

APOLLO2-A and ARTEMIS-B for BWR

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Safety Message

- Tumbleweeds – Driving Safety
 - Typical to see them rolling down the roads
 - Do not swerve around them
 - Slow down and wait for them to cross
 - Drive through them
 - Typically they will not damage your car



Image from:

<https://www.atlasobscura.com/articles/larger-hybrid-california-tumbleweed>



Image from:

<https://www.weatherationtv.com/news/tumbleweeds-swallow-cars-shut-down-highway/>

Agenda

Introduction and Background	Alex Bennett
Computer Code Changes	Alex Bennett
APOLLO2-A V&V	Alex Bennett
ARTEMIS-B V&V	Alex Bennett
Power Distribution Uncertainty	Alex Bennett
Validation Requirements	Alex Bennett
Implementation into BWR Methods	Paul Smith
Summary and Next Steps	Paul Smith

Introduction and Background

Alex Bennett

Objectives

- Outline plans for the topical report:
 - APOLLO2-A and ARTEMIS-B for BWR (ANP-10350)
- Provide an opportunity for NRC feedback

Introduction and Background

- Current BWR Core Simulation Package
 - EMF-2158P-A Revision 0, CASMO-4 / MICROBURN-B2, 1999.
- Current PWR Core Simulation Package
 - ANP-10297P-A and Supplement 1P-A, APOLLO2-A/ ARTEMIS, 2018.
- Extend APOLLO2-A/ ARTEMIS for BWR use and replace:
 - CASMO-4 with APOLLO2-A
 - MICROBURN-B2 with ARTEMIS-B
- Interface ARTEMIS-B with downstream methods

Motivation

- ARTEMIS-B gives better agreement with TIP results

Overview of Current Methodology

Extended Flow Window

ATWS Instability
RAMONA5

Stability Protection System
Enhanced Option III

Best Estimate
Enhanced Option III

Mechanical

Fuel Rod Thermal-Mechanical
RODEX4

Neutronics

Core Simulation

CASMO-4

MICROBURN-B2

Stability / DIVOM

STAIF / RAMONA5

Core Monitoring

POWERPLEX

Criticality Safety

SCALE / KENO

Interface Code

AUTOBOW

Safety & Licensing

Critical Power

ACE

Steady State Methods

MICROBURN-B2

LOCA

AURORA-B LOCA

Transients

AURORA-B AOO

Control Rod Drop Accident

AURORA-B CRDA

MCPR Safety Limit

SAFLIM-3D

Legend

Code Replaced

Code System Updated

No Change

ANP-10350 Table of Contents

Introduction

APOLLO2-A Methodology

ARTEMIS-B Methodology

Reflector Treatment

CPR Correlations

APOLLO2-A V&V

ARTEMIS-B V&V

Benchmarking Results

Power Distribution Uncertainty

Applicability to EPU/EFW Conditions

Slow Transients

Infrequent Events

Computer Code Changes

Alex Bennett

Computer Codes

- APOLLO2-A
 - Lattice physics code for cross section library generation
- HERMES
 - Cross section functionalization tool
- ARTEMIS-B
 - Reactor core simulator, consisting of:
 - Neutronic module
 - Thermal-Hydraulic module
 - Fuel rod module
 - Depletion module
- Most of the computer codes are the same as those presented in ARCADIA (ANP-10297P-A)
- Major changes since the ARCADIA topical reports:
 - New Thermal-Hydraulic solver
 - Added models specific to BWR
- Most of the BWR models are the same or similar to the models in MICROBURN-B2 (EMF-2158P-A)

APOLLO2-A Code

- Lattice physics code
 - Calculate the few group cross sections (XS) for the ARTEMIS core simulator
- Solves the 2D neutron transport equation
 - Uses a 3 level computational scheme consisting of the following methods:
 - Collision Probability
 - Integro-Differential Transport Solver
 - Method of Characteristics
 - Uses 281 neutron energy groups and 94 gamma energy groups
 - Uses the JEFF 3.1.1 cross sections with modifications
 - Modifications defined in ANP-10297 Supplement 1P-A (ARCADIA)
- No additional computational models were added since the ARCADIA topical reports

HERMES Code

- Cross section library functionalization tool
 - Functionalizes: XS, form factors, discontinuity factors, detector reaction rates
- Separate XS libraries are created for hot and cold conditions
 - In ARCADIA, the XS span both hot and cold conditions
 - In MICROBURN-B2, separate XS libraries are created for hot and cold conditions
- Additional state parameters have been added for BWR simulation:
 - Historical coolant density
 - Moderator density
 - Control blade depletion

ARTEMIS-B: Neutronic Module

- Solves the 3D diffusion equation using the semi-analytical method
 - The flux solver is the same as was presented in the ARCADIA topical report
- Models added for BWR simulation:
 - Coolant / Moderator Parameters
 - BWR Detector Model
 - BWR Spacer Grid Model
 - Control Blade Depletion Model
 - LPRM Tube Model
 - Variable Axial Material Zoning Method

BWR Detector Model

- BWR are equipped with LRPM and TIP Detectors
- LPRM - Local Power Range Monitors
 - Located at 4 axial locations and a number of radial locations
 - Used for core monitoring
- TIP - Traversing In-core Probes
 - Performs axial measurements at LPRM locations
 - Measurements performed about once a month
 - Used to calibrate LPRM's and validate core simulators

BWR Detector Model

- Calculates the LPRM and TIP responses
- Can calculate neutron detectors or gamma detectors



- This model is the same as in MICROBURN-B2
- This model is validated through the core follow TIP results

BWR Spacer Grid Model

- The spacer grid multipliers are defined in a table as a function of dependent state parameters
 - Multipliers are calculated using interpolation
- This model is similar to the model in MICROBURN-B2
 - Multipliers are recalculated with APOLLO2-A for new lattice types
 - Added additional state parameters
- This model is validated against:
 - The core follow eigenvalue results
 - The axial gamma scan results

Control Blade Depletion Model

- Control Blades
 - Loaded with B4C and Hafnium pins to absorb neutrons
 - As the absorber pins burn out, the control blades become less effective
- Control Blade Depletion Model

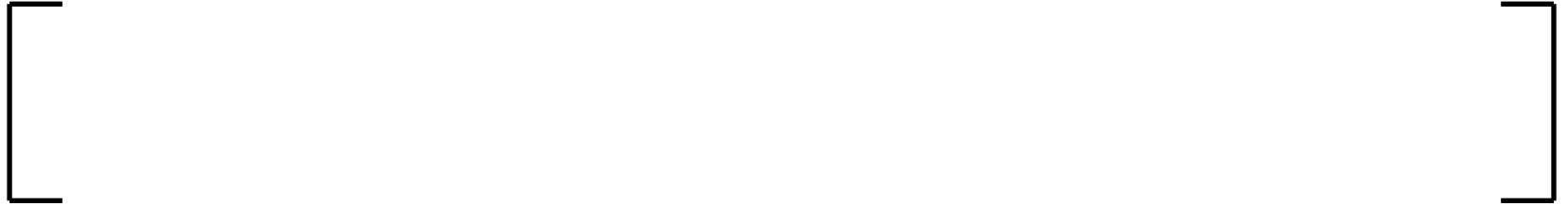


- This model is similar to the model in MICROBURN-B2
 - Parameterized into the Delta XS
 - $\Delta XS = \text{Controlled XS} - \text{Uncontrolled XS}$
- The ARTEMIS-B control blade B10 concentrations are verified against APOLLO2-A



LPRM Tube Model

- LPRM Tubes
 - Located at a number of radial locations in the core
 - Span the entire axial length of the active core
 - Main effect of the LPRM tubes, is the decreased volume of moderator



- This model is the same as in MICROBURN-B2



Variable Axial Zoning Method

- ARTEMIS-B models reactors using []
- Modern fuel assemblies do not always align with these boundaries:
 - Part length fuel rods (upper and lower plenum)
 - Shortened full length fuel rods
 - Some fuel designs (neutronic lattice transitions)

- This method is similar to the VAX method used in MICROBURN-B2
- The VAX XS are verified in ARTEMIS-B by comparing against explicitly modeled regions

ARTEMIS-B: Thermal Hydraulic Module

- The COBRA-F code is used to solve for the fluid conditions in the core
 - This is the same Thermal Hydraulic code as is used in MICROBURN-B2



ARTEMIS-B: Fuel Rod Module

- Solves the 1D heat conduction equation
- Same computational approach as in ARCADIA, except the following have been updated:
 - Material properties and radial power profile
 - These are taken from the RODEX4 fuel performance code
 - Gap conductance and fuel porosity tables
 - These are generated using the RODEX4 code
- The effective temperature equation is updated to be consistent with downstream BWR methods

ARTEMIS-B: Depletion Module

- The depletion solver burns the fuel materials
- The Bateman equations are solved using a Krylov subspace solver
- No updates have been made to the depletion solver since ARCADIA
 - The isotopes tracked in ARTEMIS-B have been updated

CPR Correlations

- The ACE CPR correlations that have been implemented in ARTEMIS-B include:
 - ATRIUM 10 ANP-10249P-A
 - ATRIUM 10XM ANP-10298P-A
 - ATRIUM 11 ANP-10335P-A
- The results in ARTEMIS-B will be shown to be the same as in their respective approved reports.
- If additional CPR correlations are needed in the future, the same methodology will be used.

Reflector Treatment

- The reflector nodes are modeled explicitly in ARTEMIS-B
- The reflector XS are generated using APOLLO2-A

- The reflector model is similar to ARCADIA (ANP-10297P-A)
- The reflector cross sections are verified using SERPENT2 calculations
 - Radial reflectors are verified on 2D core calculations
 - Axial reflectors are verified on 3D assembly calculations

APOLLO2-A V&V

Alex Bennett

APOLLO2-A V&V

- V&V is performed using three methods:
 - Critical Experiments
 - Spent Fuel Measurements
 - Monte Carlo Comparisons

APOLLO2-A: Critical Experiments

- Critical experiments are used to validate the following results from APOLLO2-A:
 - Reactivity
 - Fission Rate Distribution (only measured in some experiments)
- Critical Experiments:
 - BASALA (BWR)
 - EPICURE (PWR – includes voided conditions)
 - B&W (PWR)
 - KRITZ (PWR)
 - CAMELEON (PWR)

APOLLO2-A: Spent Fuel Measurements

- Spent fuel measurements are used to validate the APOLLO2-A isotopic predictions
- Spent fuel measurements:
 - Fukushima Daini 1 (BWR)
 - Fukushima Daini 2 (BWR)
 - REGAL (PWR, 10% Gadolinium)

APOLLO2-A: Monte Carlo Comparisons

- The Monte Carlo comparisons are performed with the SERPENT2 code. Comparisons are made for:
 - Multiple lattice types (ATRIUM, water rod, water cross)
 - Multiple fuel designs (uranium enrichment, gadolinium concentration)
 - At BOL and with burnup
 - Various conditions (coolant density, moderator density, fuel temperature, coolant temperature)
 - Hot and cold conditions
 - Gamma Transport

ARTEMIS-B V&V

Alex Bennett

ARTEMIS-B V&V

- The V&V for ARTEMIS-B includes:
 - Verification of the Cross Section Module
 - Verification of the Fuel Rod Module
 - Verification of the ARTEMIS-B Pin Power Predictions
 - Validation of the Thermal-Hydraulic Module
 - Core Follow Results
 - Gamma Scan Results

Verification of the Cross Section Module

- The microscopic XS are represented as a functional expansion
 - The functional representation must be able to reproduce the XS values calculated in APOLLO2-A
 - The calculated XS in ARTEMIS-B are compared against the XS in APOLLO2-A
 - The interpolation error in between XS points is also calculated
 - The comparisons are made for a variety of lattice types and conditions

Verification of the Fuel Rod Module

- The ARTEMIS-B fuel rod model (FRM) is updated to be consistent with the RODEX4 fuel performance code
 - Comparison are made between the ARTEMIS-B FRM and RODEX4 to show consistency
 - The comparisons are made:
 - As a function of burnup, LHGR, and cladding temperature
 - For different Uranium enrichments and Gadolinium concentrations

Verification of the Pin Power Predictions

- The pin power predictions are verified using 2D colorset calculations
 - Colorset are typically 2x2 assembly geometries
 - The reference results are calculated using the APOLLO2-A code
 - These calculations are performed for:
 - Different lattice types
 - Variety of conditions
 - Uncontrolled and controlled
 - As a function of burnup

Validation of the Thermal-Hydraulic Module

- Validation of the Thermal-Hydraulic module is performed using pressure drop and void fraction measurements.
- Pressure Drop Data
 - KATHY Measurements
 - ATLAS Measurements
 - XN-NF-79-59 Measurements
- Channel Average Void Fraction Data
 - ATRIUM 10A
 - ATRIUM 10XM
 - FRIGG-2
 - FRIGG-3

Core Follow Results

- The ARTEMIS-B core follow benchmarking results include:

[]

- Reactor types:

[]

- US, Asian, and European Reactors
- Lattice Types: C, D, S
- Neutron and Gamma TIP Measurements
- Cold Critical Measurements

Gamma Scan Results

- The ARTEMIS-B gamma scan benchmarks include:
 - Gundremmingen-B Cycle 13
 - Oskarshamn-2 Cycle 32
 - Quad Cities-1 Cycles 2,3,4
- The pin gamma scan measurements are used to validate the ARTEMIS-B pin power predictions
- The nodal gamma scan measurements are used to validate the ARTEMIS-B nodal power predictions

Applicability to EPU / EFW Conditions

- EPU / EFW Conditions
 - EPU: Extended Power Uprate
 - EFW: Extended Flow Window
 - At these conditions, there is increased reactor power and/or decreased reactor flow
 - This results in higher void fractions
- Comparisons as a function of void will be shown for the following:
 - Cross section interpolation
 - Monte Carlo comparisons
 - LPRM, TIP, and gamma scans results
 - Pressure drop and void results

Break

Power Distribution Uncertainty

Alex Bennett

Power Distribution Uncertainty

- For plant operation, a core monitoring software must be able to show the power distribution throughout the reactor core
 - LPRM measurements are only obtained at 4 axial levels and a number of radial locations
 - The LPRM measurements and the ARTEMIS-B calculated power distribution are synthesized to get a ‘measured’ power distribution
 - The uncertainty of the ‘measured’ power distribution and ‘measured’ pin powers are calculated
- The methodology used for ARTEMIS-B is the same as for MICROBURN-B2

Power Distribution Uncertainty

- The synthesized power distribution uncertainty is calculated by combining the uncertainties of each of its components, which include:
 - Calculated TIP Uncertainty
 - Calculated using comparisons of calculated and measured TIPs for the core follow benchmarks
 - Calculated Nodal Power Uncertainty
 - Calculated using the calculated TIP uncertainty and a power correlation between assemblies
 - The power correlation is calculated using the nodal gamma scan comparisons
 - Synthesized TIP Uncertainty
 - Components given on the next slide

Power Distribution Uncertainty

- The synthesized TIP uncertainty is calculated using a summation of its uncertainty components, which include:
 - TIP Measurement Uncertainty
 - Calculated using symmetric TIP data
 - LPRM Measurement Uncertainty
 - Determined by GE and validated by Framatome
 - Synthesis Uncertainty
 - Calculated using comparisons of synthesized TIPs and measured TIPs

Power Distribution Uncertainty

- The synthesized pin power uncertainty is calculated as a combination of the synthesized power uncertainty and the pin power reconstruction uncertainty
- The pin power reconstruction uncertainty is calculated from the pin gamma scan comparisons

Validation Requirements

Alex Bennett

Validation Requirements

- The validation requirements are broken up into three sets:



- These are a similar to the requirements for MICROBURN-B2



APOLLO2-A Validation Requirements



ARTEMIS-B Validation Requirements



Measured Power Uncertainty Requirements



Range of Applicability

- Lattice Geometry
 - Uranium Oxide fuel up to 5.0 w/o U235
 - Rod average burnup limit of 70.0 GWd/MTU
 - Any lattice design included in the Monte Carlo Comparisons
 - New lattice designs must be shown to meet the Monte Carlo Comparison Requirements
- Core Geometry – No limitations



Implementation of APOLLO2-A and ARTEMIS-B into BWR methods

Paul Smith

Topics

- Slow Transients
 - Control Rod Withdrawal Error (CRWE) at power
 - Loss of Feedwater Heating (LOFWH)
 - Flow Runup
- Infrequent Events
 - Mislocation
 - Misorientation
- Standby Liquid Control System (SLCS) Shutdown Margin

Slow Transients – Control Rod Withdrawal Error

- NRC Standard Review Plan 15.4.2 “Uncontrolled Control Rod Assembly Withdrawal at Power”
- Key requirements are:
 - Critical heat flux should not be exceeded
 - Fuel temperature and fuel clad strain limits should not be exceeded
- Current Framatome Methodologies:
 - XN-NF-80-19(P)(A) Vol 4
 - XN-NF-80-19(P)(A) Vol 1 with Supplements 1 and 2
 - XN-NF-825(P)(A)

Slow Transients – Control Rod Withdrawal Error

- BWR/3 – BWR/5 Equipped with Rod Block Monitor (RBM)



- Report to demonstrate ARTEMIS-B is an adequate replacement for MICROBURN-B2

Slow Transients – Control Rod Withdrawal Error

- BWR/6 Equipped with Rod Withdrawal Limiter (RWL)
- Report to demonstrate ARTEMIS-B is an adequate replacement for MICROBURN-B2

Slow Transients – Loss of Feedwater Heating

- NRC Standard Review Plan 15.1.1 “Decrease in Feedwater Temperature”
- Key requirements are:
 - Critical heat flux should not be exceeded
 - Fuel temperature and fuel clad strain limits should not be exceeded
 - Pressure < 110% of Design Value
- Current Framatome Methodologies:
 - ANF-1358(P)(A) “The Loss of Feedwater Heating Transient in Boiling Water Reactors”

Slow Transients – Loss of Feedwater Heating

- Event initiated by feedwater bypass of heater or steam extraction line valve closure
 - Gradual collapse of voids
 - Axial power shape change
 - Overall increase of reactor power



- Report to demonstrate ARTEMIS-B is an adequate replacement for MICROBURN-B2

Slow Transients – Flow Runup

- Steady-state analysis in ARTEMIS-B used in creation of flow-dependent limits
- Current Framatome Methodologies:
 - XN-NF-80-19(P)(A) Volume 4 Revision 1
 - Appendix B describes protection of fuel design limits at off-rated conditions
 - Clarifications to this report in NRC:99:030 discusses the use of flow-dependent LHGR limits for this purpose

Slow Transients – Flow Runup

- Flow-dependent limits based on flow excursion characteristics
- Report to demonstrate ARTEMIS-B is an adequate replacement for MICROBURN-B2

Infrequent Events – Misload

- NRC Standard Review Plan 15.4.7 “Inadvertent Loading and Operation of a Fuel Assembly in an Improper Position”
- Key requirements are:
 - Offsite consequences should be a small fraction ($< 10\%$) of the 10 CFR Part 100 criteria (10 CFR Part 50.67 when using alternate source term)
 - Key requirement conservatively met if less than 0.1% of rods experience boiling transition
- Two types of misload are considered
 - Mislocation
 - Misorientation
- Current Framatome Methodologies:
 - XN-NF-80-19(P)(A) Vol 4
 - XN-NF-80-19(P)(A) Vol 1 with Supplements 1 and 2

Infrequent Events – Misload

- Mislocation – The inadvertent placement of an assembly in the incorrect core location
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- Misorientation – The inadvertent rotation of an assembly from its nominal orientation
[]
- Report to demonstrate ARTEMIS-B is an adequate replacement for MICROBURN-B2

Standby Liquid Control System Cold Shutdown Margin

- NRC Standard Review Plan 4.3 “Nuclear Design” and 9.3.5 “Standby Liquid Control System (BWR)”
- Key requirements:
 - The adequacy of the control systems to assure that the reactor can be returned to and maintained in the cold shutdown condition at any time during operation.
- Shutdown margin criteria is based upon calculation and measurement uncertainty
 - Lattice code borated eigenvalue uncertainty (comparison to Monte Carlo)
 - Cross section boron interpolation uncertainty
 - Cold critical uncertainty for commercial reactors
 - Operational uncertainties
 - Actual vs Predicted core conditions
 - Inexact tracking of parameters
 - Depletion uncertainties
 - Fuel manufacturing tolerances
- 95/95 criterion for shutdown margin with liquid poison system will be established including all listed uncertainties

Other Licensing Methodologies

- The inclusion of ARTEMIS-B core physics into other NRC approved Framatome methodologies to be covered in future topical reports
- Inclusion into the MCPR safety limit
 - SAFLIM-3D
- Inclusion into the fuel rod thermal mechanical analysis
 - RODEX4
- Inclusion into the stability methods
 - RAMONA5
 - STAIF
- Inclusion into the AURORA-B code package
 - Fast Transient methodologies
 - Reactivity Insertion Accidents

Summary and Next Steps

Paul Smith

Summary

- APOLLO2-A/ARTEMIS has been previously validated for PWR applications
- APOLLO2-A will be validated for BWR conditions
- ARTEMIS-B is an extension of ARTEMIS to perform BWR design and licensing calculations
 - Verification and validation for BWR applications to be demonstrated
- Interface APOLLO2-A/ARTEMIS-B with downstream slow transient methodologies will be demonstrated

Next Steps



Questions/Discussion

Acronyms

ARTS:	Average Power Range Monitor, Rod Block Monitor, and Technical Specification Improvement	LHGR:	Linear Heat Generation Rate
ASEA:	General Swedish Electrical Limited Company	LOFWH:	Loss of Feedwater Heating
BOC:	Beginning of Cycle	LRPM:	Local Power Range Monitor
BLPRM:	Local Power Range Monitor Multiplier	MCPR:	Minimum Critical Power Ratio
BOL:	Beginning of Life	MELLLA+:	Maximum Extended Load Line Limit Analysis Plus
BWR:	Boiling Water Reactor	OLMCPR:	Operating Limit MCPR
CPR:	Critical Power Ratio	PWR:	Pressure Water Reactor
Δ CPR:	Critical Power Ratio change during transient	RBM:	Rod Block Monitor
CRWE:	Control Rod Withdrawal Error	RMS:	Root Mean Square
DF:	Discontinuity Factor	RWL:	Rod Worth Limiter
EPU:	Extended Power Uprate	TIP:	Traverse In-core Probe
ERM:	Equivalent Reflector Model	US:	United States
FRM:	Fuel Rod Model	V&V:	Verification and Validation
GE:	General Electric	XS:	Cross Section

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