APOLLO2-A and ARTEMIS-B for BWR

Alex Bennett, Paul Smith, Alan Meginnis

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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.weathernationtv.com/news/tumbleweeds-swallow-cars-shut-down-highway/

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Introduction and Background

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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

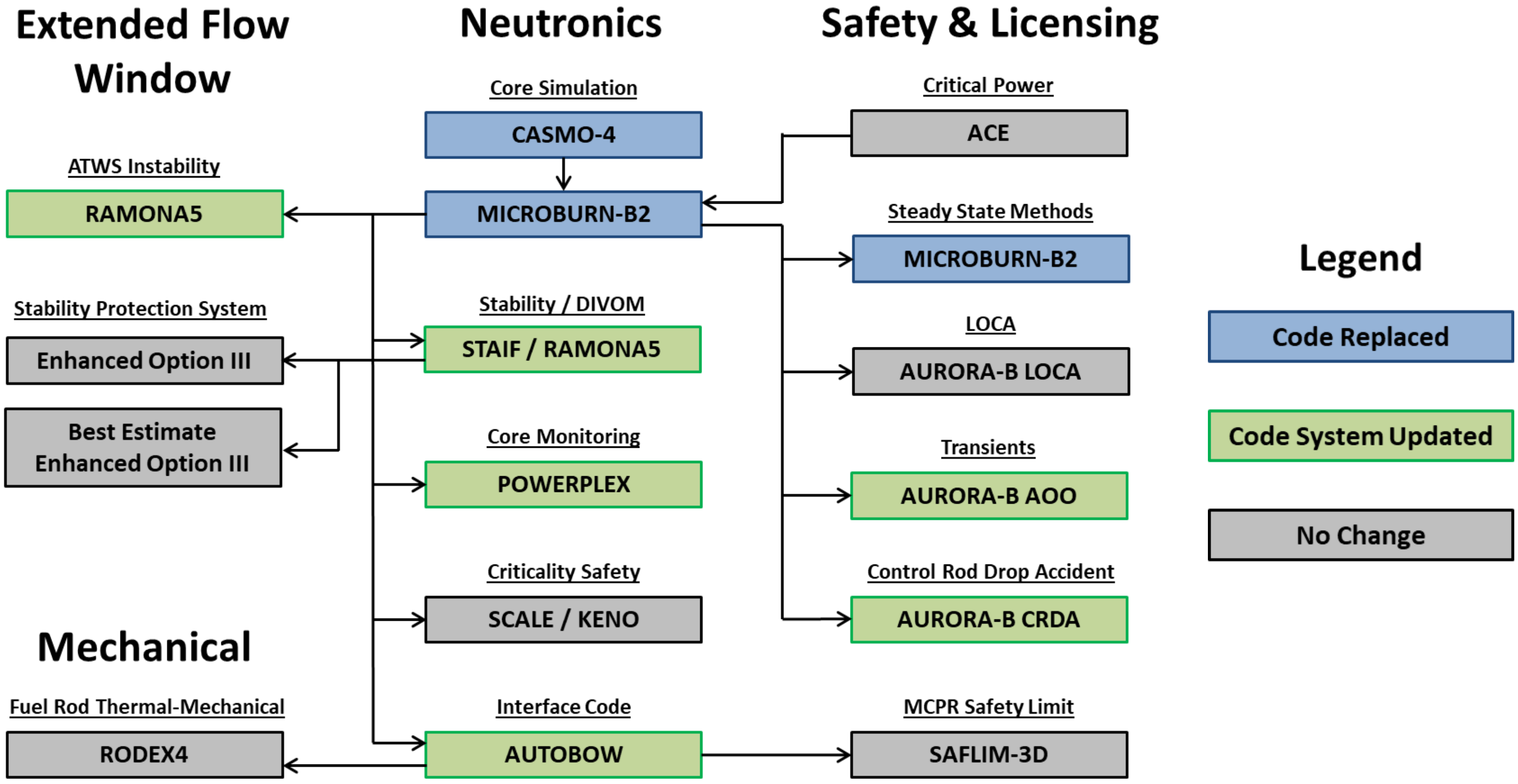
- Interface ARTEMIS-B with downstream methods

Motivation

[ ]

- ARTEMIS-B gives better agreement with TIP results

Overview of Current Methodology



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ANP-10350 Table of Contents

Computer Code Changes

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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 = Controlled XS – 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

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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

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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

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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

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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

[ ]

- 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

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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

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Questions/Discussion

Acronyms

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

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