity**

Enhancements improved detector response predictions

Cross Section Adjustments

- Impact on core reactivity

- Cross sections changes were intended to increase reactivity as a function of burnup

Cross Section Adjustments

Impact on pin power

- The power differences are provided :
  - W 17X17 lattice, average 4.95 wt% 235U
  - W 17X17 lattice, 4.47 wt% 235U and 20 rods at 8 wt% gad plus 8 rods at 2 wt% gad
  - CE 14X14, average 4.11 wt% 235U
- These lattices are typical lattices used in commercial reactors

CE example

- The observed power differences are within [ ] and the maximum RMS X 100 is less than [ ]

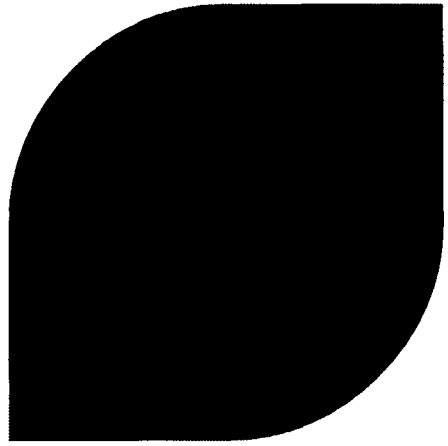
Changes observed in assembly pin power were not significant

Large Core Configurations

- **The capability has been added to APOLLO2-A to allow for the modelling of larger 2D geometries**
  - **This allows:**
    - Configurations for problems up to a 1/4 geometry including radial reflectors
- **This feature can be used for generating reference solutions for comparison to models used in nodal design calculations**

Surface Spectral History Model

- Adjustments were made to APOLLO2-A to support the Surface Spectral History model in ARTEMIS™
  - Generates a set of coefficients that describe the rate of change of macroscopic cross sections as a function of the change in the neutron flux spectrum.
  - The neutron spectrum is defined to be the ratio of the thermal to fast flux for a two energy group system. The changes in the cross sections are derived from a series of single assembly and 2X2 assembly configuration calculations.
- The tabulated cross section changes are generated for use in ARTEMIS™ for the Spectral Cross Section Model.
- This model corrects the nodal surface cross sections for flux spectrum differences between neighboring assemblies the nodal solution in ARTEMIS™ and the infinite lattice solution in APOLLO2-A.



APOLLO2-A
Validation

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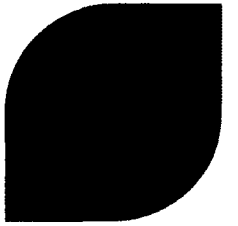
Verification & Validation Strategy

- Functional verification with an automated test matrix
- Physical validation
  - Against critical experiments
  - Through cycle calculations (e.g., ANP-10297P-A benchmarks)

APOLLO2-A Developments V&V Database



- **Changes to:**
  - **Extended Validation & Verification Database**
    - Verification
      - Non-regression (comparisons between the current and the previous APOLLO2-A version)
      - Self-consistency (to check the correct behaviors of specific parts of the code)
    - Validation
      - Physical (comparisons against experimental data)
  - **Over 625 configurations tested (392 configurations tested for ANP-10297P-A)**

APOLLO2-A Developments V&V Database

- Critical Experiments:
  - BASALA (Gad)
  - B&W*
  - CAMELEON* (Gad)
  - EPICURE-MOX*
  - EPICURE-UOX*
  - KRITZ-KWU-crit (Pu)*
  - KRITZ-KWU-crit (U)*
  - MISTRAL
  - SAXTON (MOX)
  - VIPEX-VENUS

[ ]

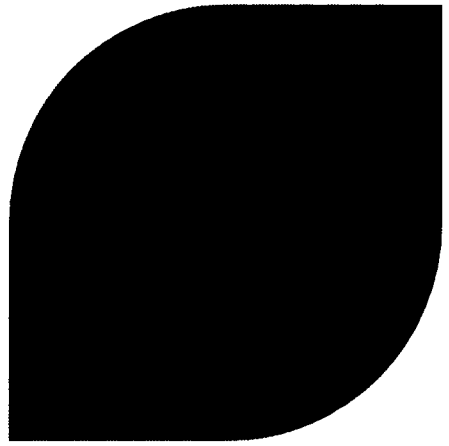
* Presented in the ANP-10297P-A

Conclusions

- Overall reactivity remains in range with respect to the criteria presented in the topical report
- Improved power sharing (in/out tilt)

[ ]

  - Results show good physical accuracy
  - Extension of validation to MOX and BWR underway (not part of the submittal)



ARCADIA® Updates: ARTEMIS™ Neutronics Changes and Enhancements

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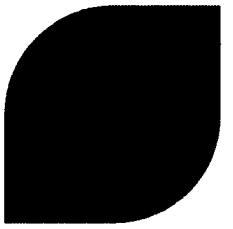
ARTEMIS™ Neutronics Changes and Enhancements



▶Main code changes

- Cross section model
- Pin reconstruction
- Spacer grid model
- MEDIAN (Measured Dependent Interpolation Algorithm using NEM (Nodal Expansion Method))

Cross Section Model

- Equivalent or better accuracy compared to previous code systems at cold conditions

- ANP-10297P-A: V&V of reactivity
  - Validation of APOLLO2-A reactivity using critical experiments
  - Validation of ARTEMIS™ reactivity by comparison to core measurements
  - Description of fundamentals of ARTEMIS™ cross section fitting methods

Cross Section Model
Cold Condition Validation

Pin Reconstruction Enhancements

- ANP-10297P-A defined UO_2 application methods
- Development of MOX capabilities were necessary
  - MOX widely used in Europe
  - DOE MOX implementation; (project deferred)
- MOX extensions also provide benefit for UO_2 analyses

[ ]

AREVA is seeking approval for UO_2 only

Pin Reconstruction UO_2 Local Power

Sample Pin Power Reconstruction Model
(relative % (Artemis – Apollo)/Apollo)

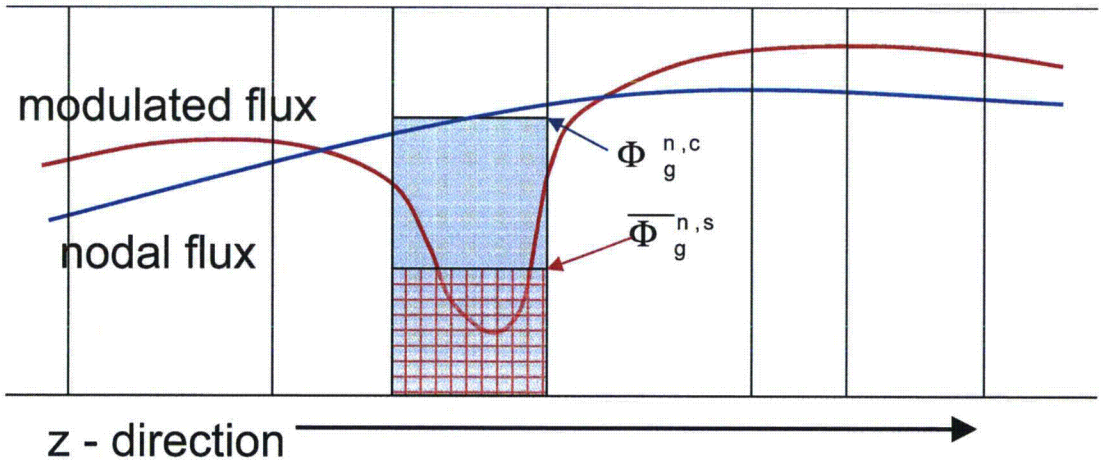
Spacer Grid Model

- Directly apply grid effect in calculated power distribution
- ANP-10297P-A uses a grid factor to account for peaking increase due to spacer grids (SG)
- ARTEMIS™ enhanced to directly calculate the effect of SG on flux, power, and burnup
  - Allows direct comparison to measured values
  - Allows elimination of grid penalty factor

ARCADIA® Supplement Grid Model

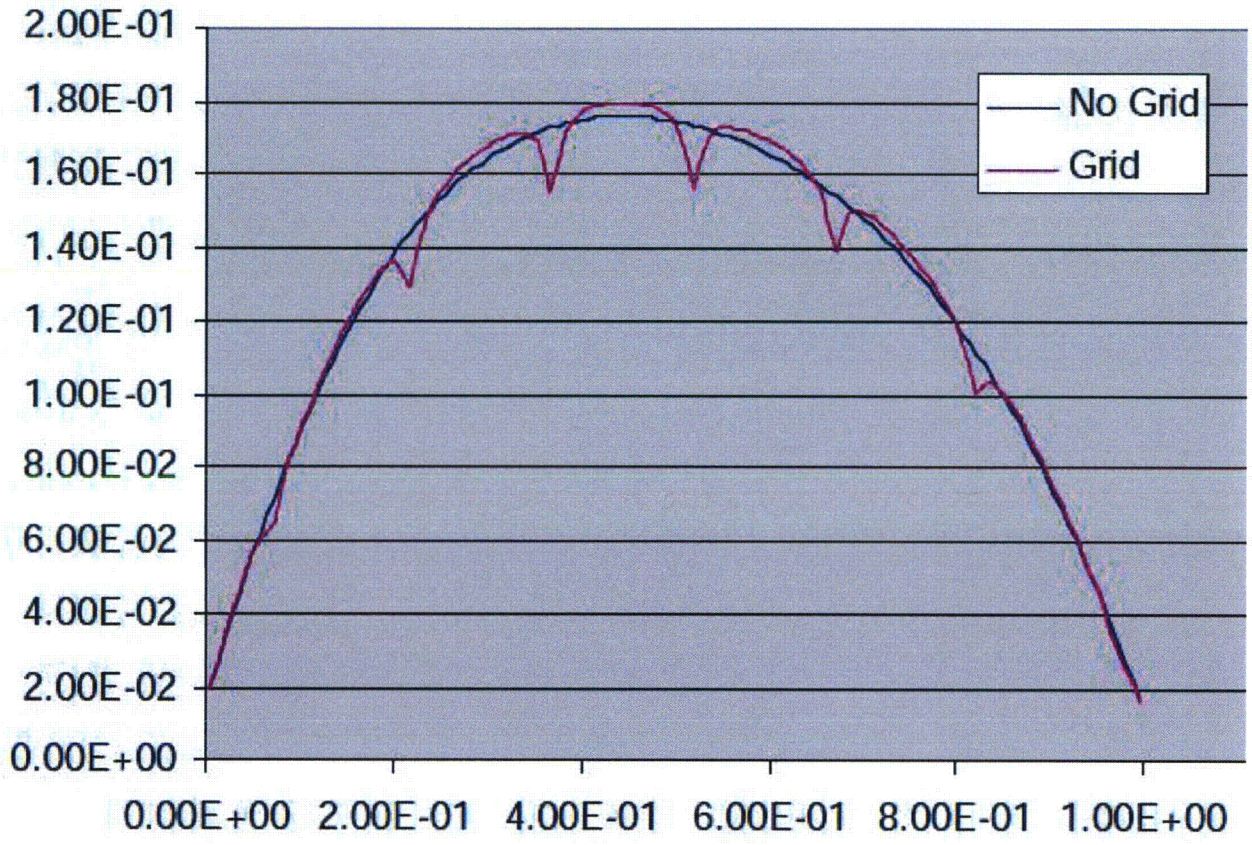
- SG cause local variations in axial flux and power distribution
  - Modeling SG material smeared over the fuel assembly only treats reactivity effect
  - SG modeled using an axial form-function concept
    - Parameterized for burnup and SG-volume
    - Form-functions are customized for power and 2 group fluxes

- Perform nodal solution using smeared SG model
- SG form function applied for axial power and flux representation



Eliminates grid factor by using explicit model

Spacer Grid Model Example

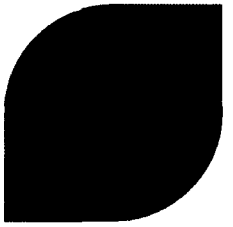


ARCADIA® Supplement
Full MEDIAN Implementation

- MEDIAN is a power reconstruction method presented in ANP-10297P-A for the Aeroball Measurement System
- Extend use of MEDIAN to movable (fission) and fixed (rhodium) incore detector systems
- Provides a single measurement system
- Full implementation will allow transition from legacy topical reports

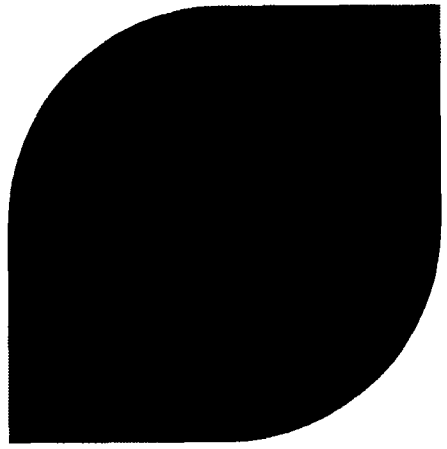
A single methodology to be applied for all incore measurement systems

ARCADIA® Supplement Additional Enhancements



Summary/Conclusions

- Cross section fitting methodology has been updated with additional cross terms
  - No impact for hot conditions
  - Improved agreement with measurement at cold conditions
- Pin reconstruction methodology has been enhanced to allow MOX application
  - Uncertainty for UO_2 core application maintained or improved
- Spacer grid model has been implemented
  - Direct comparison of calculated and measured powers between grids
  - Grid penalty factor can be eliminated
- MEDIAN methodology extended to all plant types



ARCADIA® Validation

Michelle Guzzardo
ARCADIA® Supplement Technical Lead

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Benchmarks (1/22)

▶Re-analysis of benchmark data (Criteria)

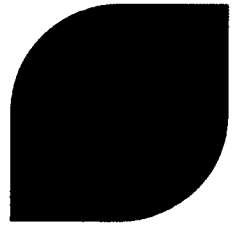
◈ HZP Physics Testing

- ARO CBC (within ±50 ppm or ±500 pcm equivalent)
- Individual Rod Worth (within ±15% or ±100 pcm, whichever is larger)
- Total Rod Worth (within ±10%)
- ARO ITC (within ±2 pcm/°F)

◈ Core Follow Data

- HFP Boron letdown curve (within ±50 ppm or ±500 pcm equivalent)
- Average assembly power distribution (RMS * 100 of the absolute difference < 5.0)
- Average core axial power distribution (RMS * 100 of the absolute difference < 5.0)

Benchmarks (2/22)



▶Plant A

- Westinghouse Reactor
- 157 assembly
- 17x17 fuel assembly
- Moveable fission probe

▶Plant C

- Combustion Engineering Reactor
- 217 assembly
- 14x14 fuel assembly
- Fixed Rhodium SPNDs

Benchmarks (3/22)

▶Plant A, HZP Physics Testing (Supplement results)

HZP ARO CBC

Cycle	Measured (ppm)	Calculated (ppm)	Difference, C-M (ppm)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			

HZP ARO ITC

Cycle	Measured (pcm/°F)	Calculated (pcm/°F)	Difference, C-M (pcm/°F)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			

Benchmarks (4/22)

▶Plant A, HZP Physics Testing (Supplement results)

Individual Rod Worth (Ex, Cycle 14)

Bank	Measured (pcm)	Calculated (pcm)	C-M (pcm)	100*(C-M)/M (%)
A				
B				
C				
D				
SDA				
SDB				
SDC				
Total				

Total Rod Worth

Cycle	Measured (pcm)	Calculated (pcm)	C-M (pcm)	100*(C-M)/M (%)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				

Benchmarks (5/22)

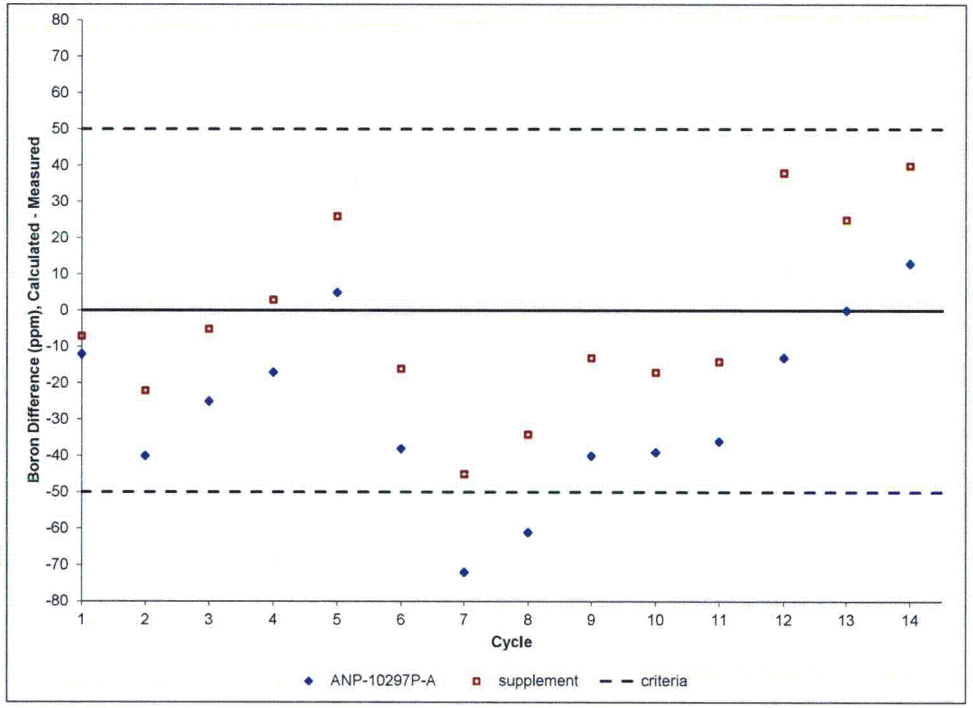
Plant A, HZP Physics Testing Comparisons

HZP ARO CBC

Cycle	ANP-10297P-A (C-M), ppm	Supplement (C-M), ppm
1	-12	-7
2	-40	-22
3	-25	-5
4	-17	3
5	5	26
6	-38	-16
7	-72[a]	-45
8	-61[a]	-34
9	-40	-13
10	-39	-17
11	-36	-14
12	-13	38
13	0	25
14	13	40

[a] Using the ±500 pcm equivalent criteria for Cycles 7 and 8 results in limits of ±78 ppm and ±80 ppm, respectively.

HZP ARO CBC



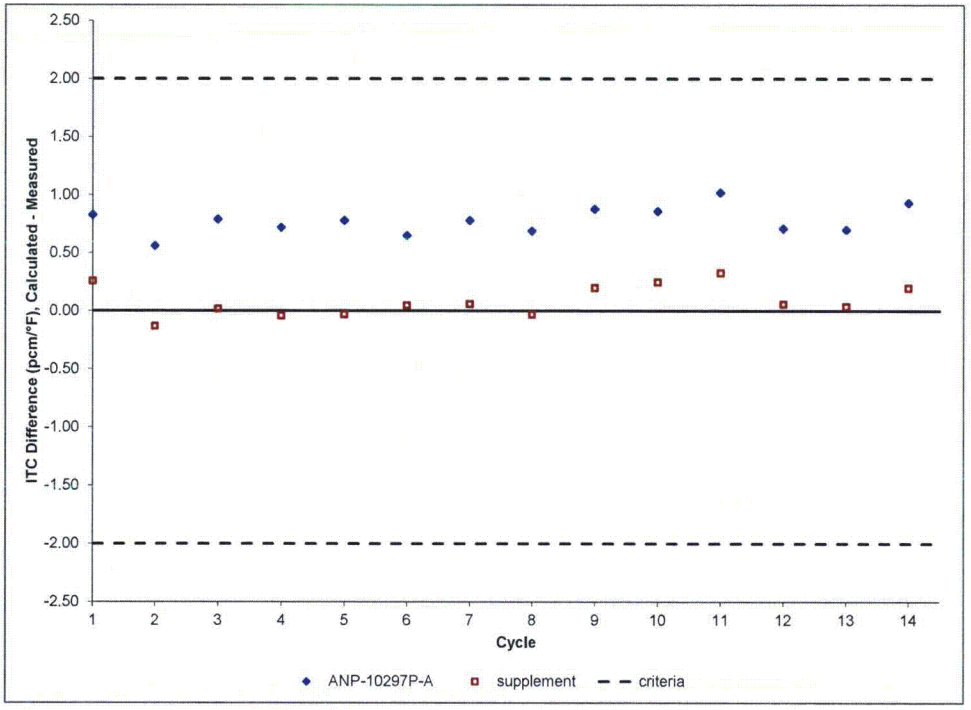
Benchmarks (6/22)

Plant A, HZP Physics Testing Comparisons

HZP ARO ITC

Cycle	ANP-10297P-A (C-M), pcm/°F	Supplement (C-M), pcm/°F
1	0.83	0.26
2	0.56	-0.13
3	0.79	0.02
4	0.72	-0.04
5	0.78	-0.03
6	0.65	0.05
7	0.78	0.06
8	0.69	-0.03
9	0.88	0.20
10	0.86	0.25
11	1.02	0.33
12	0.71	0.06
13	0.70	0.04
14	0.93	0.20

HZP ARO ITC



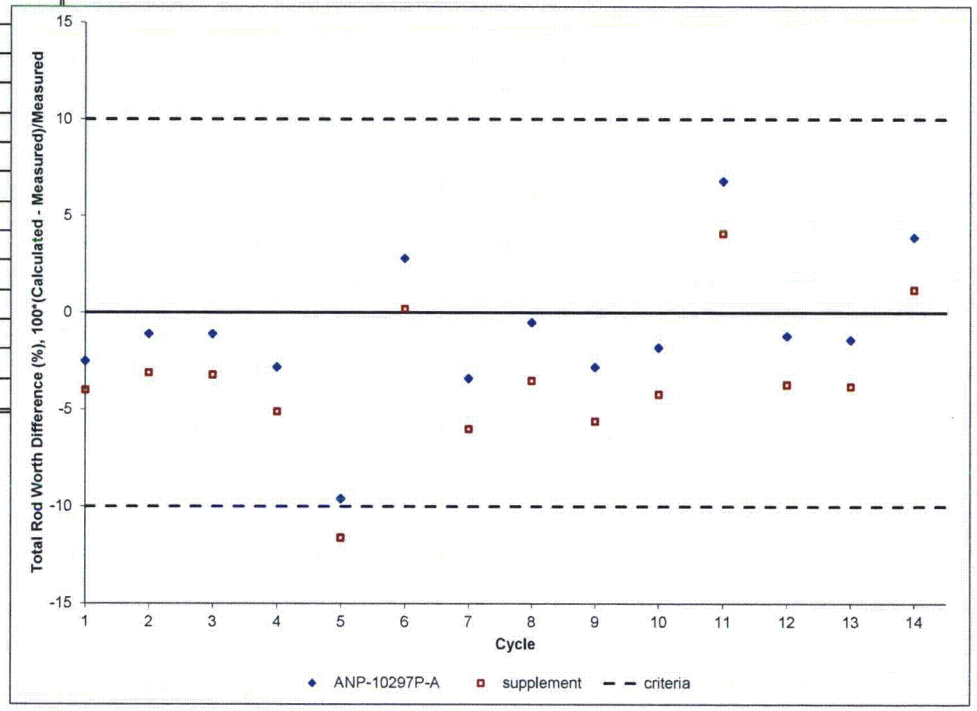
Benchmarks (7/22)

Plant A, HZP Physics Testing Comparisons

Total Rod Worth

Cycle	ANP-10297P-A (C-M), pcm	Supplement (C-M), pcm	ANP-10297P-A 100*(C-M)/M, %	Supplement 100*(C-M)/M, %
1	-170	-272	-2.5	-4.0
2	-69	-195	-1.1	-3.1
3	-65	-194	-1.1	-3.2
4	-164	-304	-2.8	-5.1
5	-620	-752	-9.6	-11.6
6	167	14	2.8	0.2
7	-213	-381	-3.4	-6.0
8	-29	-196	-0.5	-3.5
9	-166	-326	-2.8	-5.6
10	-108	-260	-1.8	-4.2
11	369	227	6.8	4.1
12	-70	-213	-1.2	-3.7
13	-81	-223	-1.4	-3.8
14	224	71	3.9	1.2

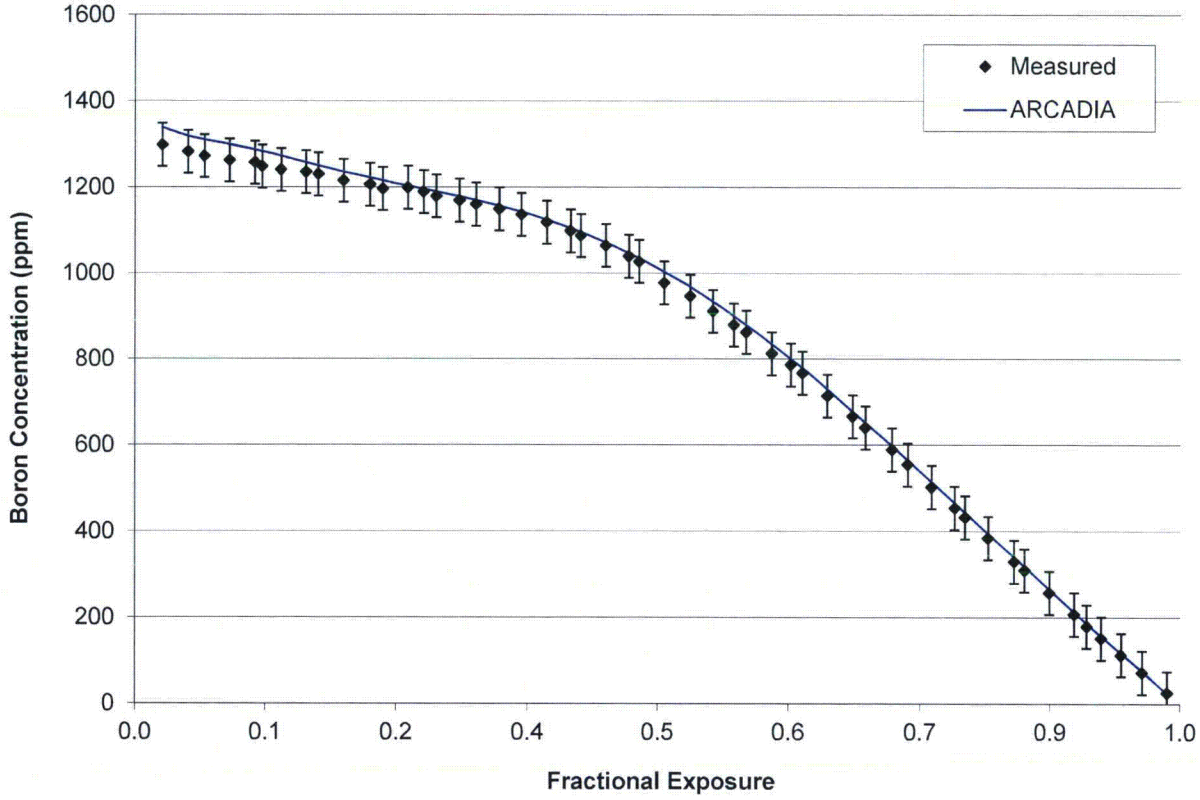
Total Rod Worth



Benchmarks (8/22)

Plant A, Core Follow (Supplement results)

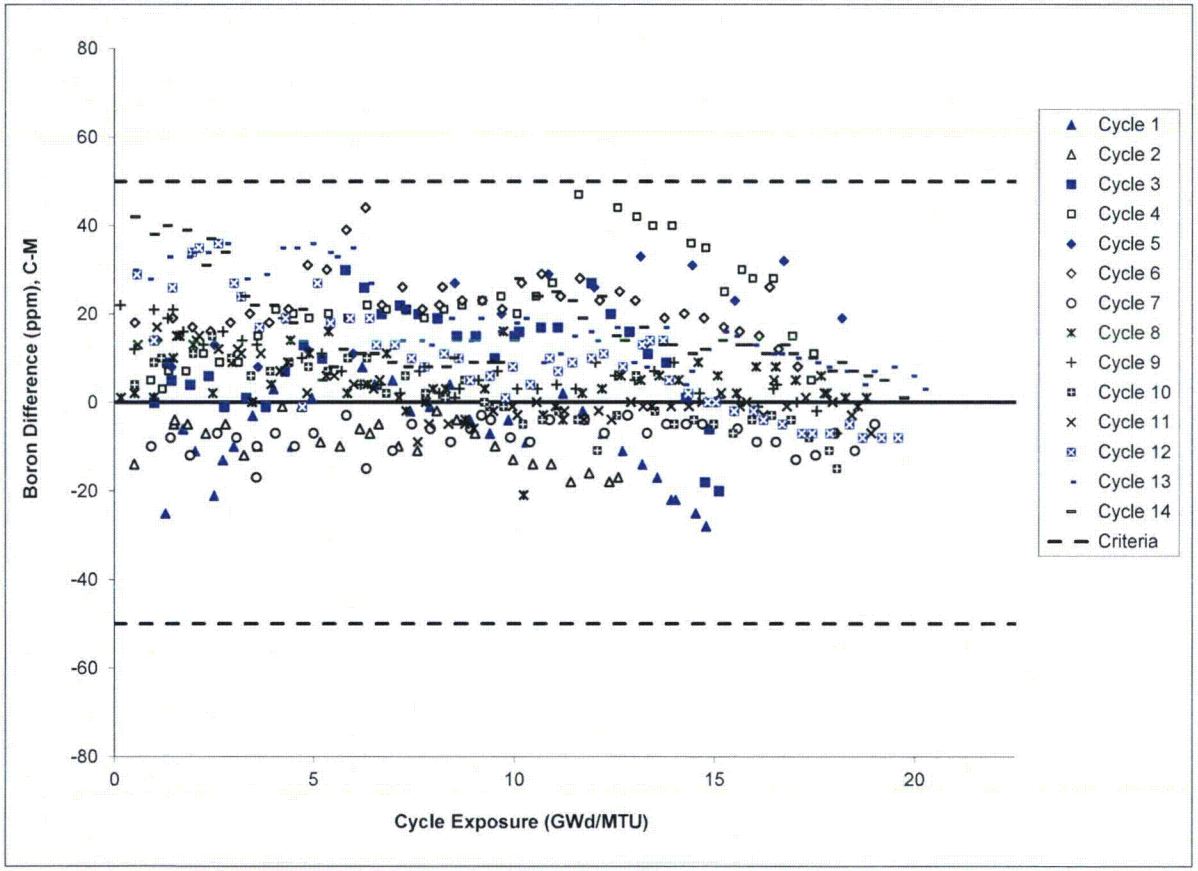
Boron Letdown (Ex, Cycle 14)



Benchmarks (9/22)

Plant A, Core Follow (Supplement results)

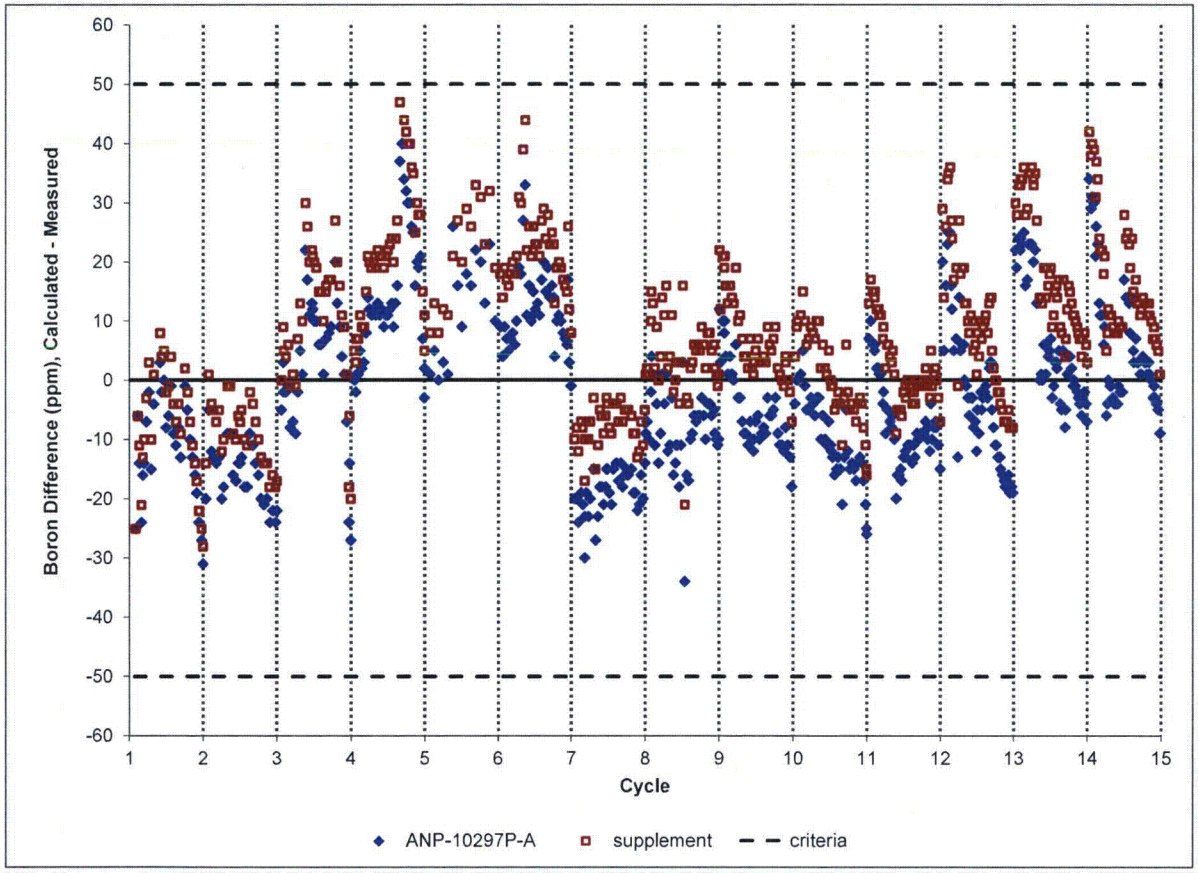
Boron Concentration Differences



Benchmarks (10/22)

▶Plant A, Core Follow

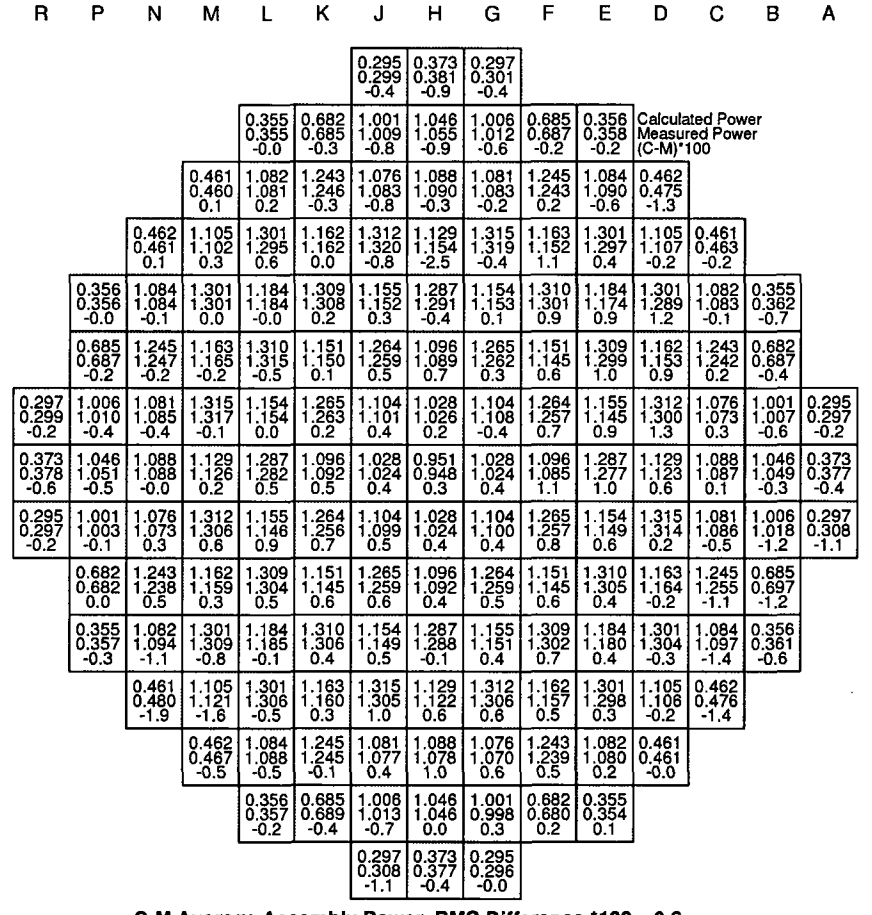
Boron Concentration Comparisons



Benchmarks (11/22)

▶Plant A, Core Follow (Supplement results & comparison)

Average assembly power (Ex, Cycle 14, MOC) (provided only for cycles included in the uncertainty analysis)



C-M Average Assembly Power, RMS Difference *100 = 0.6

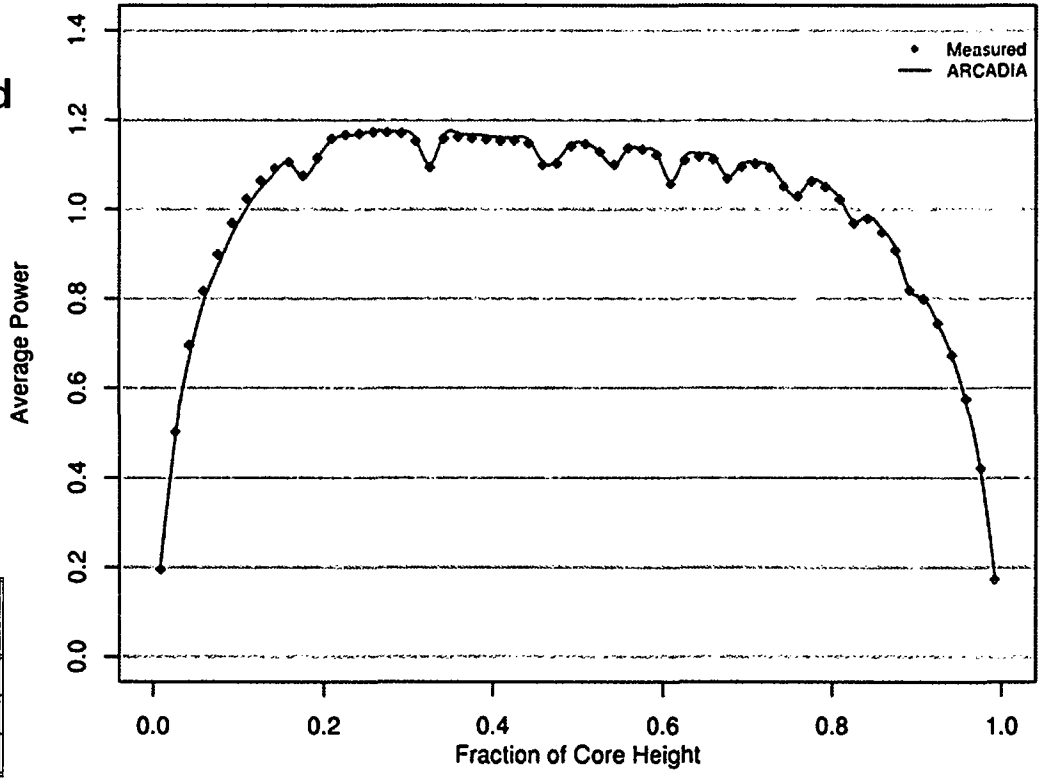
summary of RMS differences for each plant

	ANP-10297P-A (C-M), RMS*100	Supplement (C-M), RMS*100
Cycle 14 BOC	0.7	0.6
Cycle 14 MOC	0.6	0.6
Cycle 14 EOC	0.6	0.7

Benchmarks (12/22)

▶Plant A, Core Follow (Supplement results & comparison)

Average core axial power
(Ex, Cycle 14, MOC)
(provided only for cycles included in the uncertainty analysis)



C-M Average Axial Power, RMS Difference *100 = 0.5

summary of RMS differences for each plant

	ANP-10297P-A (C-M), RMS*100	Supplement (C-M), RMS*100
Cycle 14 BOC	2.6	1.2
Cycle 14 MOC	2.3	0.5
Cycle 14 EOC	2.7	1.3

Benchmarks (13/22)

▶Plant C, HZP Physics Testing (Supplement results)

HZP ARO CBC

Cycle	Measured (ppm)	Calculated (ppm)	Difference, C-M (ppm)
10			
11			
12			
13			
14			
15			
16			
17			
18			

HZP ARO ITC

Cycle	Measured (pcm/°F)	Calculated (pcm/°F)	Difference, C-M (pcm/°F)
10			
11			
12			
13			
14			
15			
16			
17			
18			

Benchmarks (14/22)

▶Plant C, HZP Physics Testing (Supplement results)

Individual Rod Worth (Ex, Cycle 16)

Bank	Measured (pcm)	Calculated (pcm)	C-M (pcm)	100*(C-M)/M (%)
A				
B				
1				
2				
3				
4				
5				
6				
7				
Total				

Total Rod Worth

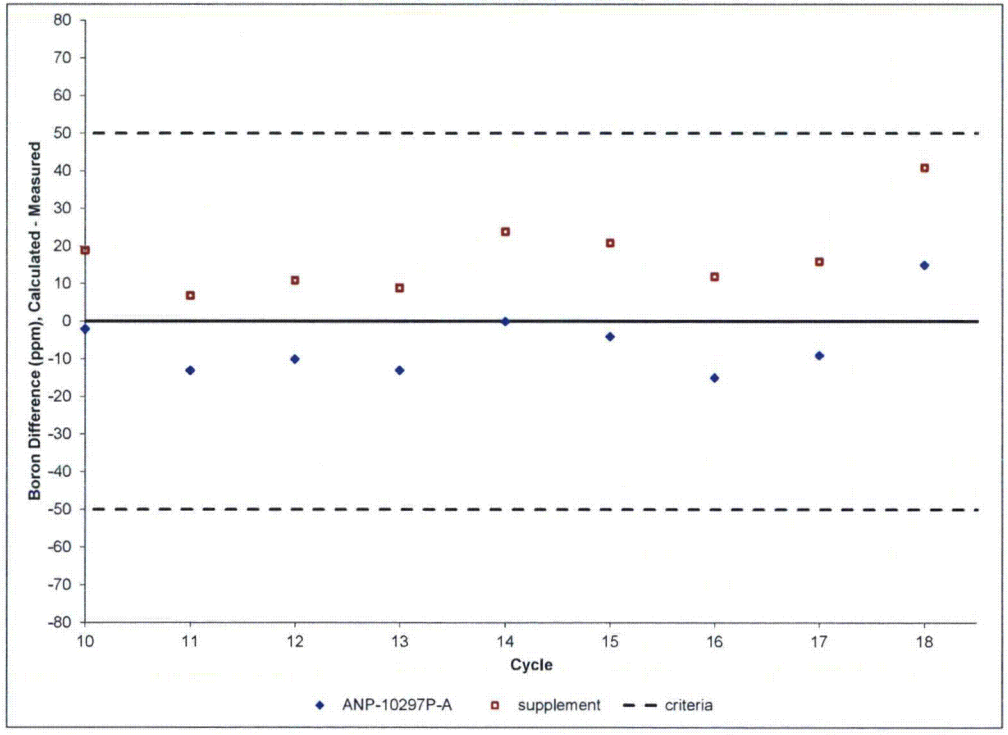
Cycle	Measured (pcm)	Calculated (pcm)	C-M (pcm)	100*(C-M)/M (%)
10				
11				
12				
13				
14				
15				
16				
17				

Benchmarks (15/22)

Plant C, HZP Physics Testing Comparisons

HZP ARO CBC

Cycle	ANP-10297P-A (C-M), ppm	Supplement (C-M), ppm
10	-2	19
11	-13	7
12	-10	11
13	-13	9
14	0	24
15	-4	21
16	-15	12
17	-9	16
18	15	41

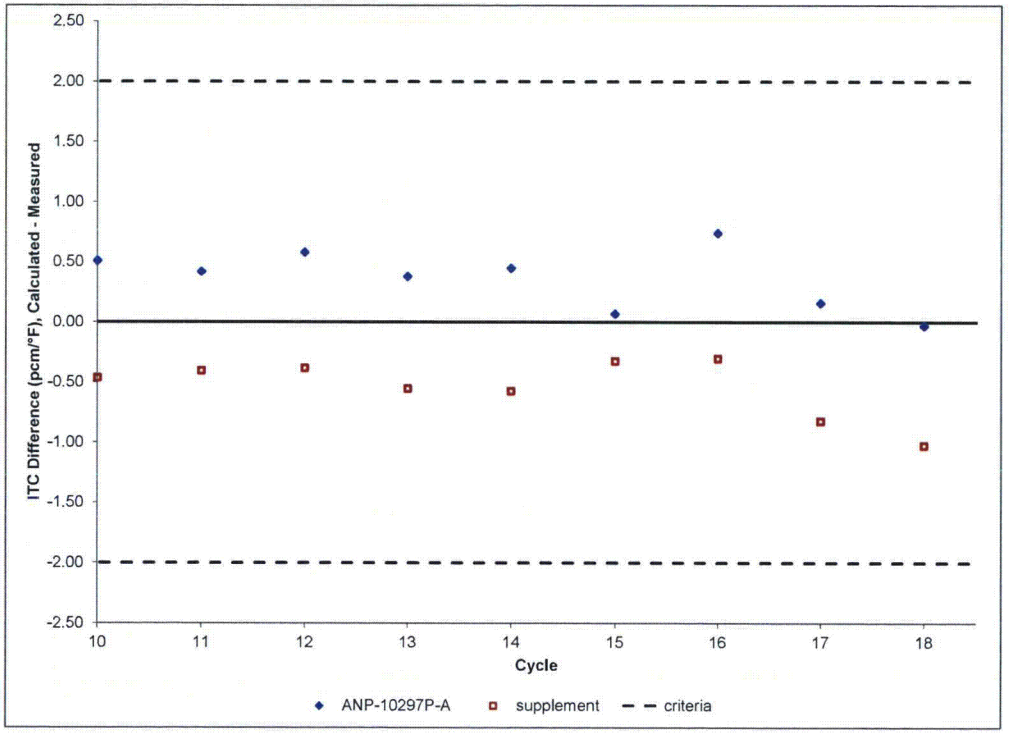


Benchmarks (16/22)

Plant C, HZP Physics Testing Comparisons

HZP ARO ITC

Cycle	ANP-10297P-A (C-M), pcm/°F	Supplement (C-M), pcm/°F
10	0.51	-0.46
11	0.42	-0.40
12	0.58	-0.38
13	0.38	-0.55
14	0.45	-0.57
15	0.69	-0.32
16	0.74	-0.30
17	0.16	-0.82
18	-0.03	-1.02



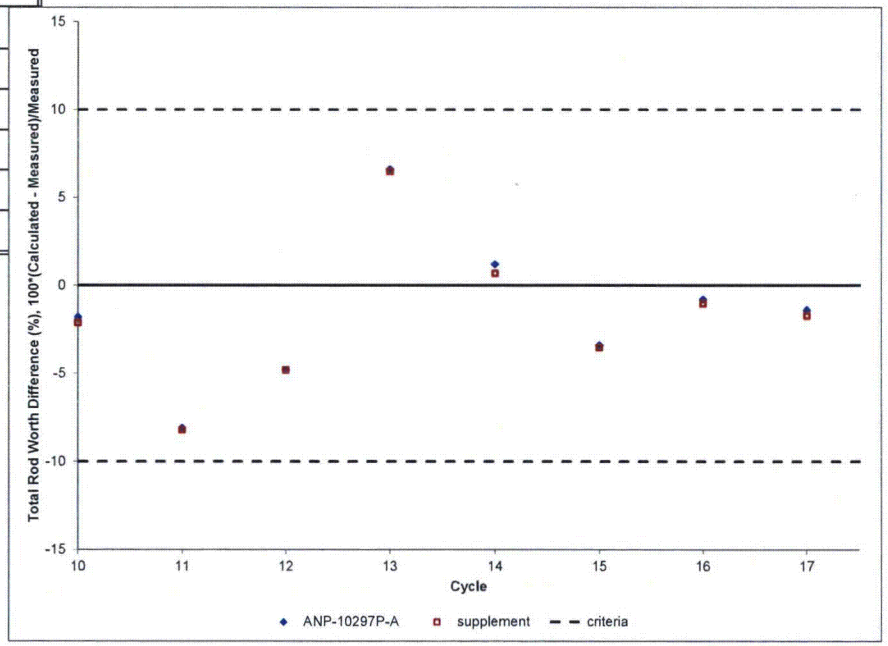
Benchmarks (17/22)

Plant C, HZP Physics Testing Comparisons

Total Rod Worth

Cycle	ANP-10297P-A (C-M), pcm	Supplement (C-M), pcm	ANP-10297P-A (C-M)/M, %	Supplement (C-M)/M, %
10	-107	-125	-1.8	-2.1
11	-509	-517	-8.1	-8.2
12	-272	-277	-4.8	-4.8
13	342	339	6.6	6.5
14	62	39	1.2	0.7
15	-205	-215	-3.4	-3.5
16	-42	-54	-0.8	-1.0
17	-84	-99	-1.4	-1.7

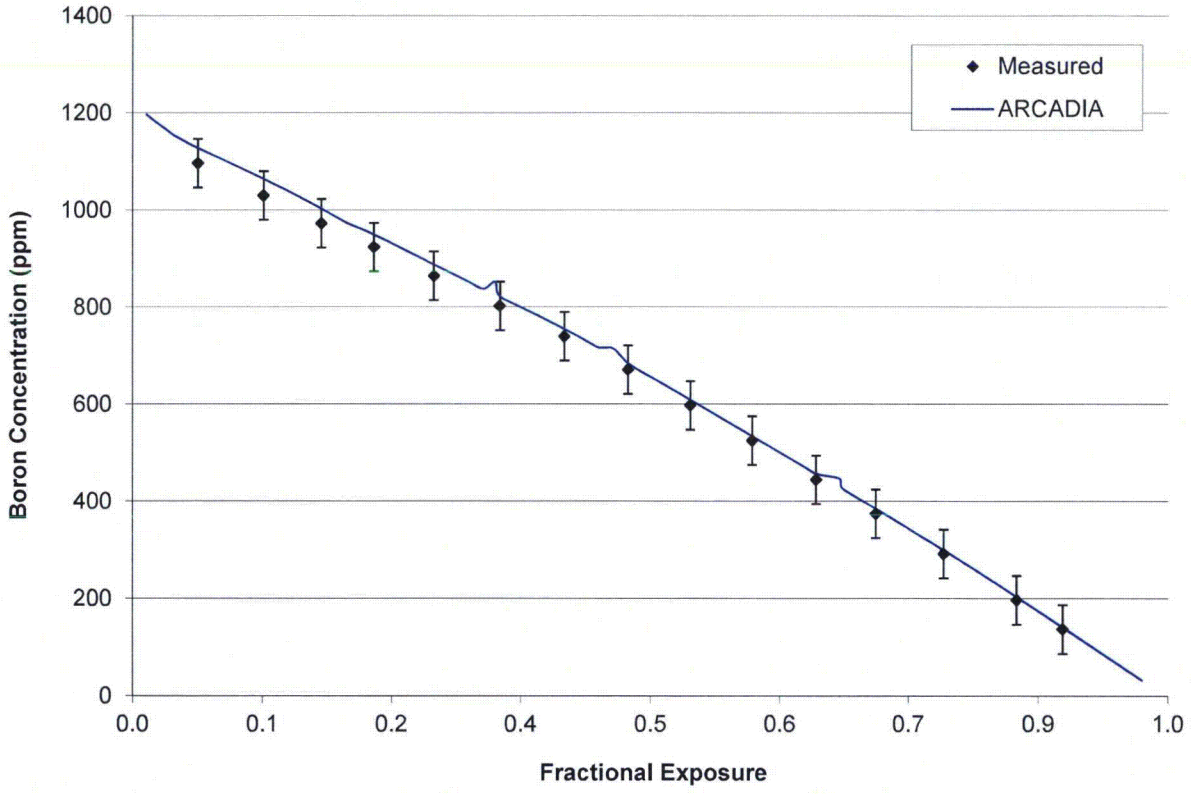
Total Rod Worth



Benchmarks (18/22)

Plant C, Core Follow (Supplement results)

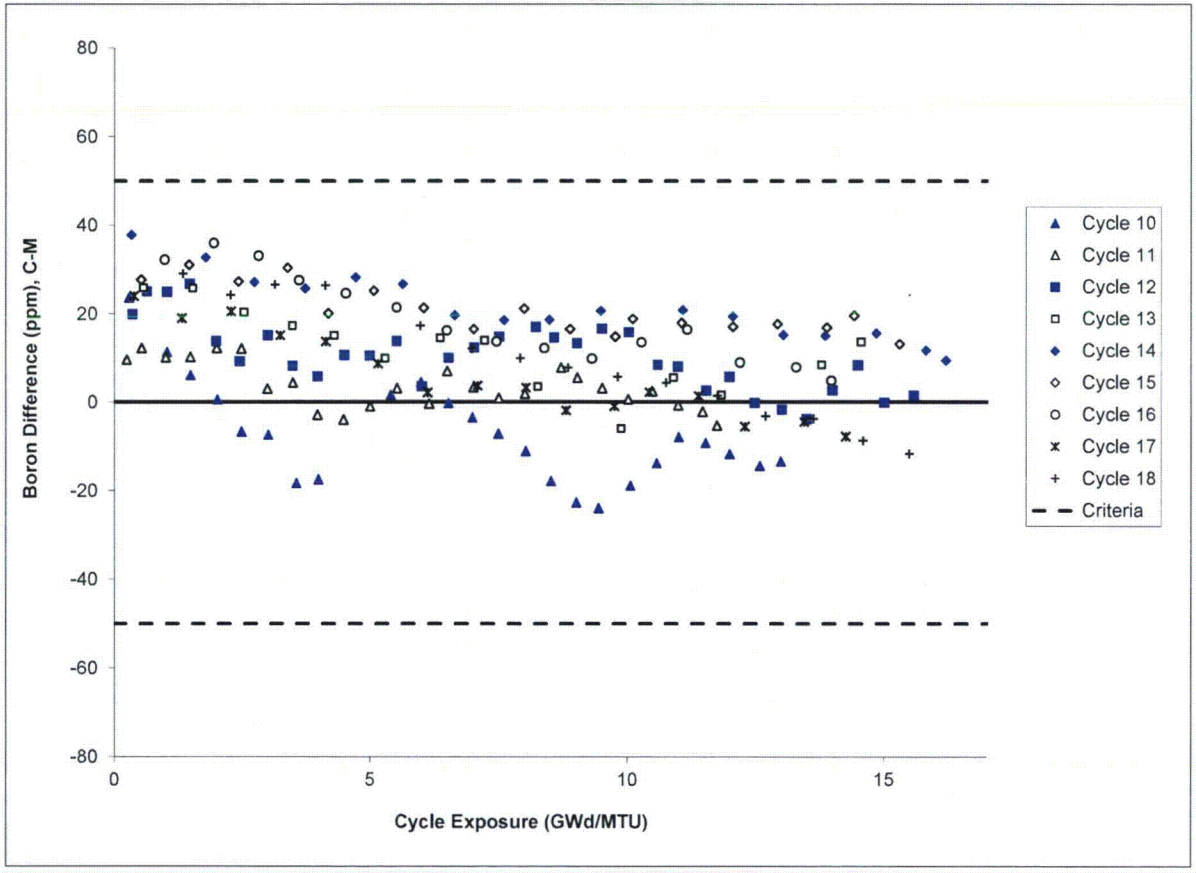
Boron Letdown (Ex, Cycle 16)



Benchmarks (19/22)

Plant C, Core Follow (Supplement results)

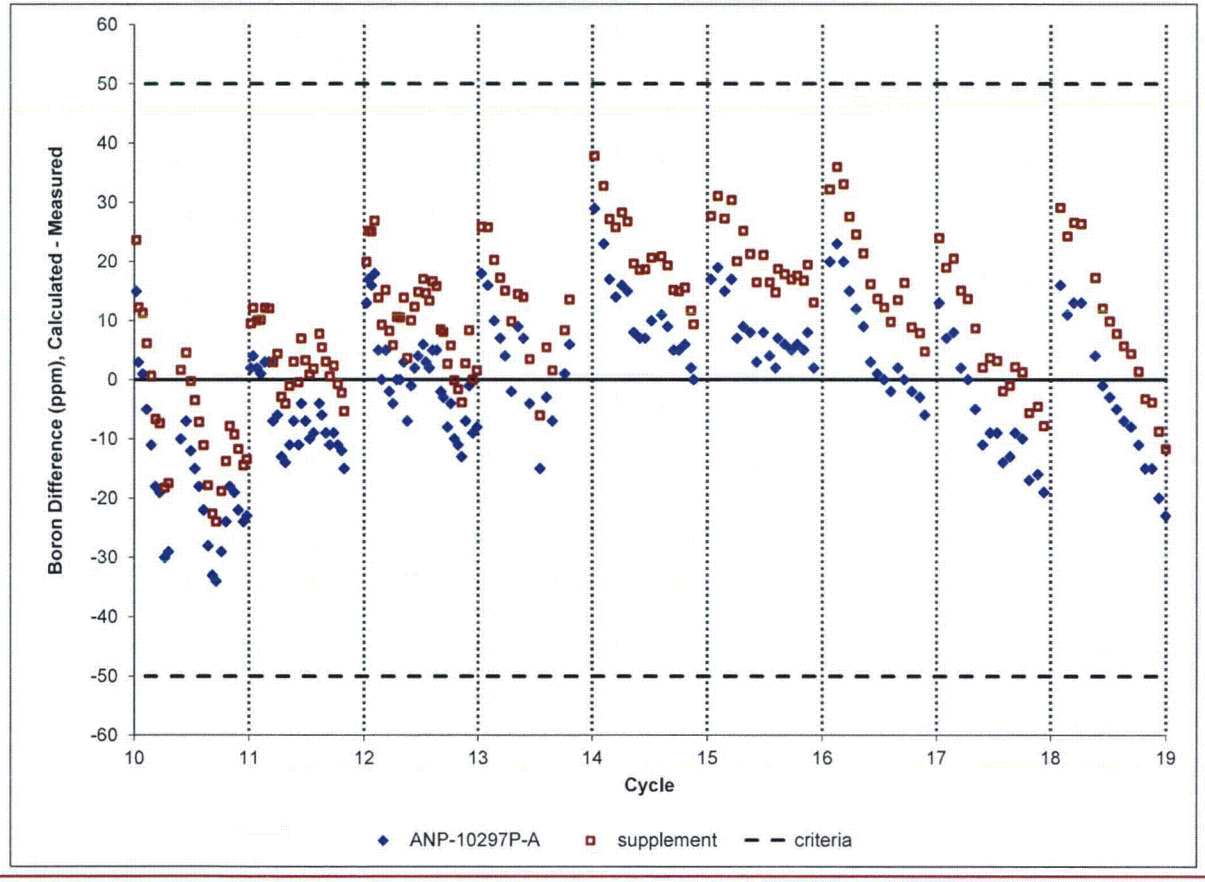
Boron Concentration Differences



Benchmarks (20/22)

Plant C, Core Follow

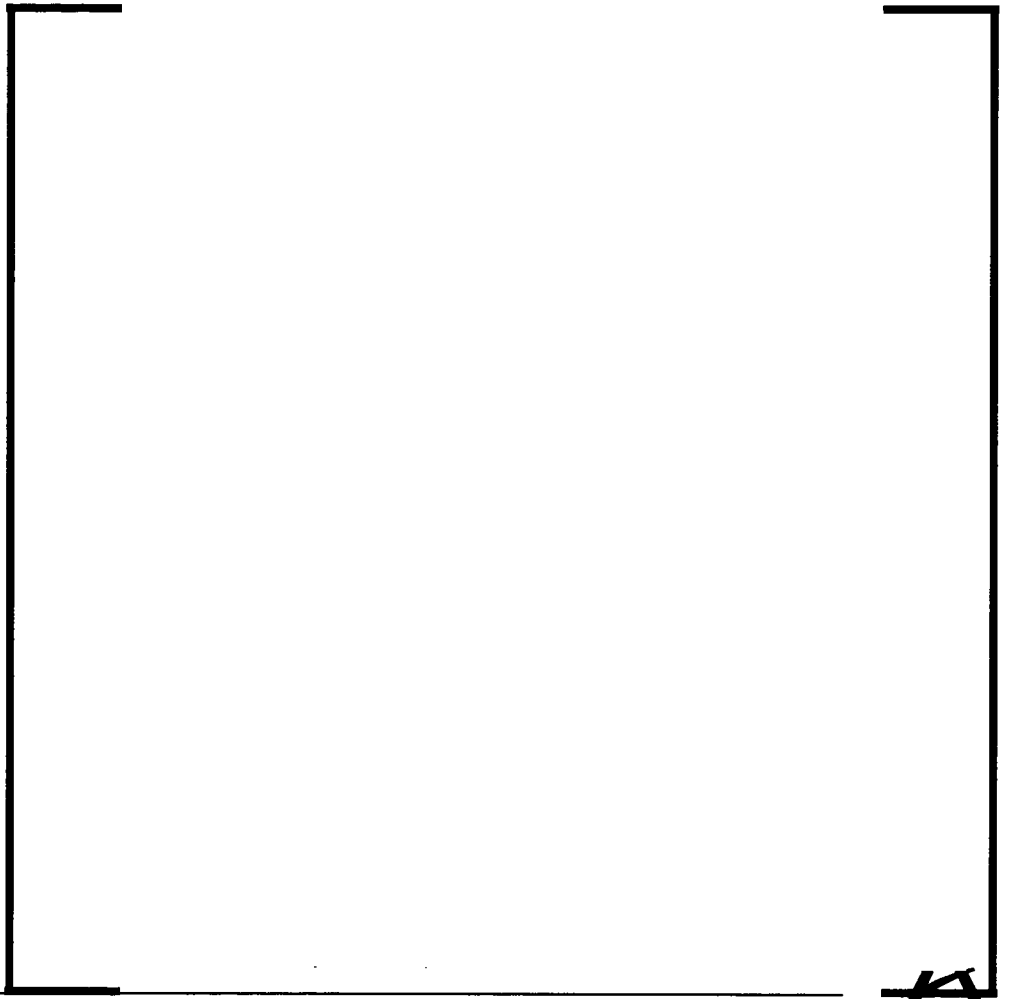
Boron Concentration Comparisons



Benchmarks (21/22)

▶Plant C, Core Follow (Supplement results & comparison)

Average assembly power
(Ex, Cycle 16, MOC)
(provided only for cycles included in the uncertainty analysis)



summary of RMS differences for each plant

	ANP-10297P-A (C-M), RMS*100	Supplement (C-M), RMS*100
Cycle 16 BOC	1.8	1.4
Cycle 16 MOC	0.9	0.8
Cycle 16 EOC	1.1	1.0

Benchmarks (22/22)

▶Plant C, Core Follow (Supplement results & comparison)

Average core axial power
(Ex, Cycle 16, MOC)
(provided only for cycles included in the uncertainty analysis)

summary of RMS differences for each plant

	ANP-10297P-A (C-M), RMS*100	Supplement (C-M), RMS*100
Cycle 16 BOC	1.5	1.2
Cycle 16 MOC	0.6	0.4
Cycle 16 EOC	1.4	1.2

Addition of Benchmark (1/7)

▶Plant E

- Westinghouse Reactor
- 157 assembly
- 17x17 fuel assembly
- Moveable fission probe
- Contains Enriched Reprocessed Uranium
- 6 Cycles
  - Maximum cycle length = 12,078 MWd/MTU

Addition of Benchmark (2/7)

▶Plant E, HZP Physics Testing

HZP ARO CBC

Cycle	Measured (ppm)	Calculated (ppm)	Difference C-M (ppm)
12			
13			
14			
15			
16			
17			

HZP ARO ITC

Cycle	Measured (pcm/°F)	Calculated (pcm/°F)	Difference C-M (pcm/°F)
12			
13			
14			
15			
16			
17			

Addition of Benchmark (3/7)

▶Plant E, HZP Physics Testing

Individual Rod Worth (Ex, Cycle 14)

Bank	Measured (pcm)	Calculated (pcm)	C-M (pcm)	100*(C-M)/M (%)
R				
G1				
G2				
N1				
N2				
SB				
SC				
SAD				
Total				

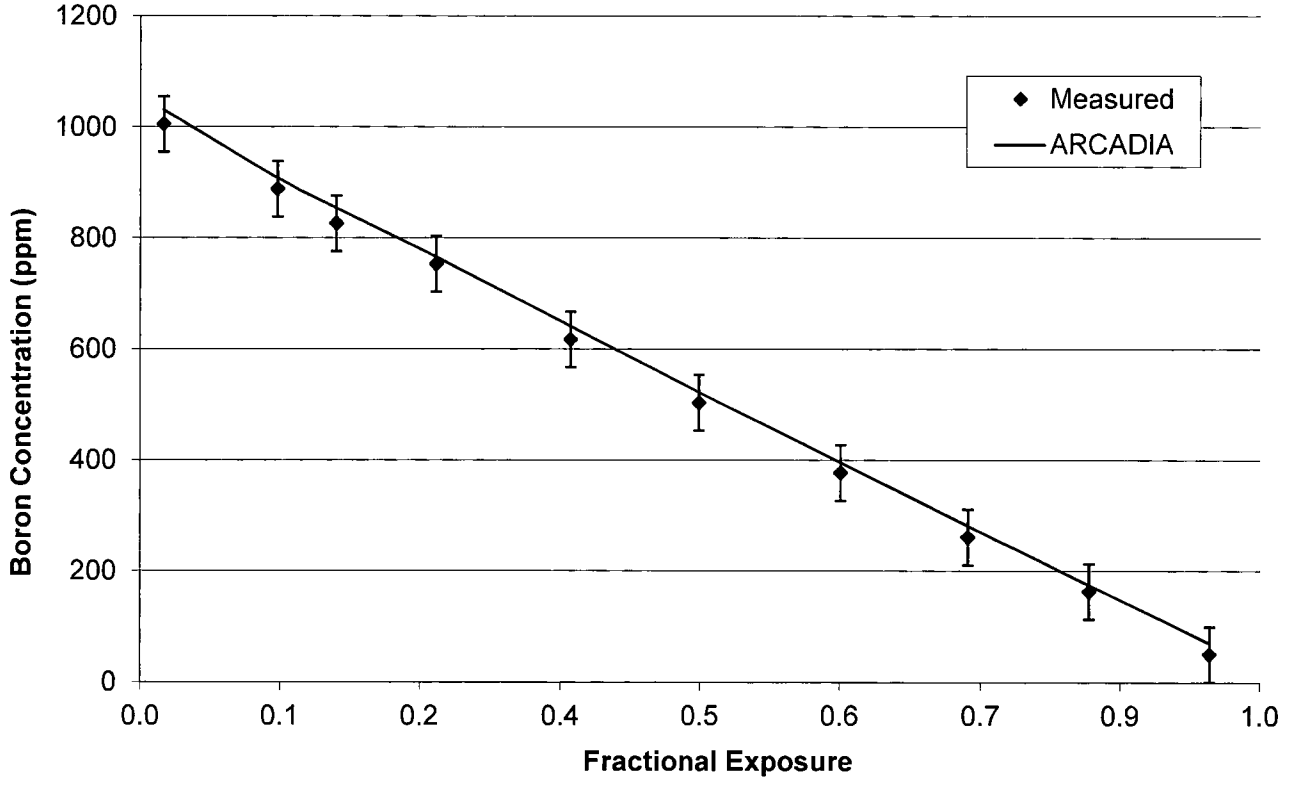
Total Rod Worth

Cycle	Measured (pcm)	Calculated (pcm)	C-M (pcm)	100*(C-M)/M (%)
12				
13				
14				
15				
16				
17				

Addition of Benchmark (4/7)

▶Plant E, Core Follow

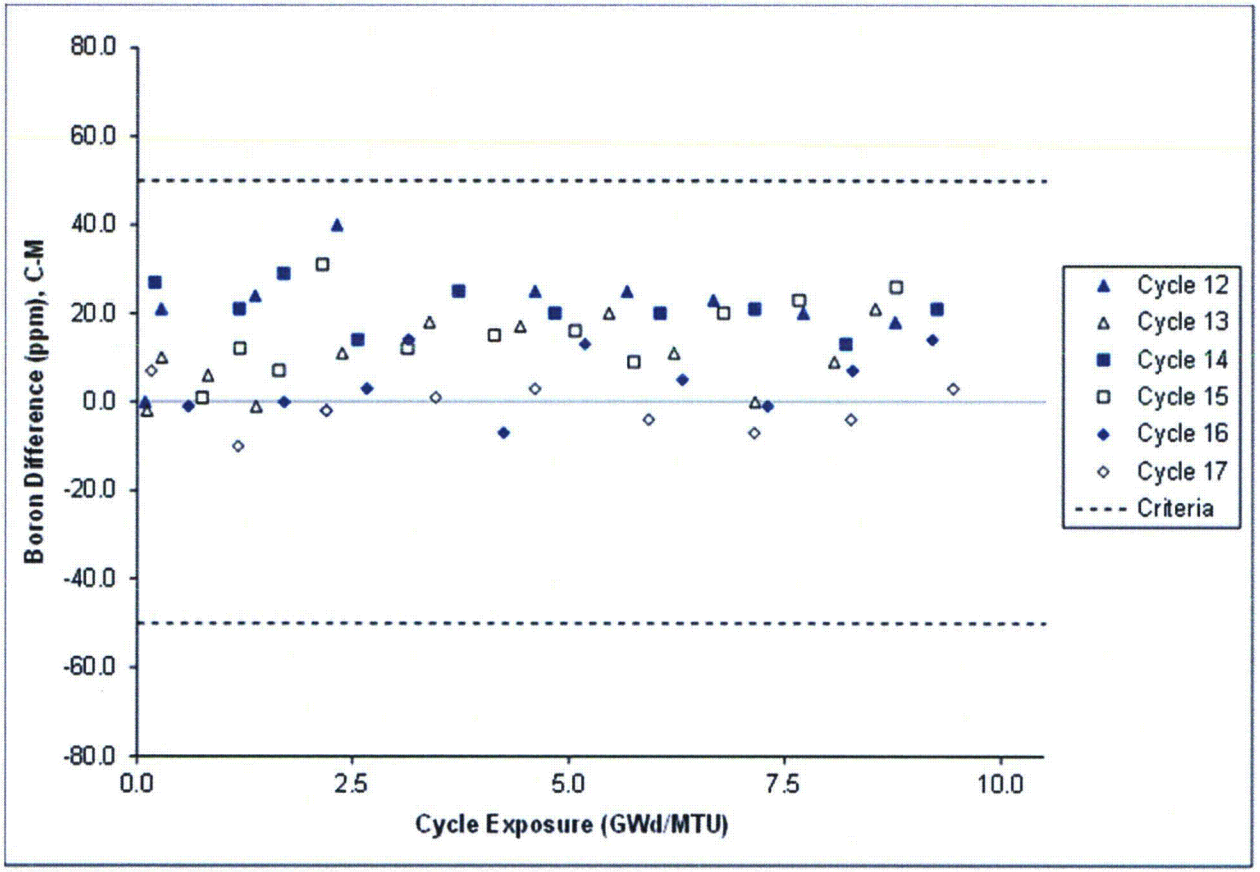
Boron Letdown (Ex, Cycle 14)



Addition of Benchmark (5/7)

Plant E, Core Follow

Boron Concentration Differences



Addition of Benchmark (6/7)

▶Plant E, Core Follow

Average assembly power
(Ex, Cycle 14, MOC)

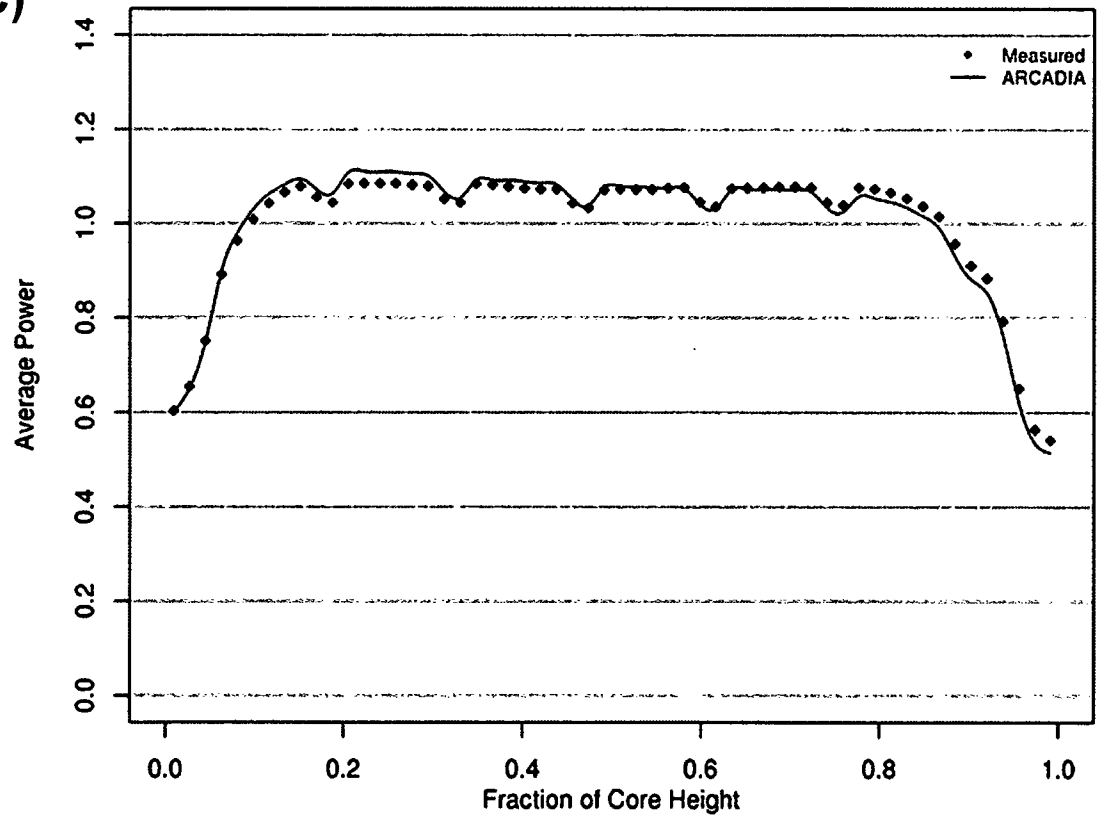
	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							0.346 0.346 -0.0	0.407 0.409 -0.3	0.346 0.344 0.1						
2					0.758 0.759 -0.1	1.016 1.013 0.3	1.163 1.158 0.5	1.195 1.191 0.4	1.167 1.157 1.0	1.021 1.003 1.8	0.759 0.750 0.9	Calculated Power Measured Power (C-M)*100			
3				0.472 0.482 -1.1	1.172 1.172 0.0	0.909 0.905 0.5	0.983 0.976 0.7	0.858 0.857 0.1	0.989 0.982 0.7	0.909 0.897 1.2	1.169 1.160 0.9	0.470 0.474 -0.4			
4			0.471 0.464 0.8	1.126 1.118 0.7	1.025 1.014 1.2	1.242 1.232 1.0	1.221 1.215 0.5	1.051 1.057 -0.5	1.232 1.225 0.7	1.238 1.218 1.9	1.019 1.008 1.2	1.120 1.112 0.8	0.469 0.465 0.4		
5		0.760 0.743 1.7	1.174 1.140 3.4	1.025 1.009 1.6	1.193 1.180 1.3	1.125 1.117 0.8	1.248 1.238 0.9	1.261 1.259 0.2	1.260 1.256 0.5	1.130 1.119 1.1	1.190 1.170 2.0	1.019 1.008 1.3	1.162 1.147 1.5	0.753 0.744 0.9	
6		1.021 1.007 1.4	0.912 0.898 1.4	1.244 1.230 1.4	1.127 1.119 0.8	1.217 1.215 0.2	1.027 1.032 -0.5	1.194 1.193 0.1	1.031 1.035 -0.4	1.224 1.219 0.5	1.124 1.112 1.2	1.239 1.221 1.8	0.907 0.893 1.4	1.014 0.997 1.8	
7	0.346 0.347 -0.0	1.167 1.164 0.4	0.989 0.982 0.7	1.230 1.224 0.5	1.249 1.247 0.2	1.022 1.031 -0.9	0.907 0.933 -2.6	1.192 1.213 -2.2	0.911 0.935 -2.3	1.025 1.029 -0.4	1.246 1.235 1.0	1.221 1.199 2.2	0.985 0.971 1.4	1.164 1.138 2.6	0.347 0.340 0.6
8	0.408 0.412 -0.4	1.199 1.207 -0.8	0.861 0.870 -0.9	1.049 1.053 -0.3	1.255 1.255 0.0	1.185 1.196 -1.0	1.181 1.204 -2.3	1.018 1.041 -2.3	1.191 1.215 -2.4	1.186 1.189 -0.3	1.251 1.245 0.6	1.048 1.039 0.9	0.857 0.856 0.1	1.195 1.172 2.3	0.407 0.405 0.2
9	0.348 0.352 -0.4	1.167 1.183 -1.5	0.986 0.999 -1.3	1.218 1.226 -0.9	1.243 1.245 -0.2	1.021 1.029 -0.8	0.893 0.908 -1.5	1.181 1.207 -2.6	0.905 0.936 -3.1	1.021 1.030 -0.9	1.248 1.242 0.5	1.229 1.215 1.5	0.989 0.979 1.0	1.166 1.157 0.9	0.345 0.355 -1.0
10		1.013 1.032 -1.9	0.906 0.925 -1.9	1.238 1.251 -1.3	1.120 1.124 -0.4	1.218 1.225 -0.7	1.024 1.038 -1.5	1.183 1.201 -1.7	1.019 1.034 -1.4	1.216 1.218 -0.2	1.130 1.119 1.1	1.247 1.219 2.8	0.913 0.899 1.4	1.021 1.003 1.8	
11		0.754 0.772 -1.8	1.165 1.194 -2.8	1.020 1.033 -1.3	1.184 1.182 0.2	1.127 1.131 -0.4	1.256 1.264 -0.8	1.253 1.263 -1.0	1.244 1.250 -0.6	1.124 1.121 0.4	1.199 1.185 1.4	1.028 1.013 1.5	1.175 1.169 0.6	0.761 0.754 0.7	
12			0.470 0.490 -2.0	1.121 1.141 -2.0	1.020 1.027 -0.7	1.240 1.245 -0.5	1.229 1.229 0.0	1.046 1.056 -0.9	1.216 1.223 -0.7	1.239 1.239 -0.0	1.024 1.015 0.9	1.127 1.104 2.3	0.473 0.485 -1.2		
13				0.470 0.478 -0.8	1.170 1.182 -1.2	0.908 0.918 -1.0	0.986 1.000 -1.4	0.854 0.872 -1.9	0.982 0.988 -0.6	0.911 0.917 -0.6	1.173 1.169 0.4	0.472 0.467 0.5			
14					0.758 0.765 -0.7	1.016 1.034 -1.8	1.163 1.194 -3.1	1.194 1.211 -1.7	1.166 1.156 1.0	1.021 1.020 0.2	0.761 0.759 0.1				
15							0.345 0.367 -2.1	0.407 0.417 -1.0	0.347 0.347 -0.0						

C-M Average Assembly Power, RMS Difference *100 = 1.3

Addition of Benchmark (7/7)

▶Plant E, Core Follow

Average core axial power
(Ex, Cycle 14, MOC)



C-M Average Axial Power, RMS Difference *100 = 1.4

Addition of Cold Criticals (1/2)

▶G2, EOC8

- 9 measurements in temperature interval [ ]
- Various control rod configurations
- Critical boron concentration for each configuration compared
- Measured isothermal temperature coefficient and boron worth were available at [ ]

Addition of Cold Criticals (2/2)

▶Results

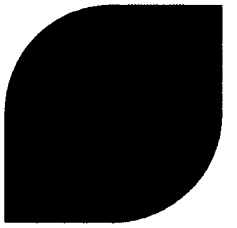
◈ Critical Boron Comparisons

Step	CR Configuration	TM Meas. (°C)	TM Calc. (°C)	CBC Meas. (ppm Bnat)	CBC Calc. (ppm Bnat)	Diff (C-M) (ppm Bnat)
1	LD0					
2	LD383, D10:0					
3	LD383, D10:0					
4	LD383, D10:0					
5	LD383, D10:0					
6	LD383, D10:0					
7	LD383, D10:0					
8	D145					
9	LD0					

◈ Coefficient Comparisons

Parameter	Measured	Calculated	Diff (C-M)
Boron worth (pcm/ppm)			
ITC (pcm/°F)			

Addition of Pseudo-Ejected Rod Worths (1/2)



▶Four measurements available

- 3 reactors
- Cycle 1 cores
- HZP BOC
- Measurement Method
  - Withdrawal of a single rod during boration
  - Insertion a single rod during boron dilution

Addition of Pseudo-Ejected Rod Worths (2/2)

▶Results

Plant	Measured worth, pcm	Calculated worth, pcm	Diff (C-M) pcm	Diff (C-M)/M %
D1				
T1, boron swap				
T1, rod drop				
S1				

Individual rod worth differences are within the ±15% single bank worth uncertainty

Addition of Power Coefficients (1/3)

- **Objective**
  - Supports DPC uncertainty used for transient calculations
- **Number of plants = 5**
- **Number of data points = 21**
  - 6 power coefficient values
  - 15 Doppler coefficient values
  - Detailed measurement methodology and data for 12 points

Addition of Power Coefficients (2/3)

▶Results

◈ Power coefficients

Plant	Initial Power	Measured pcm/% power	Calculated pcm/% power	Diff (C-M) pcm/% power	Diff (C-M)/M %
S1	30				
S1	50				
S1	75				
S1	90				
S2	30				
S2	50				

Addition of Power Coefficients (3/3)

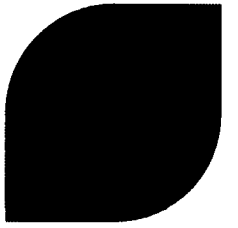
▶Results

PRELIMINARY

◆ Doppler Power coefficients

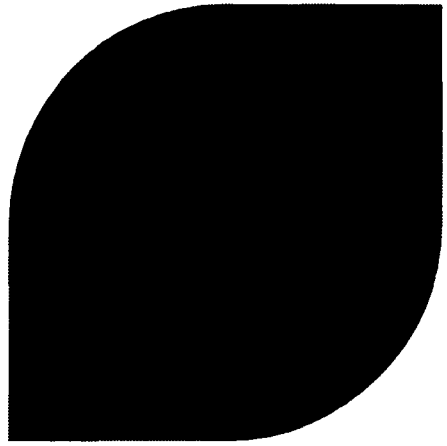
Plant	Initial Power	Measured pcm/% power	Calculated pcm/% power	Diff (C-M) pcm/% power	Diff (C-M)/M %
D1	30				
D1	50				
D1	75				
F1	100				
P2	50				
P2	74				
P2	90				
P1	45				
P1	50				
P1	75				
P1	76				
P1	92				
P1	92				
P1	102				
P2	50				

Addition of Safety Parameter Uncertainties (1/1)



- Statistical combination of differences to obtain uncertainties for total rod worth and moderator temperature coefficients
- Number of data points =[ ]for TRW,[ ]for ITC
  - [ ]from benchmark models, including Plant E
  - Additional values from extended cycles of Plants A, S1, and S2 (not included as benchmarks)
- Results:
  - Total rod worth: uncertainty =[ ]
  - MTC: uncertainty =[ ]pcm/°F

PRELIMINARY



ARCADIA® Transient Validation

Michelle Guzzardo
ARCADIA® Supplement Technical Lead

AREVA

Transient Benchmarks

▶Validation of transient model with:

- Rerun of NEACRP UO_2 control rod ejection
- Rerun of Rod drop tests
- Addition of SPERT-IIIE rod ejection benchmark

Transient Benchmarks NEACRP (1/4)

▶Description

- **Analytical control rod ejection benchmarks**
- **157 assembly core**
- **6 cases**
  - 2 with center rod ejected
  - 2 with ejection of a group of periphery rods (symmetric)
  - 2 with ejection of single periphery rod (asymmetric)
  - Zero power (fully inserted rods)
  - Full power (partially inserted rods)

Transient Benchmarks NEACRP (2/4)

▶ Steady-state parameters (Ex, Case A1, A2)

◈ Summary (Ex, Case A1, A2) - Supplement results

	ARTEMIS	Reference	Diff	%Diff
A1				
Steady State Boron (ppm)	557.4	567.7	-10.3	-1.8
Steady State Fuel Temperature (°C)	286	286	0.0	0.0
Steady State Nodal Peak	2.868	2.874	-0.006	-0.2
Reactivity Release (pcm)	822	822	0	0.1
A2				
Steady State Boron (ppm)	1154.3	1160.6	-6.3	-0.5
Steady State Fuel Temperature (°C)	549	546.1	2.7	0.5
Steady State Nodal Peak	2.218	2.221	-0.003	-0.1
Reactivity Release (pcm)	91	90	1	0.9

◈ Comparison (Ex, Case A1, A2)

	ANP-10297P-A Diff	Supplment %Diff	ANP-10297P-A Diff	Supplement %Diff
A1				
Steady State Boron (ppm)	-7.6	-10.3	-1.3	-1.8
Steady State Fuel Temperature (°C)	0	0	0.0	0.0
Steady State Nodal Peak	0.000	-0.006	0.0	-0.2
Reactivity Release (pcm)	-1	0	-0.1	0.1
A2				
Steady State Boron (ppm)	-8.2	-6.3	-0.7	-0.5
Steady State Fuel Temperature (°C)	2.1	2.7	0.4	0.5
Steady State Nodal Peak	0.007	-0.003	0.3	-0.1
Reactivity Release (pcm)	2	1	2.2	0.9

Transient Benchmarks NEACRP (3/4)

Power Distribution at time of Maximum Power (Supplement results)

- (Ex, Plane 6 - Case A1)

				0.128 0.124 -0.004	0.150 0.147 -0.003		
			0.362 0.362 0.000	0.242 0.242 0.000	0.214 0.213 -0.001	0.120 0.118 -0.002	
		0.316 0.309 -0.007	0.390 0.392 0.002	0.188 0.184 -0.004	0.169 0.168 -0.001	0.088 0.085 -0.003	
	0.790 0.792 0.002	0.562 0.565 0.003	0.540 0.541 0.001	0.371 0.373 0.002	0.140 0.136 -0.004	0.126 0.125 -0.001	0.093 0.092 -0.001
1.000 1.000 0.000	0.778 0.785 0.007	0.390 0.381 -0.009	0.513 0.517 0.004	0.474 0.474 0.000	0.248 0.248 0.000	0.093 0.090 -0.003	0.117 0.115 -0.002

Peak Location

Rodded Location

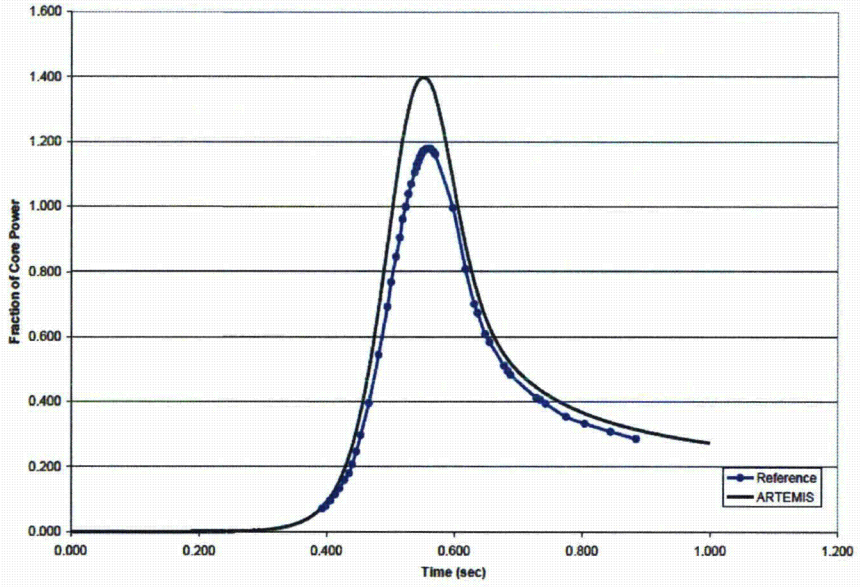
- Also at initial conditions and at 5 sec

Transient Benchmarks NEACRP (4/4)

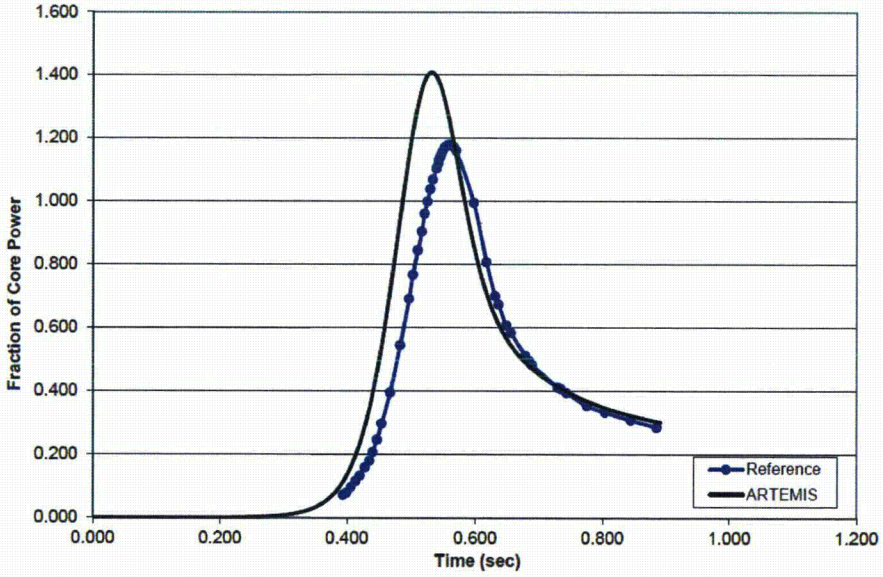
Core Power Fraction (Ex, Case A1)

- Also core average fuel temperature and core exit moderator temperature
- Case A1, Case B2 and Case C1 (same as presented in ANP-10297P-A)

ANP-10297P-A



Supplement



Transient Benchmarks
Rod Drop Test (1/5)

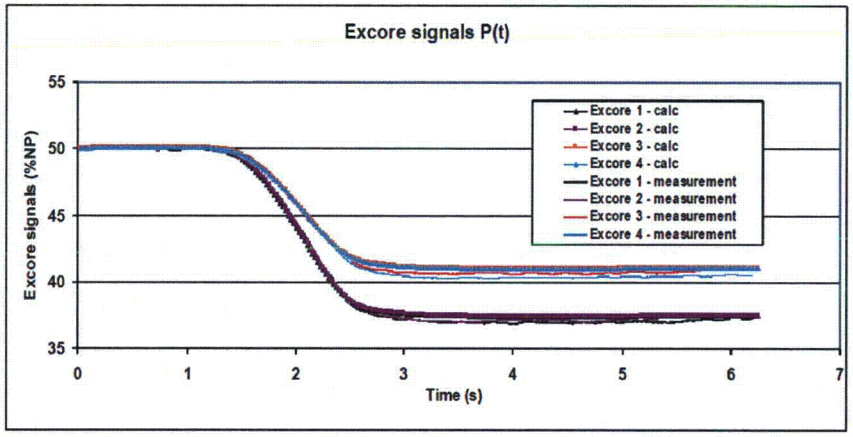
Description

- **193 fuel assembly plants**
- **5 rod drop tests**
  - 1 @ BOC, 3 @ MOC, 1 @ EOC
  - ~50% power
  - Two interior, half core symmetric rods dropped
- **Control rod velocity and four excore responses processed to obtain control rod position and excore response versus time.**
- **Cross sections generated with APOLLO2-A**

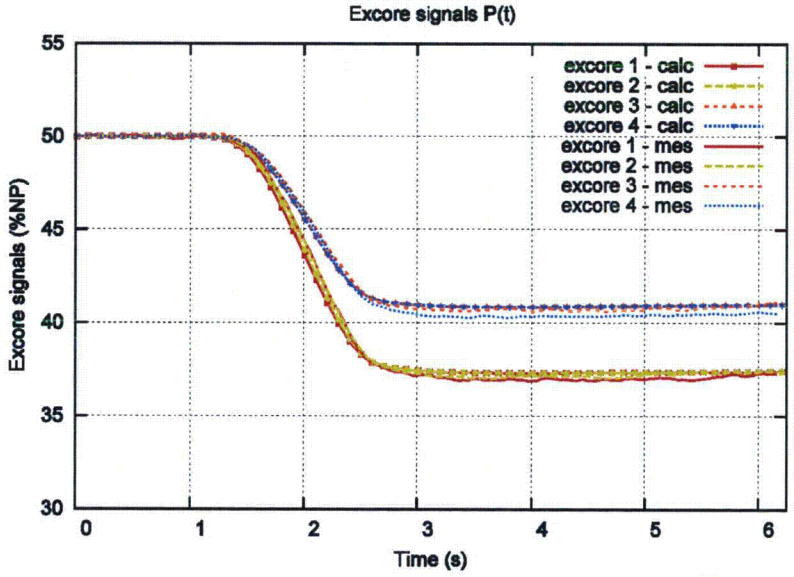
Transient Benchmarks
Rod Drop Tests (2/5)

- **Nuclear flux (normalized to core power) versus time**
  (Ex, Rod Drop Test 1 – 0.7 GWd/mtU, F6K10(SD bank))

ANP-10297P-A



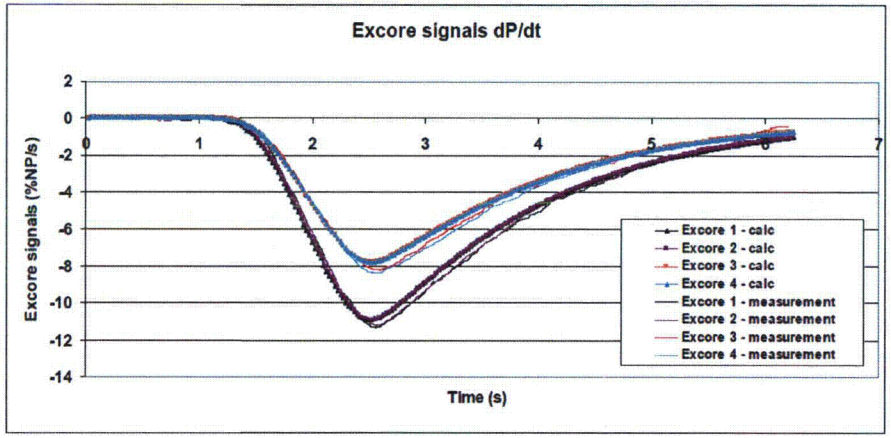
Supplement



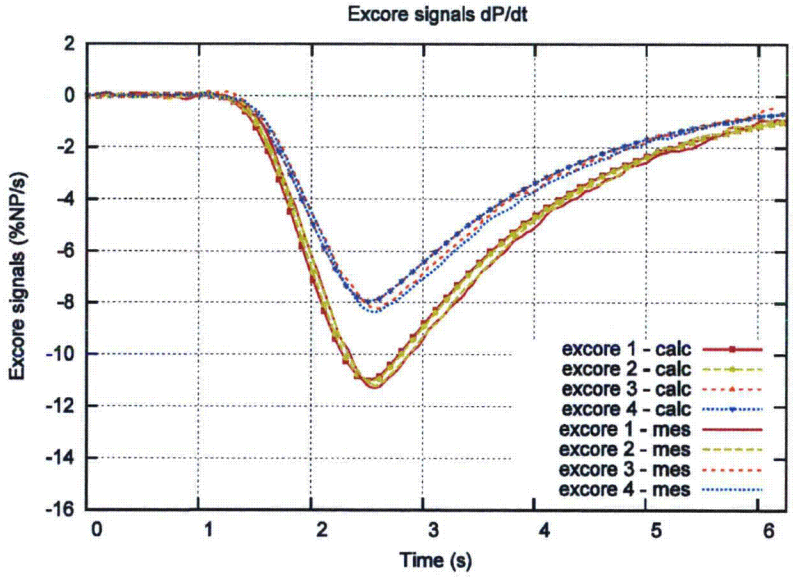
Transient Benchmarks
Rod Drop Tests (3/5)

- **Derivative of nuclear flux dP/dt calculated with the Laplace transform function**
  (Ex, Rod Drop Test 1 – 0.7 GWd/mtU, F6K10(SD bank))

ANP-10297P-A



Supplement



Transient Benchmarks
Rod Drop Tests (4/5)

Comparison (Prediction – Measurement) - Time of the Minimal dP/dt

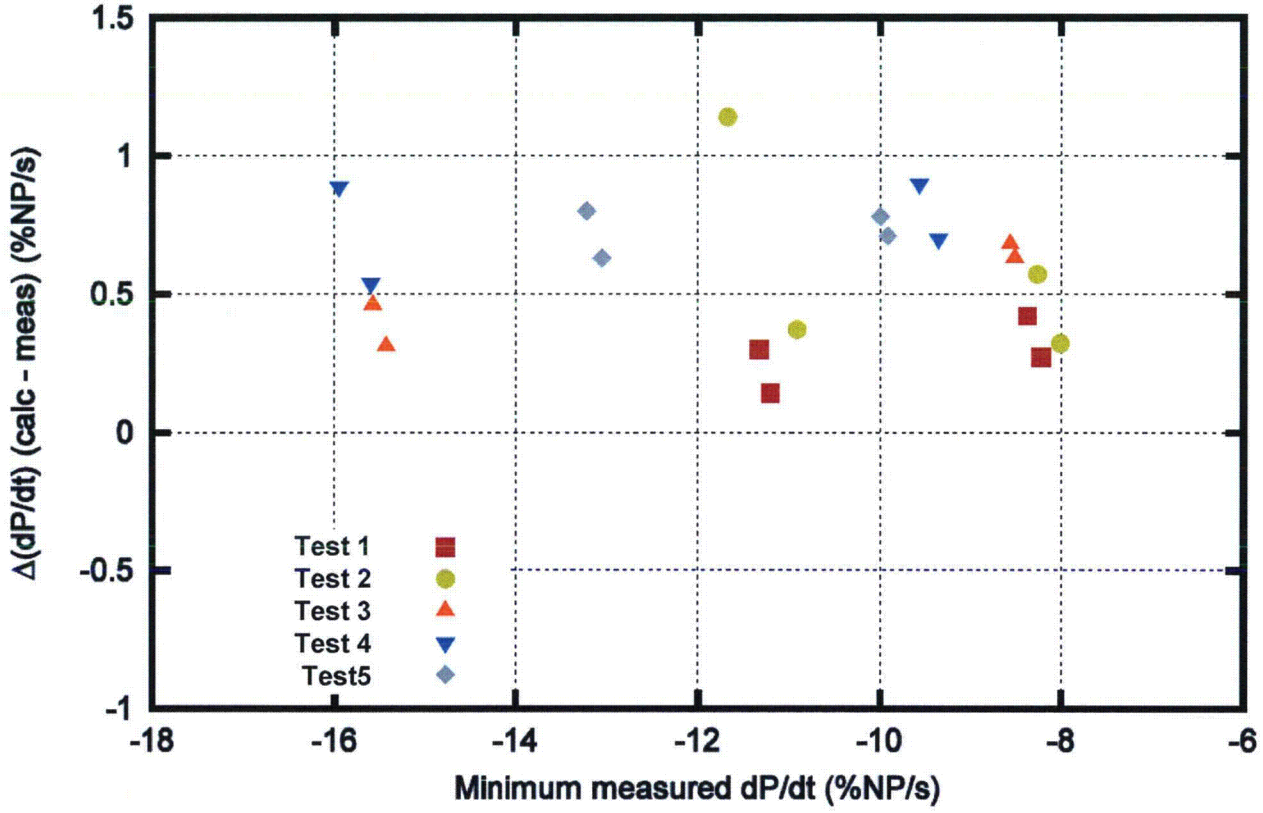
	Time of minimal dP/dt (s)			
	Average	1σ	Min	Max
ANP-10297P-A	-0.08	0.04	-0.16	-0.02
Supplement	-0.07	0.08	-0.30	0.01

Comparison (Prediction – Measurement) - Minimal dP/dt

	Minimal dP/dt (%NP/s)				95% of confidence	
	Average	1 σ	Min	Max	Min	Max
ANP-10297P-A	0.38	0.34	-0.44	0.81	-0.28	1.04
Supplement	0.58	0.26	0.14	1.14	-0.12	1.28

Transient Benchmarks
Rod Drop Tests (5/5)

- **Synthesis of Deviation on Minimal Derivative of the Nuclear Flux dP/dt – Supplement Results**



Transient Benchmarks SPERT-IIIE (1/5)

▶Description

- **Two rod ejection experiments from SPERT III Core Facility**
  - Test 60 – HZP initial condition
  - Test 86 – HFP initial condition
- **Cross sections and delayed neutron precursor data provided by NRC**

Transient Benchmarks SPERT-IIIE (2/5)

▶Key Modeling Assumptions

- Position of regulating control rod bank was adjusted until the calculated initial k_{eff} was 1.0 prior to ejection of the transient control rod
- Initial position of the transient control rod was adjusted to yield the measured value of the ejected rod worth, within measurement uncertainty
- Direct energy deposition into the coolant is based on typical PWR value of 2.6% of the total energy produced
- Gap conductance for HZP and HFP tests assumed constant at 1.3042 and 2.0000 $W/cm^2/K$ (NRC published values)

Transient Benchmarks SPERT-IIIE (3/5)

▶Validation

- **HZP static control rod worth of transient rod at 500°F**

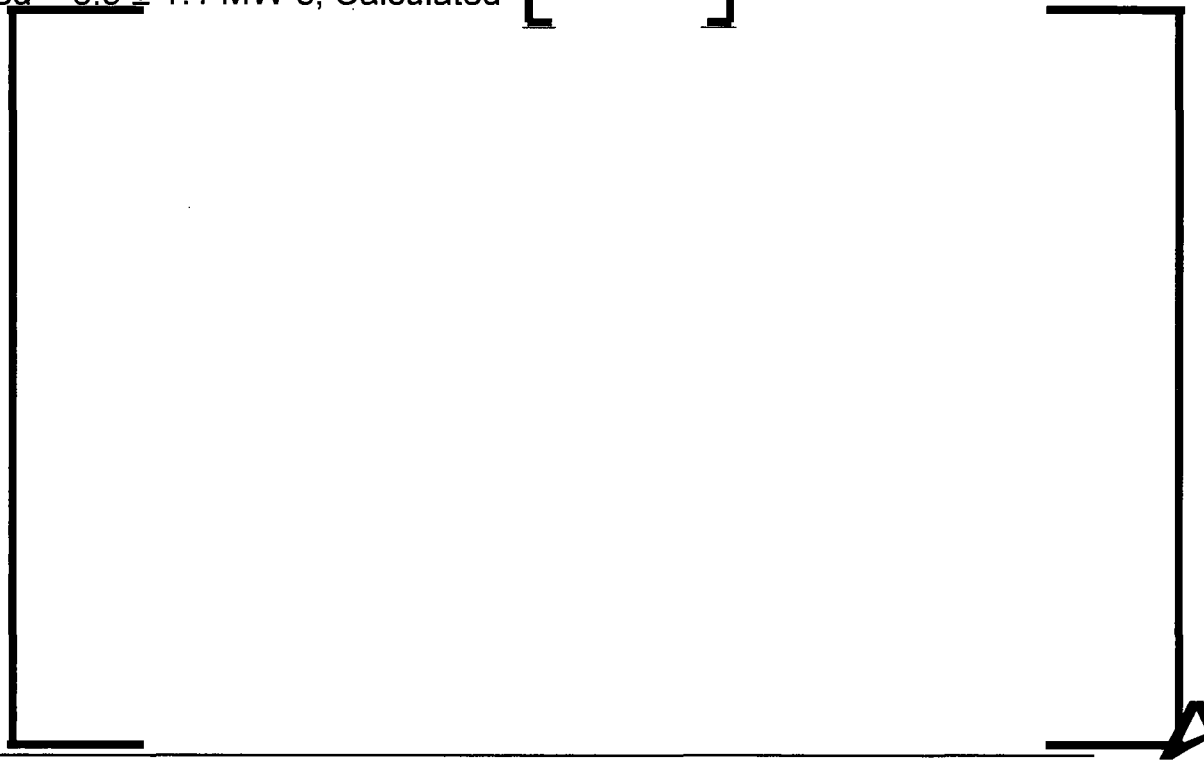
[ ]

- **HZP moderator temperature coefficient**
  - Measured = -4.0 ¢/°F; Calculated = [ ]
- **HZP excess reactivity worth**
  - Measured = $4.7; Calculated = [ ]

Transient Benchmarks SPERT-IIIE (4/5)

▶ Test 60 (ejected control rod test):

- **Peak Power**
  - Measured = 410 ± 41 MW; Calculated = [ ]
- **Integrated Power**
  - Measured = 8.5 ± 1.1 MW-s; Calculated = [ ]
- **Power Response**

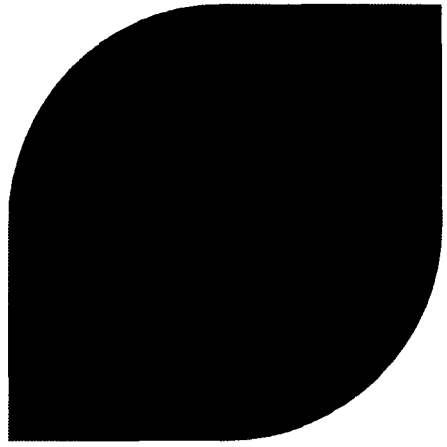


Transient Benchmarks SPERT-IIIE (5/5)

▶ Test 86 (prompt critical rod ejection):

- **Peak Power**
  - Measured = 610 ± 60 MW; Calculated = [ ]
- **Integrated Power**
  - Measured = 17 ± 2 MW-s; Calculated = [ ]
  - Calculated result slightly outside measurement uncertainty
    - Large uncertainty in at-power conditions,
    - Lack of refinement in the model (configuration is not typical of a commercial PWR)
- **Power Response**
  - Measured values begin to increase before ARTEMIS™
  - ARTEMIS™ still predicts peak power accurately

[ ]



ARCADIA®
Uncertainty Analysis

Michelle Guzzardo
ARCADIA® Supplement Technical Lead

AREVA

Uncertainty Analysis (1/5)

▶Provide uncertainties for power peaking predictions for licensing applications

▶Objectives

- **Implement spacer grid model (not included in ANP-10297P-A)**
  - Remove bias on axial peaking factor
  - Include cycles with Inconel grids (axial uncertainty (F_q))
    ⇒ Remove SER restriction for Inconel
- **Extend MEDIAN methodology to additional detector types**
  - Aeroball measurement system (included in ANP-10297P-A)
  - Moveable fission incore detectors
  - Fixed Rhodium incore detectors
- **Add data for reprocessed uranium core (Plant E)**

Uncertainty Analysis (2/5)

▶ Calculational Uncertainty

- Based on the ability of ARCADIA® to predict true value

▶ Inferred Uncertainty (uncertainty of the global reconstruction)

- Based on the ability of ARCADIA® to measure an entire core power distribution from a limited set of locations.

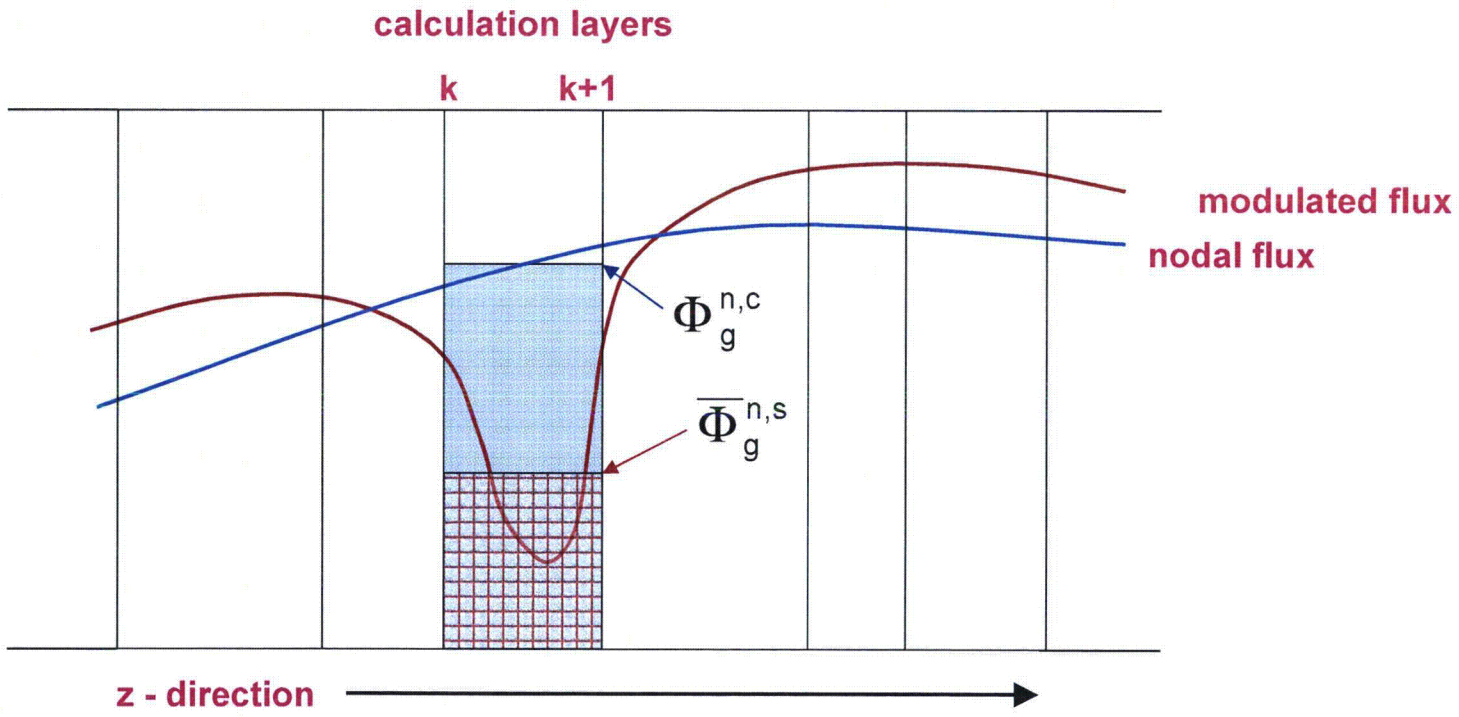
▶ MEDIAN (MEasurement Dependent Interpolation Algorithm using NEM)

- Flux adaptation method developed for core monitoring purposes
- Applicable to fixed and moveable detector system types
- Supplement extends the MEDIAN methodology presented in ANP-10297P-A

Uncertainty Analysis (3/5)

Spacer Grid Model

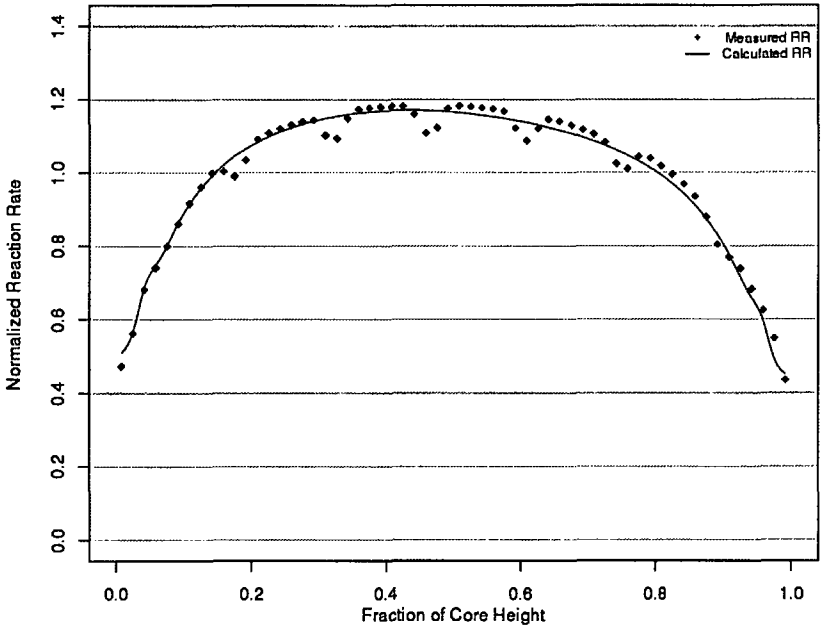
- Applied during the fine mesh pin power reconstruction
- Based on spacer material and geometry



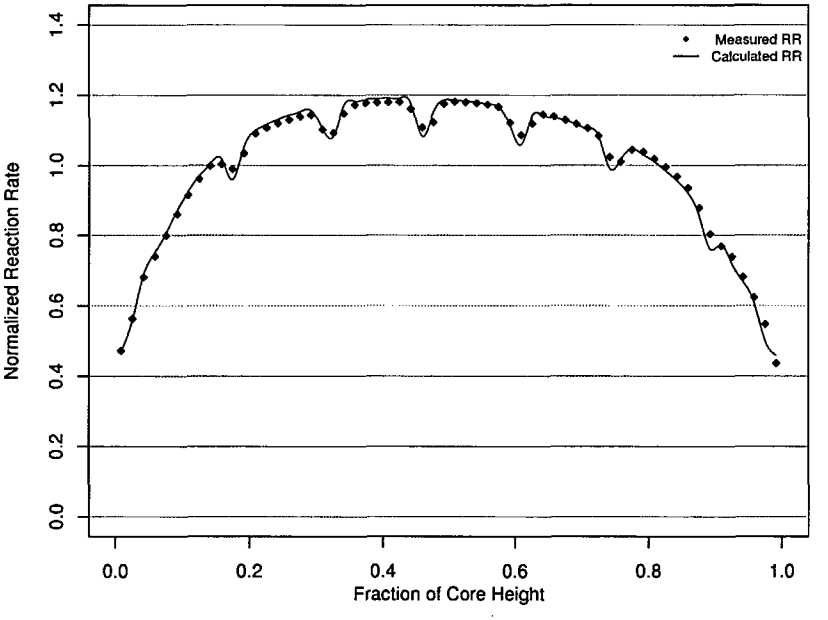
Uncertainty Analysis (4/5)

▶ Spacer Grid Model

Without Spacer Grid Model



Spacer Grid Model



Spacer grid effects are incorporated in fine mesh results

Uncertainty Analysis (5/5)

▶ Summary of Results

PRELIMINARY

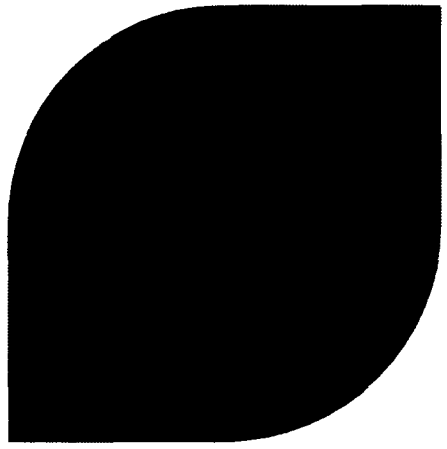
ANP-10297P-A

Type of Uncertainty	FΔH (F_R for INPAX-CE) Estimated	FΔH (F_R for INPAX-CE) Criteria	Fq Estimated	Fq Criteria
Inferred INPAX-W	[redacted]			
Inferred INPAX-CE				
Inferred MEDIAN-AMS				
Calculational				

Supplement

Type of Uncertainty	FΔH (F_R for FIC) Estimated	FΔH (F_R for FIC) Criteria	Fq Estimated	Fq Criteria
Inferred TIP	[redacted]			
Inferred FIC				
Inferred AMS				
Calculational				

Note: Fq for ANP-10297P-A includes a Grid bias factor and NO Inconel while Supplement uses grid model (no bias factor) and includes Inconel Cores



Change Process

Kevin Segard
Supervisor, Methods and Licensing

AREVA

Conclusions (1/3)

- Continued development of ARCADIA® based on experience with MOX and need to suppport transient analyses
  - Changes associated with MOX found to also benefit UO_2 analyses
  - Transient methods required specialized treatment not available in approved version of ARCADIA®
- Results from modified codes continue to meet the requirements specified in Table 13.2-1 of ANP-10297P-A.

Conclusions (2/3)

- Modifications to APOLLO2-A intended to improve reactivity with cycle exposure
  - This goal was achieved without impact to power distribution determination
- Modifications to ARTEMIS™
  - Improve core dehomogenization capability
  - Implement spacer grid model
  - Improve transient modelling with parameter penalization for safety analysis calculations
- Reduction of uncertainties on MTC and Rod Worth

Conclusions (3/3)

- All goals from planned modifications were achieved
- The ARCADIA® Supplement provides the platform on which AREVA is developing the AREA and ARITA methodologies.
  - The supplement is a perturbation to what was provided in ANP-10297P-A which should allow parallel review with AREA and ARITA

Next Steps/ARCADIA Supplement

- Pre-submittal meeting [ ]
- Topical report submittal
- Post-submittal meeting
- NRC SER requested by]

Next Steps ARCADIA® related T.R.

- AREA – AREVAs Rod Ejection Analysis
- ARITA – ARCADIA®/RELAP Integrated Transient Analysis
- ARABOW – AREVAs Rod and Assembly Bow
- Planned submittal dates
  - AREA
  - ARITA
  - ARABOW

[ ]

Acronyms/Nomenclature

- AIC – Ag-In-Cd
- AREA – AREVA Rod Ejection Analysis
- ARITA – ARCADIA®/RELAP Integrated Transient Analysis
- ARABOW—AREVA's Bow Methodology
- ARO---All Rods Out
- B&W – Babcock & Wilcox
- B4C – Boron Carbide
- CBC – Critical Boron Concentration
- CE – Combustion Engineering
- CEA – Commissariat à l'Energie Atomique
- DOE – Department of Energy
- DPC – Doppler Power Coefficient
- EOC – End of Cycle
- ERU – Enriched Reprocessed Uranium
- Hf – Hafnium
- HZP – Hot Zero Power
- HFP – Hot Full Power
- ITC – Isothermal Temperature Coefficient
- JEFF – Joint Evaluated Fission and Fusion
- MEDIAN – Measured Dependent Interpolation Algorithm using NEM (Nodal Expansion Method)
- MOX – Mixed Oxide
- MSLB – Main Steam Line Break
- MTC – Moderator Temperature Coefficient
- NEACRP – Nuclear Energy Agency Committee on Reactor Physics
- NRC – Nuclear Regulatory Commission
- PWR – Pressurized Water Reactor
- Pu – Plutonium
- RAI – Request for Additional Information
- RG 1.203 – Transient and Accident Analysis Methods
- SG – Spacer Grids
- SPERT – Special Power Excursion Reactor Test
- SRP – Standard Review Plan
- UDy – Uranium –Dysprosium
- UEr – Uranium–Erbium
- UGd – Uranium–Gadolinium
- UO2 – Uranium Oxide
- V&V – Verification & Validation
- W – Westinghouse