PWR Core Engineering Methods

Kevin Segard
Supervisor, PWR Neutronics Methods & Licensing

AREVA

Overview

- Code System Updates
- Code Topical Reports
- Implementation Objectives
- Implementation Topical Reports

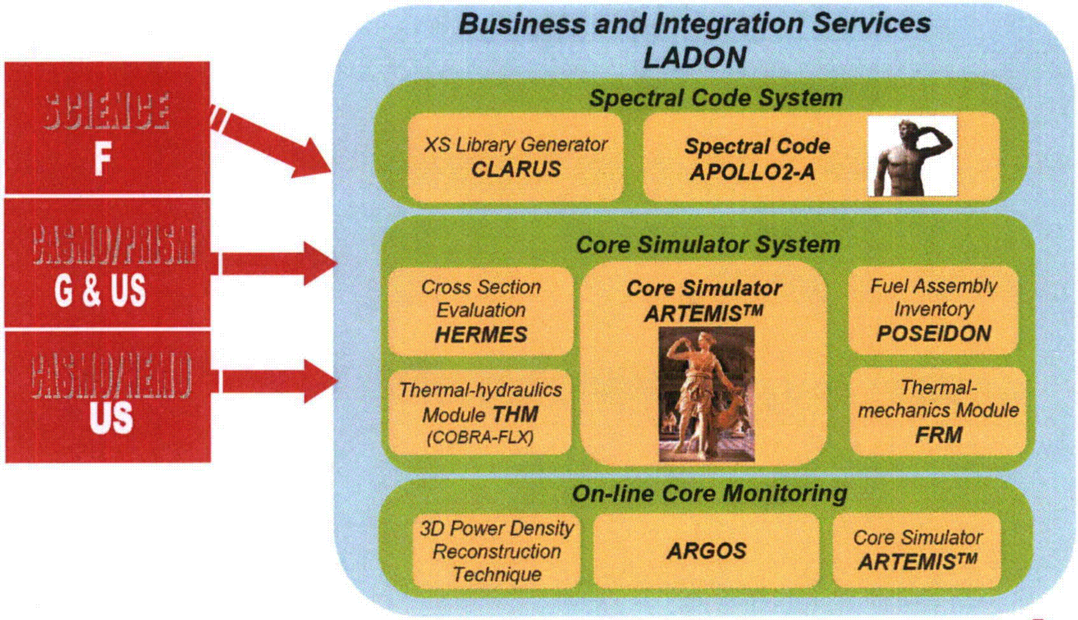
Core Engineering Codes

- Neutronics: APOLLO2-A / ARTEMIS
- Thermal Hydraulics: COBRA-FLX
- Fuel Rod: GALILEO
- Automation / Interface: "LADON"

Challenging Development Targets

- **Development of one of the world's leading industrial code systems for LWR fuel assembly and core design as well as safety analyses**
  - **State of the art in physical modeling, numerical performance, user interface, and software engineering**
  - **Maximum flexibility with respect to accuracy and performance**
    - **From: Reference capability**:
      pin-by-pin, multigroup, transport theory, detailed nuclide chain, detailed thermal-hydraulics and thermomechanics
    - **To: Scoping capability:**
      2 energy groups, diffusion theory, optimized nuclide chain, simplified thermal-hydraulics and thermomechanics
  - **Extensive verification and validation base for efficient licensing and broad acceptance by internal and external users worldwide**

The ARCADIA® LWR Design Code System



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APOLLO2-A
Lattice Physics Code

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Lattice Physics Code

- **APOLLO2-A: the lattice-physics code of the ARCADIA® System**
  - **Steady state 2D multi-group transport equation for neutrons and gammas on fuel assemblies and color-sets using MOC for Master Flux Computation**
  - **APOLLO2-A is the AREVA industrial version of APOLLO2.8 code**
    - Developed by French "Commissariat à l'Energie Atomique" (CEA) research laboratory
    - Provides fundamental computation modules
  - **Adapted by AREVA for PWR & BWR industrial applications**
    - Appropriate methodology (Calculation Scheme) for PWR lattices
    - Industrial Front-End
    - Comprehensive Verification and Validation Base
  - **It uses a 281-group evaluation library based on JEFF3.1.1**
  - **With a double purpose**
    - Generation of neutronic fuel assembly data for 3D neutronic core simulators (ARTEMIS)
    - Standalone design studies (fuel assembly-related)

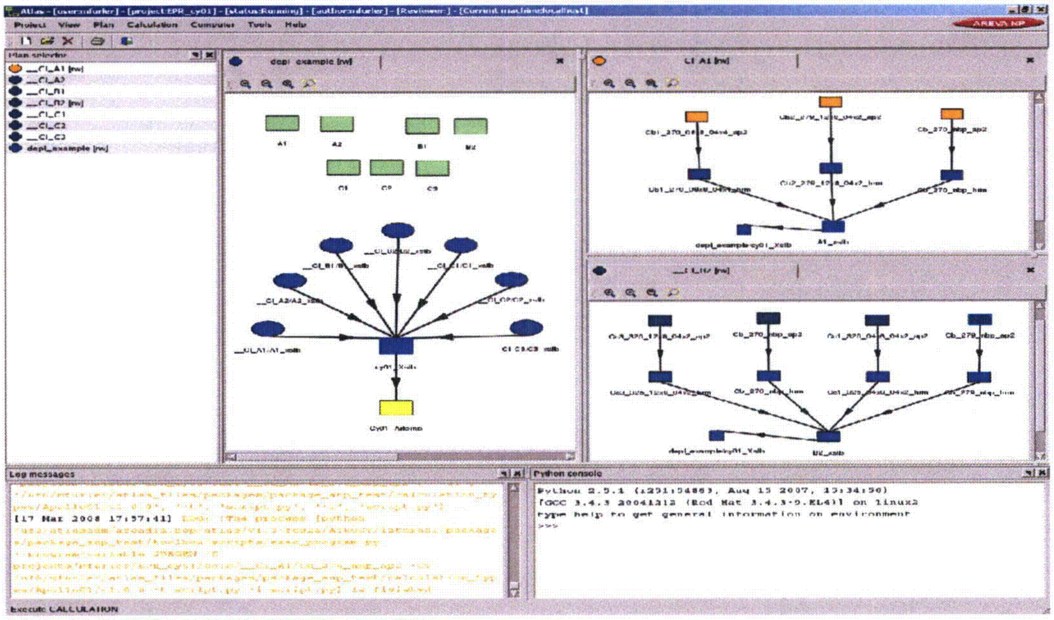
ARTEMIS

Core Simulator ARTEMIS Main Features

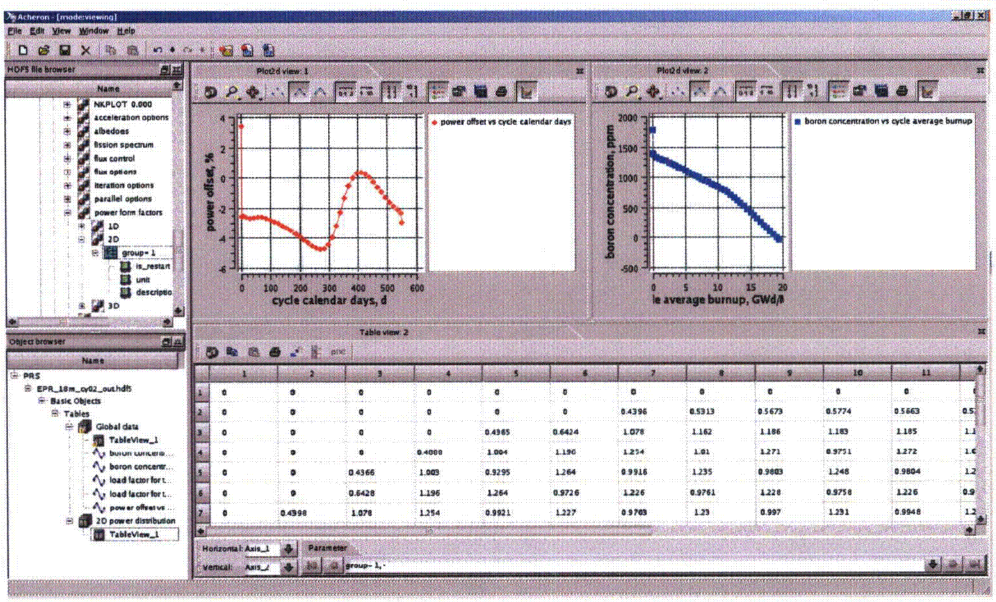
- Flexible nodal 3D multigroup diffusion and SPN transport solution from coarse mesh to pin-by-pin
- Stand-alone neutronics and coupled with thermal-hydraulics/ thermal-mechanics
- Cross section representation continuous from cold (room temperature) to hot conditions
- One code for steady-state and transient applications
- Possibility for parallelization of the entire program
- Further developed flux solution numerics for improved performance and robustness as well as enhanced iteration stability
- New software architecture – model driven approach with (Unified Modeling Language) UML

LADON

LADON–Integration and Business Services ATLAS Status



LADON–Integration and Business Services ACHERON



COBRA-FLX

Purpose of a Global Converged T-H Code

- The COBRA-FLX code will be used for applications associated with licensing safety-related analyses and for operational issue analyses.
- Examples include:
  - DNBR predictions (steady-state and transient conditions) using approved CHF correlations along with full core subchannel by subchannel calculations
  - flow redistribution analyses (full core and mixed core conditions) for quantifying crossflow velocities
  - coupled capability for coolant condition feedback for neutronic calculations
  - axial pressure drop predictions for hydraulic lift force determinations (for fuel assembly hold down requirements and core internals force analyses)
  - understanding and predicting impacts of operational phenomena, like:
    - CIPS/CILC risks
    - establishing local boundary conditions for subsequent CFD analyses to examine local effects

COBRA-FLX Coupling in ARTEMIS

- COBRA-FLX is an integral part of the core simulator ARTEMIS. ARTEMIS is the core simulator of the ARCADIA code system.
- COBRA-FLX can be applied within ARTEMIS in many flexible ways:
  - It can be called without any coupling to other ARTEMIS models
    ⇨This is the subject of the COBRA-FLX Topical Report

  In addition
  - It can be coupled with the ARTEMIS fuel rod model
  - It can be coupled solely with the ARTEMIS neutron physics model (coarse meshing, moderator thermal dynamic conditions from COBRA-FLX)
  - It can be coupled with the ARTEMIS neutron physics model (coarse meshing) and the ARTEMIS fuel rod model

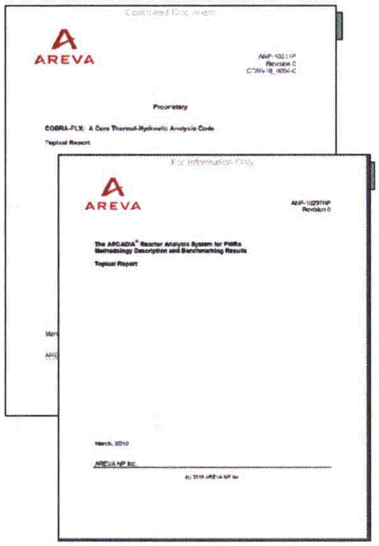
    ⇨This is the subject of the ARCADIA Topical Report

GALILEO

GALILEO Development

Code Topical Reports

Status of ARCADIA® Development



Submittal of 2 Topical Reports:

The ARCADIA® Reactor Analysis System for PWRs Methodology Description and Benchmarking Results Topical Report (Submitted March 2010)

COBRA-FLX: A Core Thermal-Hydraulic Analysis Code (in concurrence)

GALILEO (Submittal August 2012)

Immediate Use for Approved Codes

- **APOLLO2-A provides many isotopic comparisons to experimental data.**
  - **Use the code for burnup credit to support fuel pool criticality analysis**
- **APOLLO2-A provides a better tool for performing control rod heating calculations.**

Implementation Strategy

Fuels Methods Implementation

- AREVA's intent is NOT to simply replace old codes with new codes
- New methodologies being developed with the goals of:
  - Taking advantage of new code features (e.g. full core DNB evaluation coupled with neutronics calculation)
  - Taking advantage of best practices from US, French, and German experience
  - Full consideration of SRP guidance and clear traceability
  - Simplification of Topical Report structure, reduction in the number of topical reports
  - Facilitate future methods upgrades
  - "Convergence" : one set of US methods, global convergence where advantageous

Fuels Methods Implementation

- AREVA's strategy is to implement for the CE/W market first, then extend to the B&W market
- AREVA is developing ONE set of topical reports that cover both UO2 and MOX for CE and W plant types
- Expected topical reports:
  - Reload Analysis Topical
  - Power Distribution and Control
  - Rod Ejection
  - CE/W Setpoint Methodology
  - Rod Bow / Assembly Bow
  - Fuel Assembly Repair / Reconstitution
  - Fuel Assembly Design
  - Non-LOCA Transient Analysis

BWR Fuel Design Update

Norman L. Garner
Technical Sales Manager – BWR Fuel

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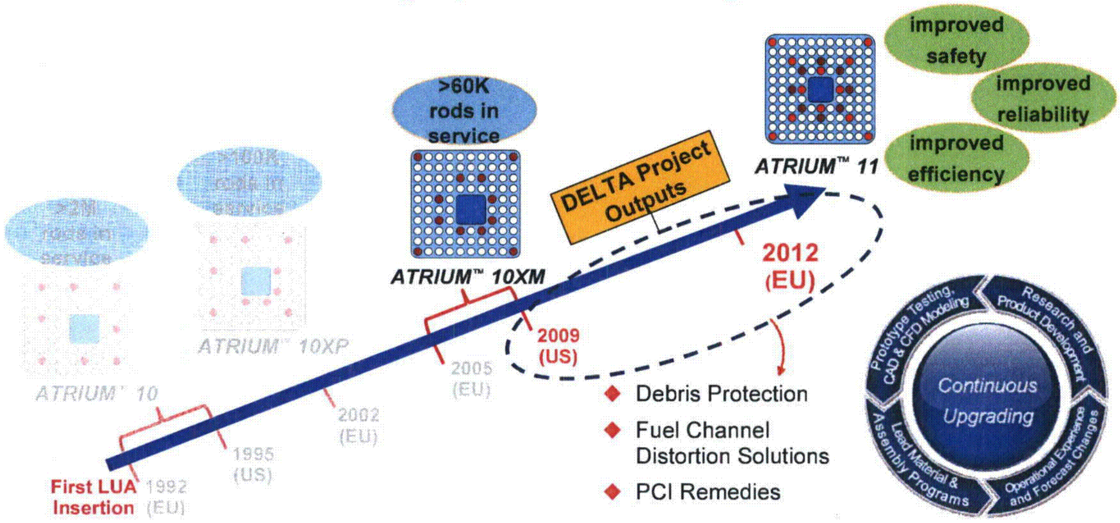
AREVA BWR Product Design Topics

- **BWR Fuel Product Development Update**
  - **ATRIUM™ 10XM**
  - **ATRIUM™ 11**
- **Directions for Improvement:**
  - **BWR Fuel**
  - **Fuel Components, and**
  - **Operational Support**

Direction for higher fuel performance
- increasing operational margins in BWRs



The ATRIUM™ 11 retains the increased critical power improvements and batch size reductions realized with the ATRIUM™ 10XM

ATRIUM™ 10XM
US Introduction Timeline

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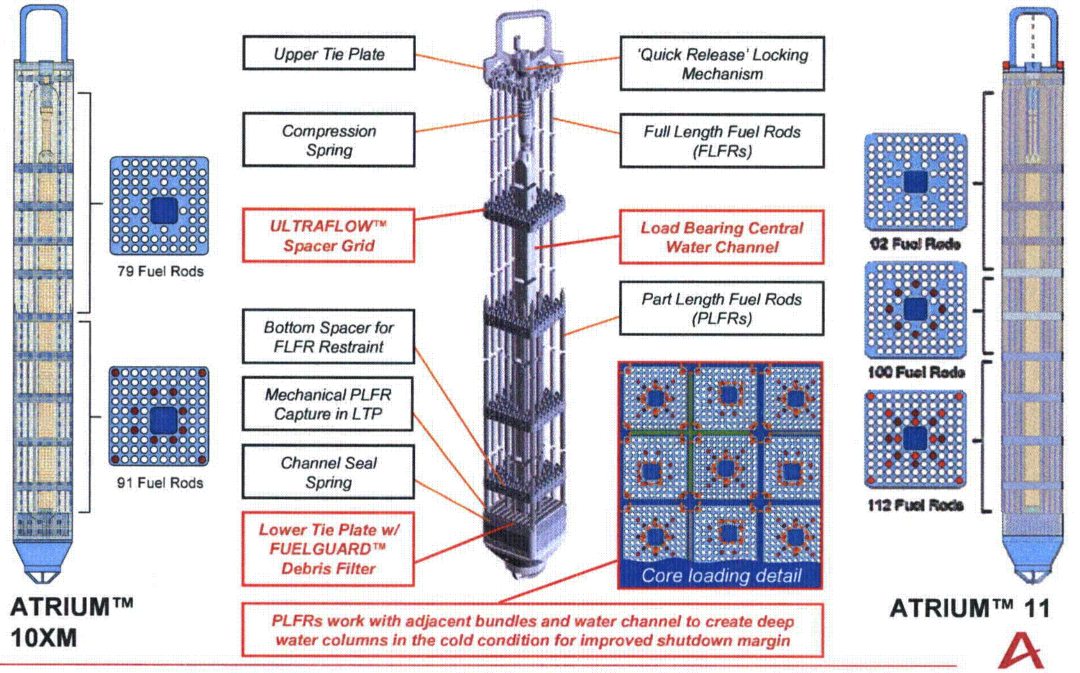
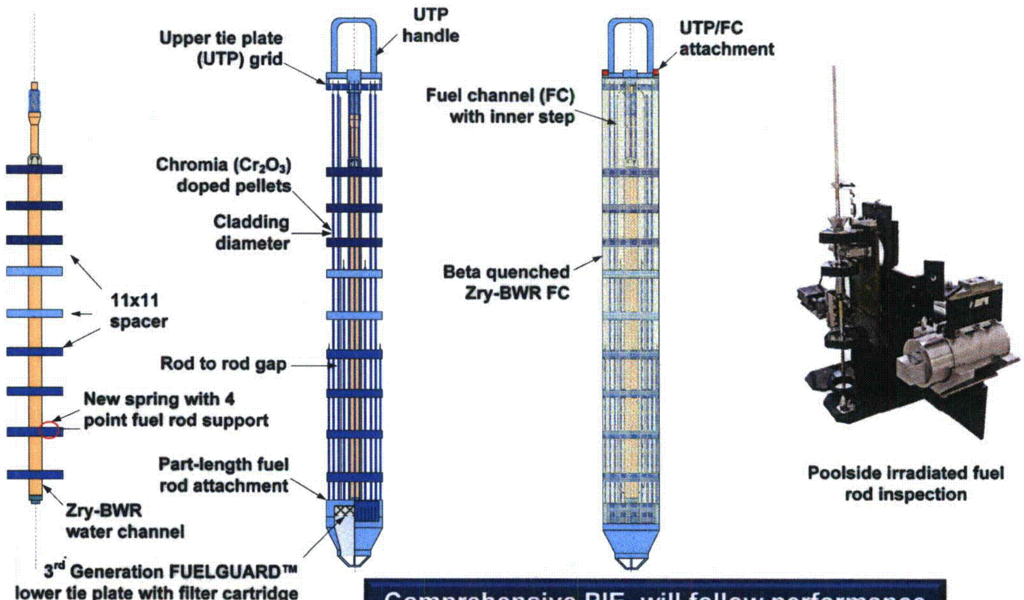
ATRIUM™ 10XM is AREVA's primary product for new supply until the ATRIUM™ 11 reload readiness program is

Common Features of the ATRIUM™ 10XM and 11 Fuel Designs



PLFRs work with adjacent bundles and water channel to create deep water columns in the cold condition for improved shutdown margin

Key New Features of the ATRIUM™ 11



Comprehensive PIE will follow performance of new features in LTA programs

ATRIUM™ 11 Spacer Grid Design and Pre-irradiation Qualification

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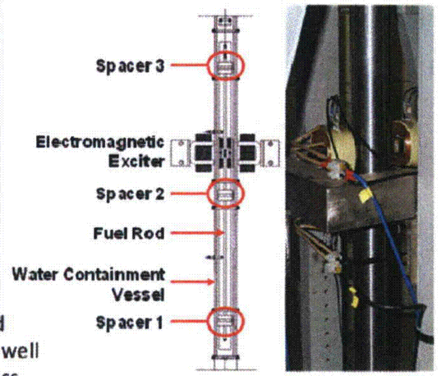
3D CAD modeling facilitated interaction with finite element and computational fluid dynamics codes and laser cutting and forming tool design software

Finite element analyses assured that maximum stresses remain well below levels of concern for stress corrosion cracking and that spacer geometry would be free from distortion when loaded



Electromagnet-driven vibration testing confirmed resistance to grid-to-rod fretting damage

Extensive pre-irradiation qualification of the spacer grid and all other new features assures readiness for LTAs

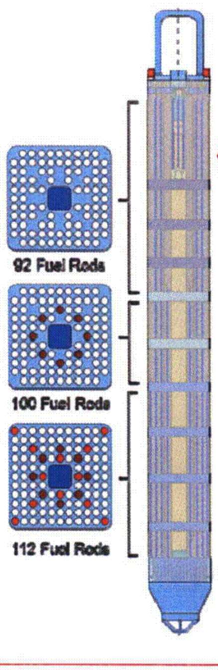
ATRIUM™ 11 LTA Readiness

- **Three ATRIUM™ 11 LTA programs have been contracted for insertion in EU BWRs**
  - **LTAs will operate under industry bounding power density and corrosion environment conditions with near limiting power histories**
  - **8 LTAs for 3Q2012 insertion, additional LTA sets in 3Q2013 and 2Q2014**
- **Mechanical and hydraulic testing has been completed to the standards required for reload qualification**
- **Sufficient critical power testing has been completed to confirm limiting condition critical power capability**
  - **Allows comparative critical power margin analysis of LTAs relative to reference reload bundle design**

ATRIUM™ 11 LTAs can be delivered to a US BWR in ~18

Direction for increased debris resistance
- improving filtering and reducing entrapment risk

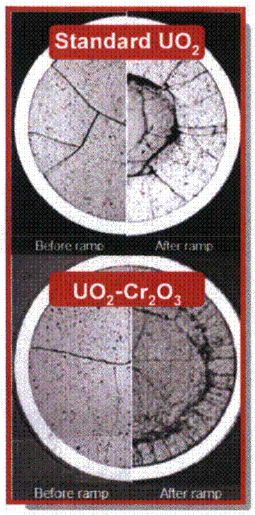
Direction for increased PCI resistance
- reducing fuel duty and cladding stress



The ATRIUM™ 11 increases total rod length by ~20% over the ATRIUM™ 10XM, reducing LHGR and pellet temperature for a given bundle power

Provides a physical offset to the increased fuel duty associated with power uprates

Doping UO_2 powder with 0.16 wt% Cr_2O_3 produces pellets which will yield under PCI, reducing the peak hoop stress generated in the fuel rod cladding during a power ramp



Remaining UO_2-Cr_2O_3 ramp testing to test high burnup rods (45 & 55 GWd/MTU)

Direction for shadow corrosion resistance
- reducing effects of Ni-alloy grids on Zry fuel rods

- **BWR fuel vendors have migrated to all Ni-alloy spacer grids:**
  - Low pressure drop allows extra grid for improved critical power capability
  - Avoids need to reduce fuel weight to compensate for extra grid
  - Eliminates spacer growth issues
- **Area of shadow corrosion on fuel rod is increased under the spacer grid**
  - Fuel rod failures due to Enhanced Spacer Shadow Corrosion have been experienced at two EU BWR sites
  - No immediate concern for other BWRs due to much lower sensitivity

[ ]

Direction for improved fuel channels
- increasing dimensional stability and corrosion resistance

[ ]

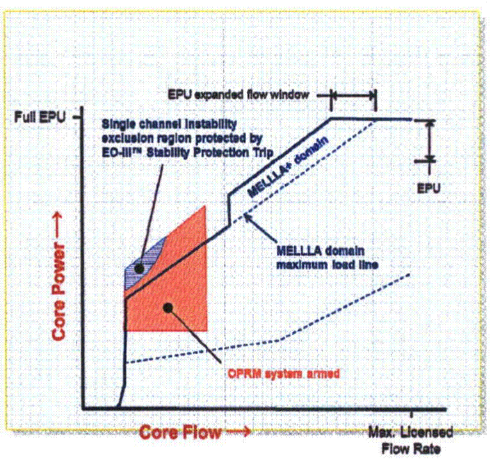
Direction for improving operations support
- increasing online information and capacity factors

- Startup goal is to get from zero power (Z) to rated power (R) as fast as practicable without incident
- Shift to higher rod lines at low power (A) can drive the reactor into the region of instability risk, but
  - Allows faster shift to higher rod line if stability margin is available
- Shift to higher rod lines at high power (B) requires conditioning time to assure adequate PCI margin

An enhanced POWERPLEX® PREDICT module will assist in maneuver planning with the new online calculator tools

Direction for MELLLA+ stability support
- implementing Enhanced Option III (EO-III™)

- EO-III™ directly addresses the reasons for restrictions of the Option III OPRM stability protection system to use only within the MELLLA domain
  - Provides the required supplemental protection for MELLLA+ operations
  - Avoids increased risk of spurious scrams due to high noise levels in LPRMs



- EO-III™ isolates the region of single channel instability risk
  - Resolves source of ill-behaved DIVOM correlation limiting OPRM extension
  - Protects plant with an independent hard scram similar to the Option I-A solution
- Allows extension of existing OPRM for MELLLA+ stability protection
  - Low risk of spurious scrams and retains current good operating experience

EO-III™ is structured as a fuel vendor neutral stability solution

BWR Codes and Methods Development

Douglas Pruitt
Manager/FDT-AR

AREVA

- Regulatory Interactions
  - Recent Interactions and submittals before NRC
- BWR Codes & Methods Roadmap
- BWR Applications - MELLLA+
  - Short Term Approach
  - Development in support of Long Term Approach
- Future Licensing methods
  - AURORA-B

Regulatory Interactions

ACE K-Factor Formulation
EXEM BWR-2000
Licensing Topical Reports

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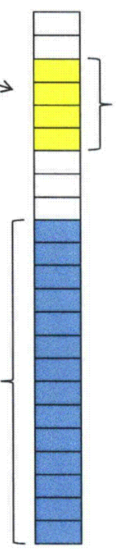
Regulatory Interactions
ACE K-Factor Recovery

- **Approved ACE/ATRIUM 10XM correlation uses an axially uniform K-Factor formulation that is non-physical**



The basic problem with the K-factor methodology is the axial averaging of the planar values over the entire heated length

- Uses data above the dryout location which is non-physical
- Equal weight is given to the pin peaking in low power regions as in high power regions
- Equal weight is given to the pin peaking far from and close to the location of dryout

Regulatory Interactions
ACE K-Factor Recovery

- Reactors operating with reloads of ATRIUM 10XM fuel have a licensing condition that requires an operability assessment to demonstrate conservatism of operating limits based on approved method
- AREVA has made good progress in preparing a revised K-Factor methodology that replaces the axial averaged value with an axial array of K-Factors used in the integration process
- AREVA submitted LTR supplements December 2012
- Latest status was that RAIs should be expected this month

Regulatory Interactions
EXEM BWR-2000

- EXEM BWR-2000, CR-2011-3695 issued in response to NRC concerns with a unique ADS configuration at a supported plant
  - A single failure can result in failure to activate the ADS valves, therefore ADS is delayed by 10 minutes to allow manual operator actuation
  - The plant configuration results in a small break LOCA scenario with an extended period of time before rated core spray is reached
  - NRC Staff expressed concern that the configuration resulted in conditions that were outside the range of applicability of approved EXEM BWR-2000 methodology
    - Predicted top down flow of LPCS in hot channel prior to end of blowdown eroded conservatism in the method during the extended blowdown resulting from this configuration
- Plant is operating under operability analyses that do not credit top down cooling in the hot channel from LPCS during blowdown
- Revised analyses for the plant with corrected ADS have been performed and audited by NRC

Regulatory Interactions EXEM BWR-2000

- A conference call was conducted with the NRC on August 15th to address generic implications
  - AREVA provided a basis that the approved EXEM BWR-2000 method is appropriate and conservative for application to other currently supported plants with a typical ADS configuration
  - Proposed to adopt a generic modified analyses approach to eliminate top down cooling from core spray in the hot channel calculation before the end of blowdown
  - Proposed implementation:
    1. Analyses for currently supported plants are conservative and adequate, no reanalyses required
    2. Future break spectrum analyses will incorporate the modified approach to address the NRC concerns about down flow cooling from core spray eroding conservatism
  - NRC requested a summary of the conference call for their "positive feedback"
- AREVA submitted summary in October 2011 and is waiting NRC feedback

Regulatory Interactions LTRs

- AURORA-B Deterministic AOO
  - Submitted December 2009, Supplemental Information August 2011
  - Upgrade multi-physics transient methods and system models for BWR plants
  - Foundation for advanced methodology (CRDA, LOCA, ATWS, Statistical AOO...)
- AURORA-B Appendix K LOCA
  - Pre-Submittal Meeting October 2011
  - 2 fluid non-equilibrium physics basis
  - System nodalization greatly expanded
- RODEX-4 for RXA cladding

Regulatory Interactions LTRs

- **RODEX-4**
  - Submitted December 2009 to expand approval for RXA cladding
  - Work is in progress on RAI questions received on the RXA Clad Supplement to RODEX4 Topical (approved in March 2008).
  - The main reason for not approving the RODEX4 application for RXA Zry-2 in 2008, was the reduced database size – additional data from AREVA GmbH were included in the RXA Supplement.
  - Also, the new data showed a significant impact of the liner inside layer on axial elongation – a model upgrade was developed to account for the liner effect on axial PCMI.
  - In addition, the RXA irradiation-induced growth model developed for channel bow in the approved RODEX4 Topical, was applied also to RXA cladding.
  - Most of the NRC questions are for clarification, one question requests a sample case for audit analysis by the NRC
  - Current schedule: RAI responses by early July

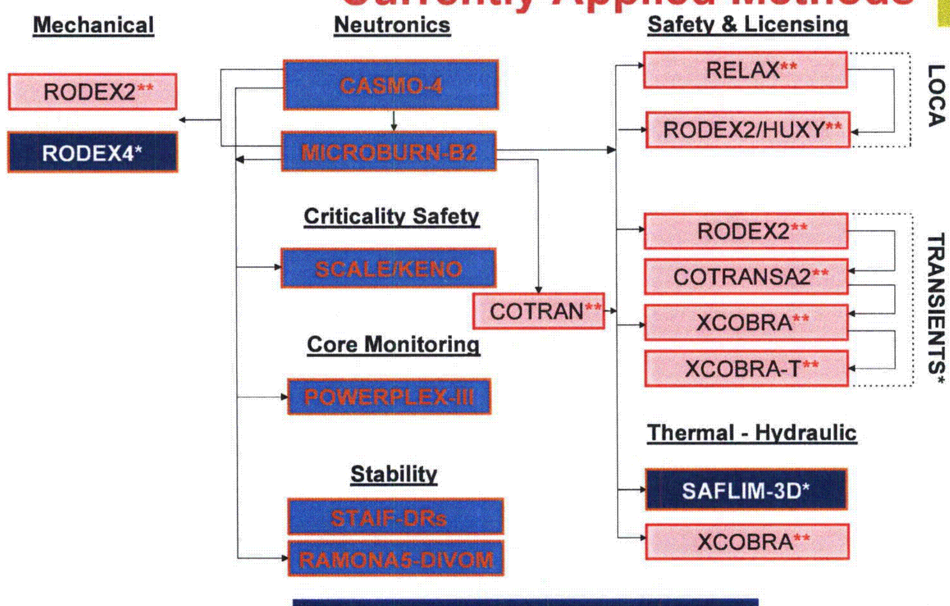
Regulatory Interactions LTRs

- **RODEX-4**
  - One RAI question related to the RXA Supplement refers to a H pickup model
  - The reason for the NRC not approving the H pickup model in 2008 (as part of the RODEX4 Topical) was insufficient database.
  - Additional data are now available over the whole irradiation exposure range.
  - An updated H pickup model is in development and it will be submitted in the near term, ideally together with the other responses to the RXA Supplement RAI's.
  - A mechanical test program is being initiated this year to gather experimental data on mechanical properties of irradiated RXA Zry-2 cladding, including measurements of H uptake from irradiation in power reactors.

Methodology Roadmap

Currently Applied Methods
Next Evolution

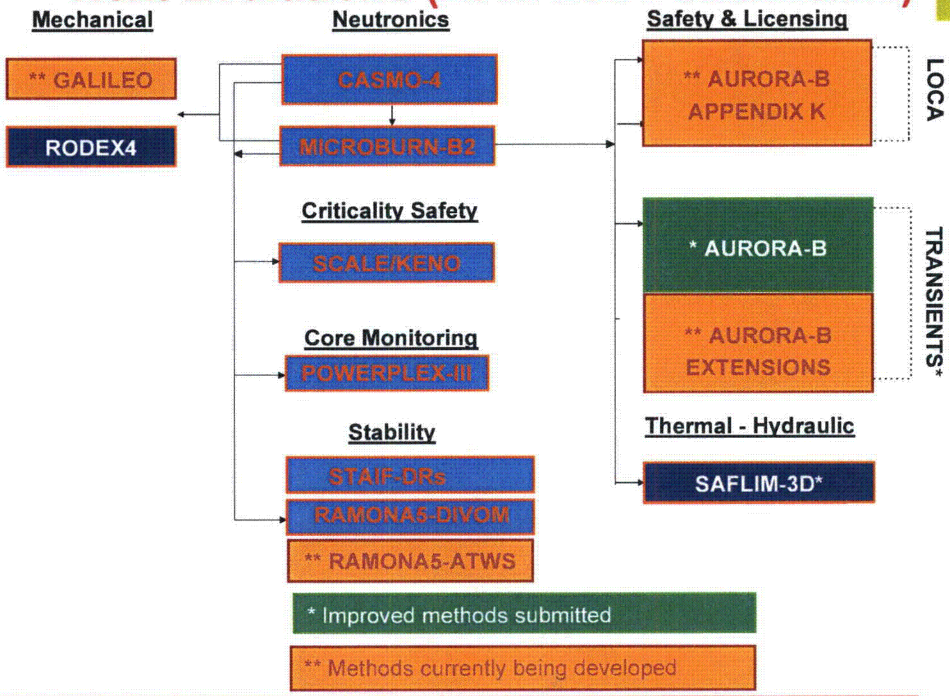
AREVA NP's US BWR Methodologies
Currently Applied Methods



* Improved methods recently implemented

** Codes will be replaced by new methods

AREVA NP's US BWR Methodologies Next Evolutions (2012-2014 Submittals)



BWR Applications - MELLLA+

Codes & Methods
MELLLA+ Licensing Approach

- AREVA methods for MELLLA+ will depend on the utility implementation schedule
- Short-term approach: use currently approved codes and methods coupled with LAR documentation that justifies this approach
- Long-term approach: use advanced AREVA methods (MICROBURN-B2, AURORA-B, RAMONA5, GOTHIC)

MELLLA+ Short Term Background

- The short term approach for MELLLA+ licensing is the same as that employed for Extended Power Uprate (EPU)
- EPU operation was supported through the LAR process by submitting documentation for NRC review and audit
  - Addressed the impact of EPU operation on each of the approved methods
  - Provided experimental and operational evidence that methods are used within their range of applicability
- NRC review, including a 6 man-week audit on AREVA transient methodology (COTRANSA2, XCOBRA, XCOBRA-T), resulted in a few concerns

MELLLA+ Short Term Background

- **Primary concern was associated with the applicability of the approved void-quality correlations for EPU operation and the impact of uncertainties or biases on thermal limits**
  - AREVA was able to provide comparisons to measured void fraction data for the ATRIUM-10 fuel
  - AREVA demonstrated that the impact of uncertainties / biases was small and no MCPR penalties were required
- **However, there were a few additional conservatisms required by the NRC**
  - Small Safety Limit impact due to increased uncertainty in pin-power distribution – plant dependent
  - Impact on Over-Pressure analyses due to uncertainties/biases in the void-quality correlation and different Doppler feedback definitions in MICROBURN-B2 and COTRANSA2 (later expanded for thermal conductivity degradation)

MELLLA+ Short Term Preparations

- **ATRIUM 10XM void measurements extended the data to higher void fractions and through the use of X-RAY tomography reduced NRC concerns with respect to correlation biases**
- **Enhanced Option III detect and suppress methodology was approved by the NRC / ACRS and AREVA has pursued eliminating the 10% DIVOM penalty for MELLLA+**
  - ACRS meetings held January 2011
  - Expecting NRC Safety Evaluation to eliminate penalty
- **Supplement to the AURORA-B LTR was submitted to the NRC that addresses the applicability of MICROBURN-B2 to the extended flow domain**
- **Supplement information for MICROBURN-B2 will be combined with EPU information to create a new document in support of LAR submittals for MELLLA+**

MELLLA+ Short Term Preparations

- Despite progress, long-term ATWS and ATWS with core instability do require special attention in the short term
  - GE analyses based on proprietary ATRIUM 10 or ATRIUM 10XM fuel data
  - AREVA to support regulatory interaction based on approved and developmental methods
- Most challenging is ATWS with core instability as plant specific analyses for MELLLA+ operation are required
- ATWS with core instability is an ongoing development project within AREVA, a status report follows...

The ATWS/Instability Transient

- General Characteristics
  - Natural circulation
  - High inlet subcooling (feedwater heaters bypassed)
  - Highly unstable in both global and regional modes
  - Without scram: severe oscillations with reverse inlet flow are expected
  - Super-prompt critical power peaks
- Mitigation
  - Decrease inlet subcooling by lowering water level
  - Boron injection
- Past Support for TVA
  - Responses to NRC RAI (Sept 2008) for TVA power upgrade under MELLLA
- Recent Concerns
  - MELLLA+ introduces highly unstable initial condition
  - Regional oscillations were not adequately addressed and may be limiting
  - Assessment of fuel damage under these conditions
  - Licensing solution required by NRC and ACRS

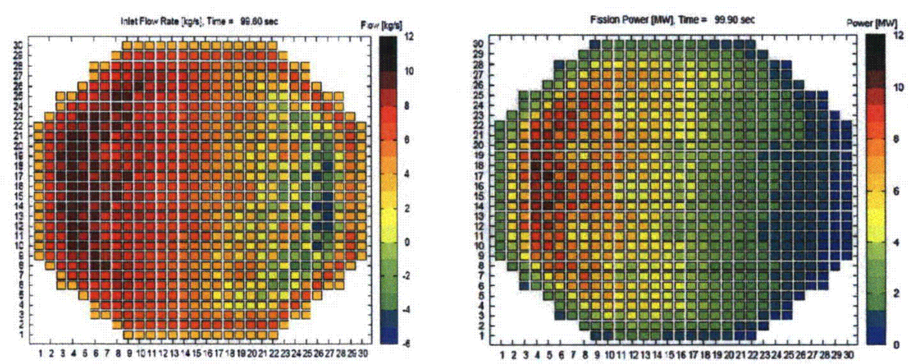
ATWS/Instability Transient Current Indications

- The consequences of ATWS/Instability event are likely not as severe as previously thought

- Recent KATHY loop stability tests for ATRIUM-10XM (2009)
  - Several runs with step increase in power
  - Several runs with power oscillations using SINAN simulated reactivity feedback
  - Observed long periods of cyclical dryout/rewetting with mild rod temperature rise
  - Failure to rewet at very large oscillation magnitude leads to large temperature excursion

ATWS/Instability Methodology Basis

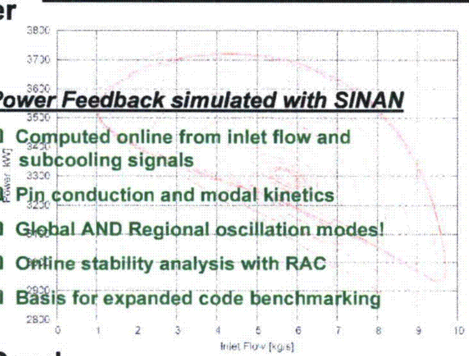
- Capability to simulate power and thermal-hydraulic transient
  - RAMONA5-FA



- Capability to simulate impact on fuel integrity
  - Transient Dryout and Rewetting
  - Experimental basis provided by the ATRIUM 10XM stability tests in the large amplitude regime with and without SINAN power feedback

ATRIUM 10XM Stability Tests

Better → **Best**



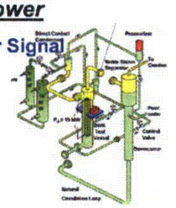
Power Feedback simulated with SINAN

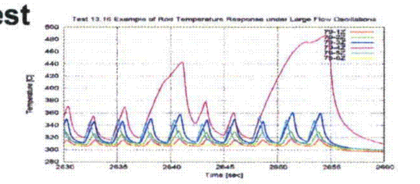
- Computed online from inlet flow and subcooling signals
- Pin conduction and modal kinetics
- Global AND Regional oscillation modes!
- Online stability analysis with RAC
- Basis for expanded code benchmarking

Good

Hydraulic Simulation at Fixed Power

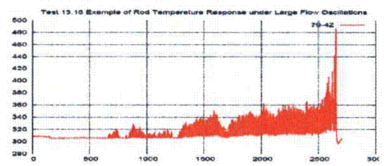
- Some with Pseudo Random Power Signal
- Decay ratio from noise analysis
- Code benchmarking
- Limited cyclical dryout data
- Basis for code benchmarking





Extensive Dryout/Rewetting Testing

- Under fixed power and oscillating flow as before, and
- Under BOTH power and flow oscillations
- Large oscillation amplitudes to reverse flow
- Extended until irreversible dryout
- Deep penetration to lower elevations



ATRIUM 10XM Stability Tests
Evaluation and Accomplishments

▶ Evaluation Tool SINANO

- Uses transient test data as boundary and forcing functions
- Calculates nodal flow state (vapor and liquid mass flow and temperatures)
- Heater rod conduction
- Reverse transient heat conduction to extract experimental measurements of heat transfer coefficient and outer rod wall temperature
- Output used for testing and creating new models and correlations

▶ Elements of a New Dryout/Rewetting Model

[ ]

ATRIUM 10XM Stability Tests
Example Comparisons with New Models

ATRIUM 10XM Stability Tests
Example Comparisons with New Models

ATRIUM 10XM Stability Tests Example Comparisons with New Models

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ATRIUM 10XM Stability Tests Example Comparisons with New Models

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Example Comparisons with New Models

Severe Oscillations in ATRIUM 10XM Quality Response to Frequency

Severe Oscillations in ATRIUM 10XM Flow Envelope Response to Frequency

New ATWS/Instability Methodology Potential Margin Gains

- Open literature information about consequences of severe oscillations are overly conservative compared with KATHY tests data so far.
  - Reverse inlet flow comparable to KATHY measurement, but much higher peak temperature (exceeding 1200 C)
  - Reference: BNL-NUREG-48969, "Instability due to a two recirculation pump trip in a BWR using RAMONA-4B computer code with 3-D neutron kinetics."

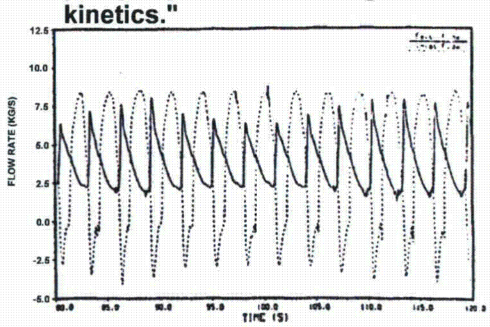


Figure 15. Channel 23, Inlet and Exit Mass Flow Rates

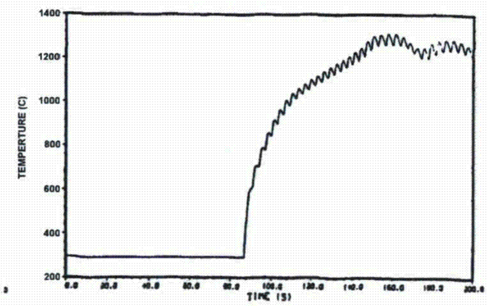


Figure 18. Peak Clad Temperature

ATWS with Instability Summary

- RAMONA5-FA code is capable of simulating large inlet reverse flow and super-prompt criticality

[ ]

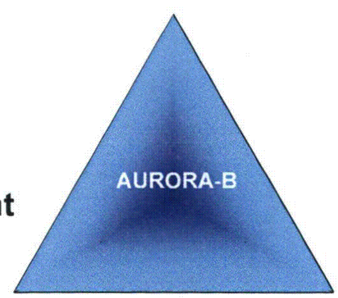
- Extensive experimental
- Clear theoretical basis and new findings
- Goal is to submit ATWS/Instability methodology 1st half 2014 coordinated with MOX methodology submittals

Future Licensing Methods

AURORA-B

AURORA-B
Next Generation Safety Analysis

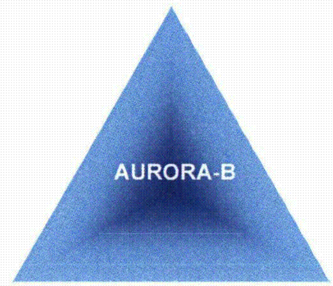
- **AURORA-B evaluation model is a best-estimate multi-physics code assembled from proven components**
  - **RODEX-4 best estimate fuel performance predictions**
  - **MB2-K 3D kinetics based on MICROBURN-B2**
  - **S-RELAP5 modern two-fluid T/H system code**
- **S-RELAP5 is the host code in which relevant kernels of RODEX4 and MB2-K have been incorporated**
  - **Builds on and allows crediting of previous USNRC approvals**



Same executable for PWR non-LOCA, SBLOCA, RLBLOCA (rev 2)

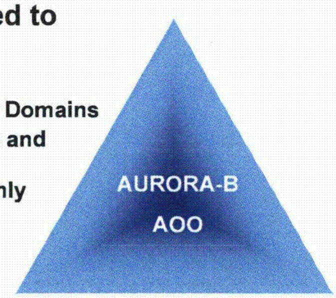
AURORA-B
Next Generation Safety Analysis

- AURORA-B: more than the sum of its parts
- S-RELAP5 physical models
  - Interfacial drag
  - Reynolds dependent form losses
  - Single and two phase friction models consistent with MICROBURN-B2
  - Critical Power Correlations
- S-RELAP5 component models
  - Jet pump
  - Mechanistic steam separator
- Automation
  - Direct data coupling with upstream MICROBURN-B2 and RODEX4



AURORA-B
AOO Licensing Topical Report

- The AURORA-B AOO methodology was a global project involving engineers from Richland, San Jose and Erlangen
- The AURORA-B AOO methodology was submitted to the NRC
  - Applicable to all forced circulation BWR plants
  - Applicable to Extended Power Uprate and Extended Flow Domains
  - Included data to assess all the improved physical models and new/revised component models
  - Included separate effect and integral tests to validate highly ranked phenomena
- Requested approval for evaluation of
  - Transient minimum MCPR
  - Peak primary system pressure
  - Evaluation of fuel integrity PCT criteria
  - Evaluation of thermal-mechanical criteria w/RODEX4
- and is currently under NRC acceptance review



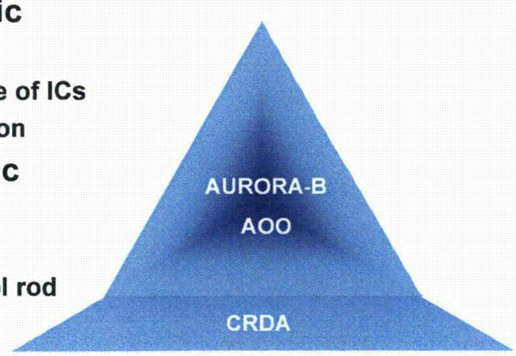
AURORA-B
Technical Capability Comparison

COTRANSA2		AURORA-B
Simple 1-D, 1 energy group kinetics	→	Modern 3-D, 2 energy group kinetics
Single channel core → 3 eqn drift flux formulation	→	Multi-channel core → two-fluid 6 eqn non-equilibrium formulation
1980 era fuel rod modeling	→	Best-estimate fuel rod modeling
Homogeneous Equilibrium Model for Vessel and Steamline dynamics	→	Two-fluid non-equilibrium model for vessel and steamline dynamics
Hardwired nodalization	→	Standardized nodalization but extensible by user

» AURORA-B establishes general BWR capabilities with solid physics basis, extensible to future methodologies

AURORA-B Extensions
Control Rod Drop Accident

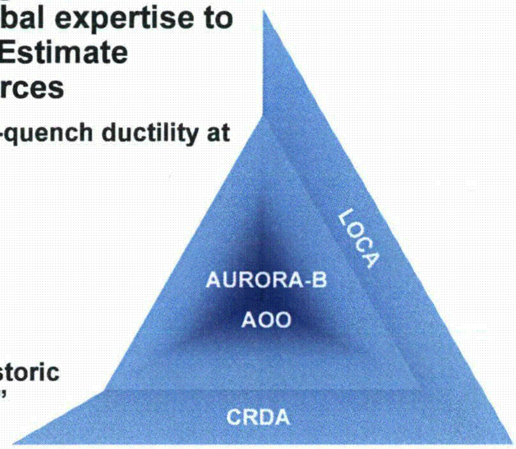
- Motivated by Regulatory changes and capitalizes on European experience with 3-D CRDA with RAMONA/RELAP5
- Relatively minor evolution of basic deterministic AOO code system
  - Cross section representation for range of ICs
  - Integration of Pin-Power Reconstruction
- Development of realistic neutronic methodology is underway
  - SPERT Benchmarks
  - Address "realistic" rod worths, control rod patterns and initial reactor conditions



Goal: Support current operation, submit January 2013

AURORA-B Extensions
LOCA

- **Multi-phase approach that leverages PWR RLBLOCA developments and global expertise to establish deterministic and Best Estimate Methods depending on market forces**
  - Regulatory changes to address post-quench ductility at high burnups
  - GSI-191
  - Design Margins
- **Address regulatory expectations**
  - Best-Estimate Methods
  - Current methodology is based on historic conservatisms that are not "realistic"
  - Limiting PCT break size may not be consistent with a best estimate methodology



Goal: Improved physics and operating margin, submit January 2013

AURORA-B Extensions
LOCA Improvements

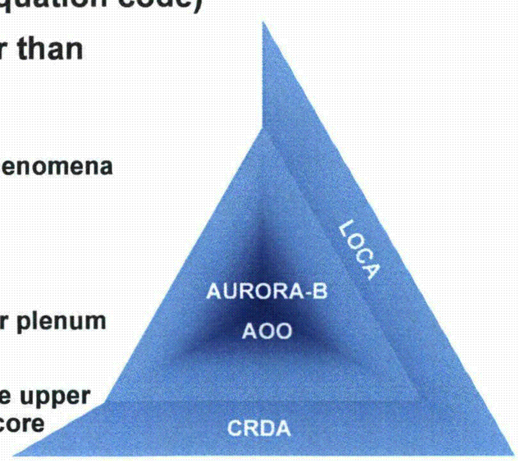
- **Non-equilibrium phenomena (6 equation code)**

Overall nodalization is much finer than EXEM BWR-2000

- Improves the solution
- Improves prediction capability of phenomena

Multi-dimensional modeling

- Multiple channel core
- 2-D bypass, upper plenum and lower plenum regions
- Accurately model the drainage of the upper plenum and the refill/reflood of the core



AURORA-B Extensions
LOCA Improvements

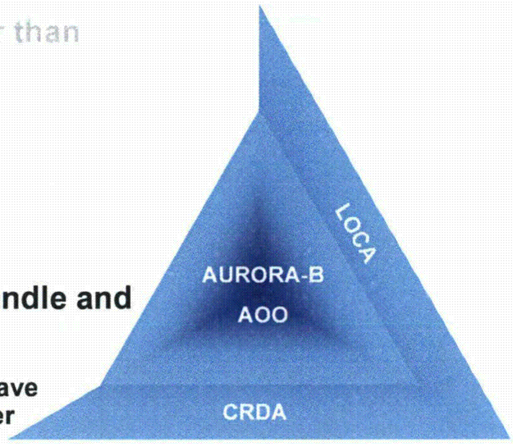
- Non-equilibrium phenomena (6 equation code)

  Overall nodalization is much finer than EXEM BWR-2000

  Multi-dimensional modeling

  Mechanistic spray heat transfer
  - **Correlations vs. HTC values**

  Leakage paths from bypass to bundle and LTP
  - **EXEM BWR-2000 bypass does not have this path, leakage is diverted to lower plenum**

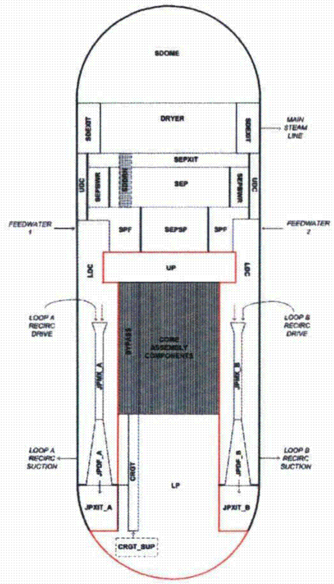


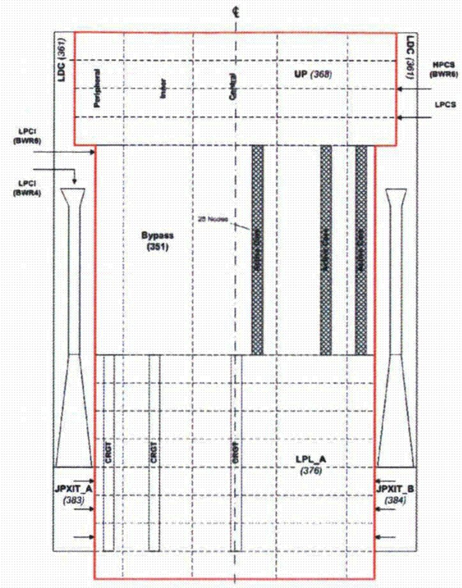
AURORA-B Extensions
LOCA Improvements

Comparison of EXEM BWR-2000 and AURORA-B LOCA Methodologies

	EXEM BWR-2000 (RELAX/HUXY) – App. K	AURORA-B LOCA (S-RELAP5) – App. K
Nodalization	1-dimensional system, total nodes < 50	2-dimensional system, Total nodes ~ several hundred
Code model	Homogeneous equilibrium model (3-equation model)	Non-homogeneous equilibrium model (2-fluid, 6-equation model)
Capability to accurately calculate BWR LOCA phenomena	Limited capability for non-equilibrium conditions (non-equal phase velocities and temperatures)	Code model has the capability to calculate non-equilibrium conditions
Multi-dimensional BWR LOCA phenomena (UP mixing, parallel core flow, CCFL at numerous places)	1-dimensional modeling precludes accurate prediction of these phenomena	2-dimensional system has capability to accurately predict these phenomena
Improved LOCA margin	Limited	Possible, through improved system responses (e.g., refill and reflood timing)

AURORA-B LOCA Nodalization





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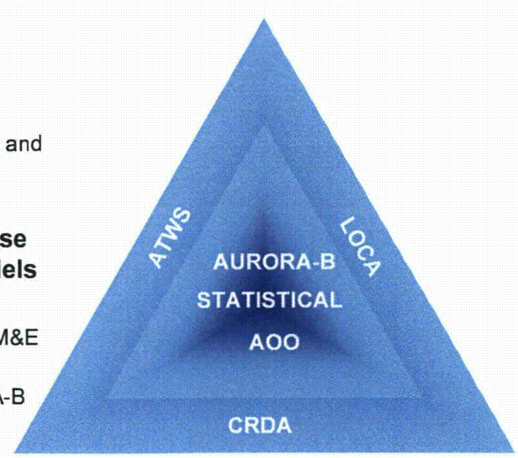
Potential AURORA-B Extensions

- **AURORA-B ATWS, initiated**
  - **Addition of boron injection and shutdown**
    - Borated cross sections within MB2-K
    - Boron injection & transport in S-RELAP5 and data interfaces to MB2-K
    - CFD support as required
  - **Utilize San Jose containment expertise to implement BWR containment models based on two step approach**
    - Generic containment methodology with M&E boundary conditions
    - Coupled containment model to AURORA-B
  - **Goal: Submit 2nd quarter 2014**
- **Long-Term, AURORA-B Statistical AOO**



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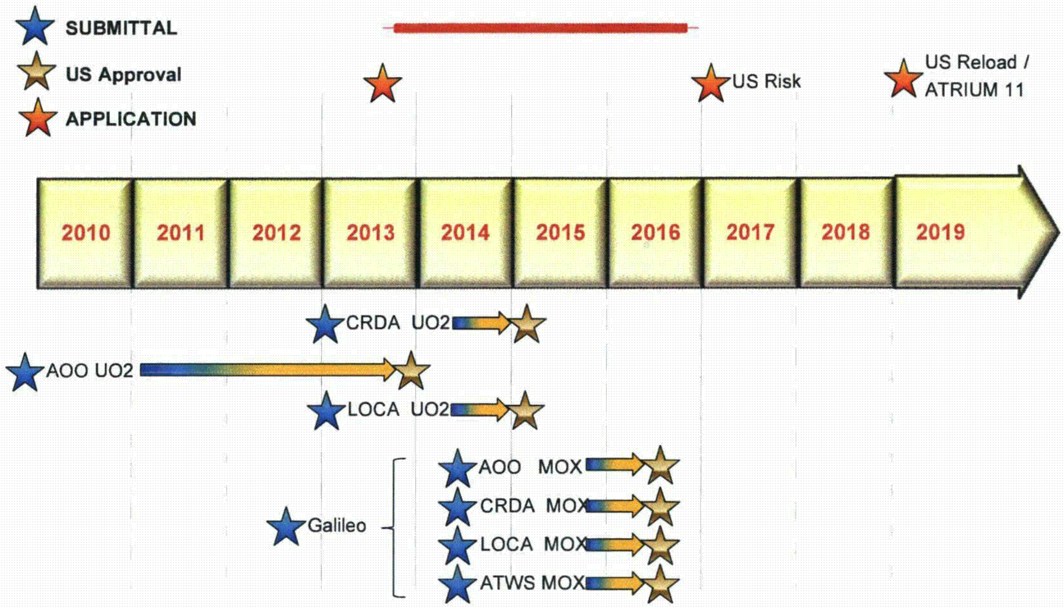
AURORA-B Schedule



Conclusions

The 2009 submittal of AURORA-B represents the first step in BWR transient and accident renovation

- Composed of well qualified and approved modules (S-RELAP5, MB2-K, RODEX4)
- Extensive qualification database

Incremental refinement and qualification of the base AURORA-B models will extend its applicability to additional transient and accident scenarios

- Reactivity Insertion Accidents
- Loss of Coolant Accidents
- Anticipated Transients Without Scram

BWR renovation facilitates the retirement of current BWR transient and accident methodologies

BWR Codes & Methods Summary

- AREVA has been and continues to actively develop advanced methods on a global scale to provide a strong physical basis in support of both customer and regulator actions
- AREVA has expanded typical industry experimental investigations to support significant steps forward in understanding of underlying physical phenomena to support EPU and MELLLA+
- AREVA will be submitting a number of topical reports in the next few years to retire our current legacy codes in a stepwise fashion
- AREVA will value pre- and post-submittal meetings as appropriate to facilitate the regulatory review process

PWR Operating Experience

John Strumpell
Manager, Materials and Thermal Mechanics

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Topics

US PWR Failure Summary

Test Assembly Programs

2011 & 2012 Poolside PIEs

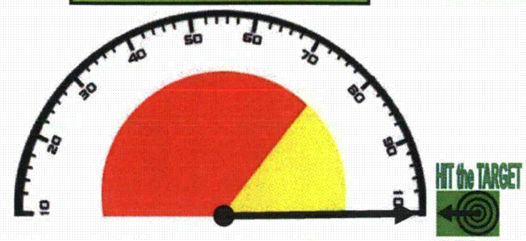
- **M5® Experience Summary**
- **Zircaloy-4 Experience Summary**

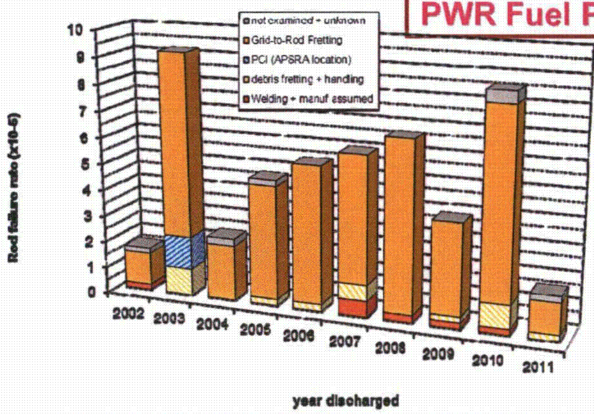
US PWR AREVA-Fueled Cores

→ complete HTP transition and sustain

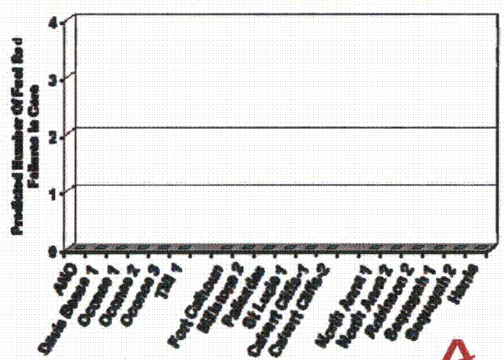
18 out of 18 Customers

- Currently operating with Zero Failures!
- Improvement in reliability as GTRF-resistant HTP™ designs are implemented





PWR Fuel Performance Status As Of 6/13/12



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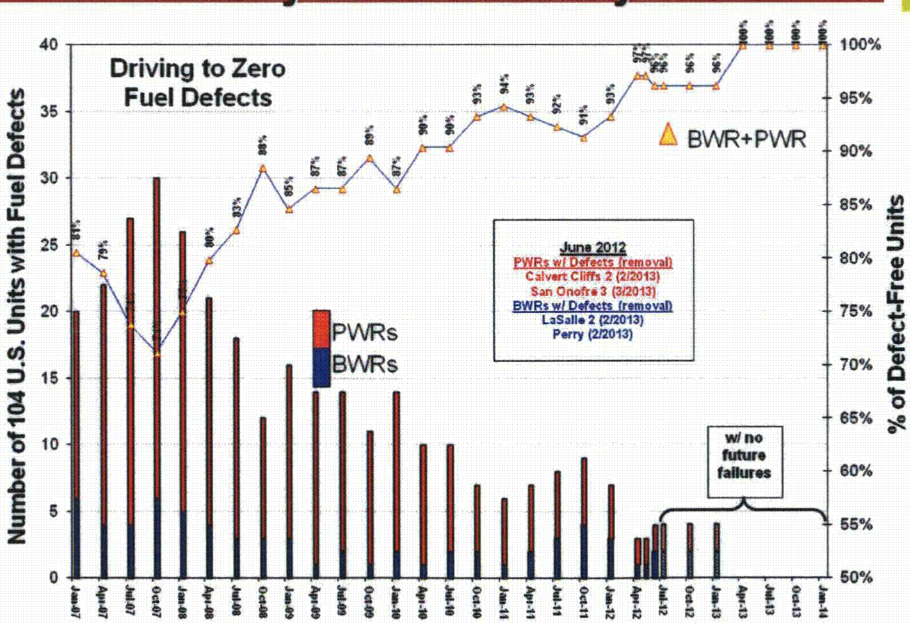
US Industry Fuel Reliability Trends



PWRs continue to show improvement as plants transition to GTRF-resistant designs

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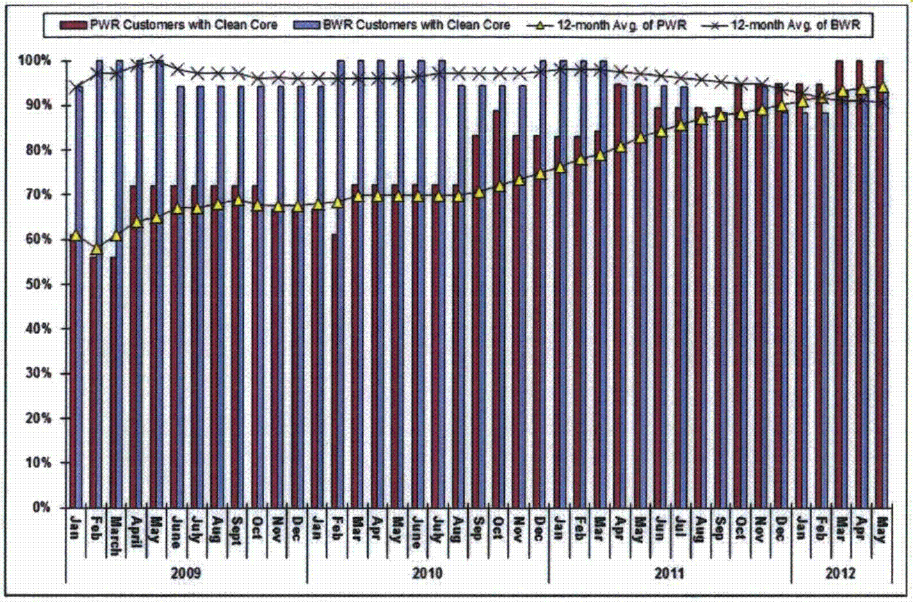
AREVA Fuel Reliability Trends

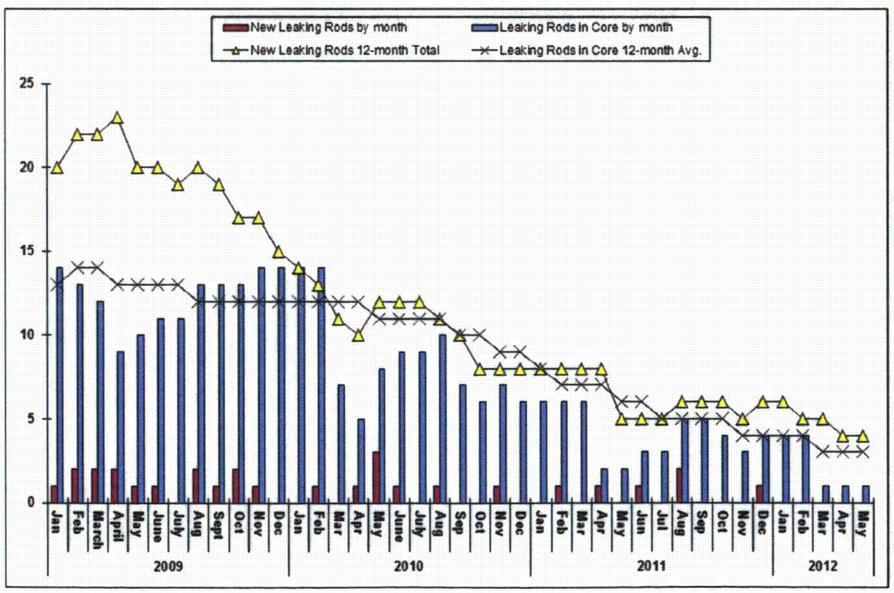
Leaker-Free Cores



The number of leaker-free cores has improved substantially with implementation of HTP.

AREVA Fuel Reliability Trends

Number of Failed Rods

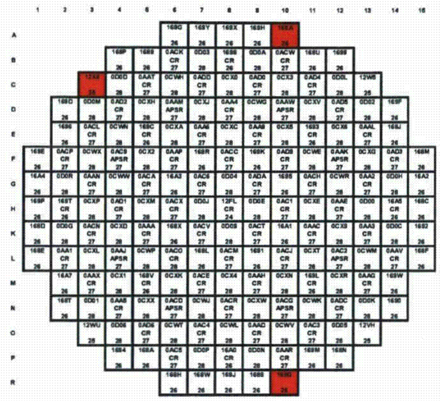


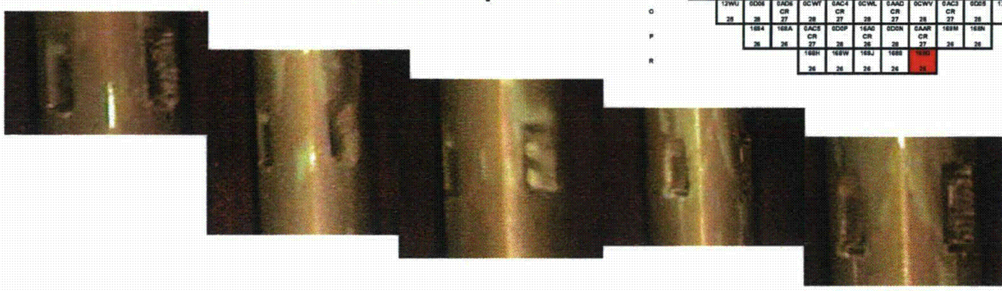
The implementation of HTP has also reduced the overall number of failed rods in operation.

2011 Cause of Failure Examinations

Oconee Unit 1 EOC 26

- 3 MK-B11 fuel assemblies were confirmed failed due to GTRF
- All 3 were in core locations which historically had GTRF failures (2 were in LOCA hole locations and 1 was in a double slot location)
- Oconee now has all HTP on the baffle and no further GTRF failures are expected





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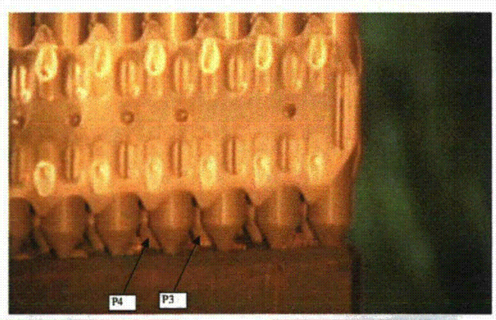
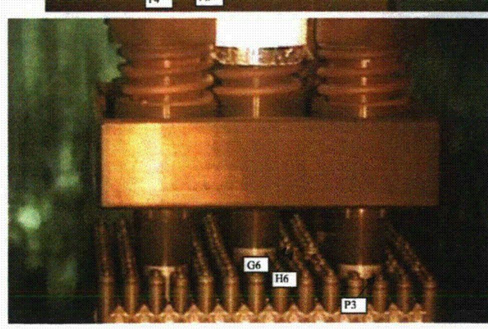
2011 Cause of Failure Examinations

Millstone Unit 2 EOC 20

- 2 fourth cycle CE14 assemblies (with no lower HMP) were identified as failed
- Both assemblies were in core locations where spinning rods had occurred in earlier cycles, and had loose rods and lower end plug wear
- Millstone has completed implementation of the lower HMP grid, and no further spinning rod failures are expected
- Effectiveness of the lower HMP grid has been demonstrated by OE and by fretting wear measurements at St. Lucie
- The lower HMP grid is now standard on CE14 and CE16 designs





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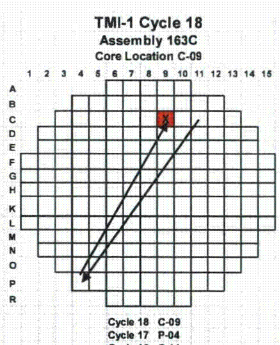
2011 Cause of Failure Examinations

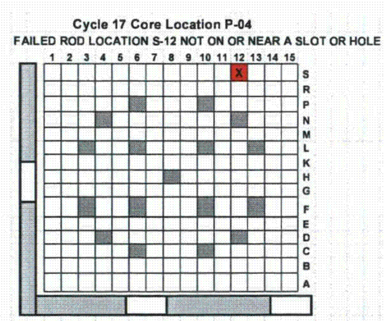
TMI Unit 1 Cycle 18

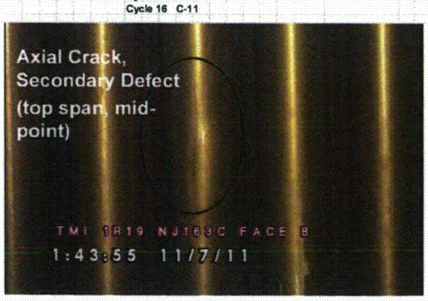
- **Less than a month after BOC 18 failure occurred**
  - Possible radiochemistry indications of additional failure
- **In-mast sipping identified one failed Mark-B12 assembly (third-cycle, from core interior after operating second cycle on the baffle) and one failed Mark-B-HTP (second-cycle, core interior)**
- **A failed rod was visually identified on the periphery of the Mark-B12 assembly (did not operate on the baffle face)**
  - Side rod lifts and visuals performed
  - Most likely cause of failure is debris
- **No failed rods were identified visually or by UT on the Mark-B-HTP assembly**
  - Additional inspections being discussed for Summer 2013

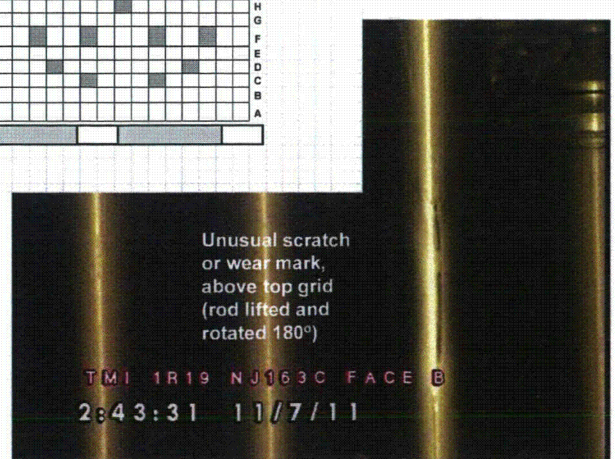
2011 Cause of Failure Examinations

TMI Mark-B12 Failure









2012 Cause of Failure Examinations

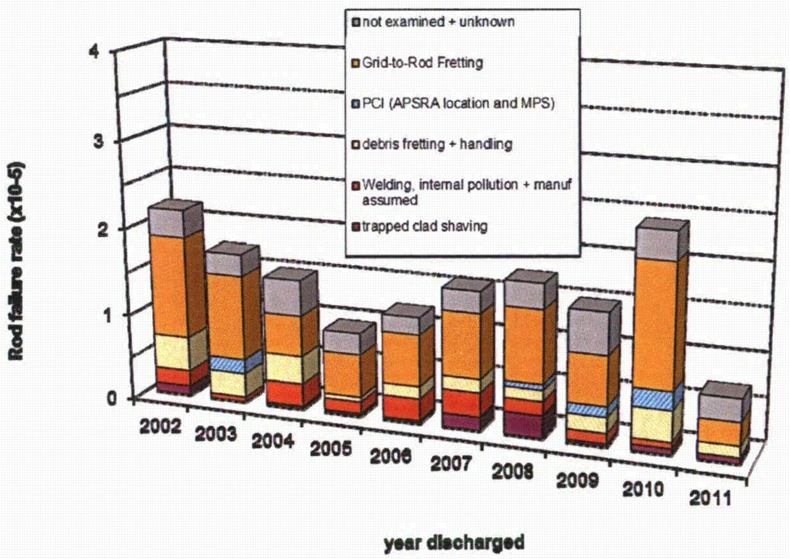
North Anna 1

- One baffle assembly identified by sipping, UT inconclusive, no other inspections performed
- One baffle assembly not sipped (equipment malfunction), AREVA UT identified 1 probable failed rod plus other suspects
- Past history of GTRF in Advanced Mark-BW design for fuel on the baffle
- Past history of debris failures
- Detailed inspections not performed

AREVA Worldwide Fuel Reliability Trends

PWR

- Improvement due to reduction in GTRF with HTP
- Decrease in TCS (AFA specific) failures with manfacturing improvements
- Recent increase in Debris/Handling failures (HTP in Germany)



Conclusions

100% Failure Free in US PWR Market

- HTP implementation has resulted in improvements in leaker-free cores and reduction in number of failed rods
- Sequoyah also planning transition to HTP to address fuel distortion; not experiencing GTRF failures in current design

Upcoming failed fuel inspections:

- TMI Mark-B-HTP (discharged 2011) – 2013

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PWR OE and Fuel Exams

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M5® Alloy on the PWR Market

(As of December 2011 – excluding assemblies manufactured under license in Korea and China)

[ ]

- **Two main designs**
  - AFA 3G™, HTP™
- **Introduced in 1997 and now delivered in 13 different countries**
- **Seven countries loaded more than 500 fuel assemblies with M5®**
  - France
  - US
  - Germany
  - China
  - Belgium
  - Sweden
  - South Africa

M5® is the reference alloy for AREVA PWR fuel

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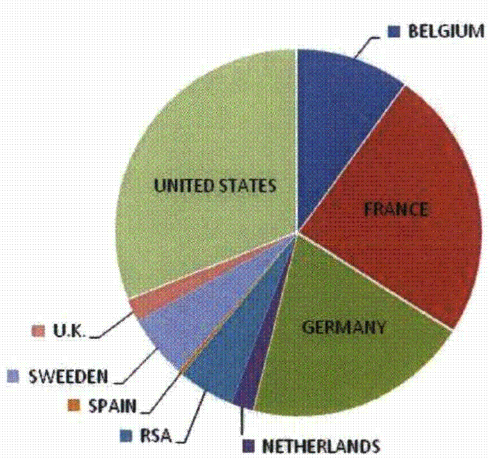
M5® Experience for Top 3 Markets

(As of December 2011 – excluding assemblies manufactured under license in Korea and China)

Fuel assemblies supplied per country



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M5® irradiation experience covers a wide range of demanding operating conditions

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PWR Exam Objectives

Purpose of the latest PIE data is to specifically support current and future designs

- CE-HTP (14x14, 15x15, 16x16, CE Reactor)
- Mark-B-HTP (15x15, B&W Reactor)
- W-HTP (15x15, 17x17, W Reactor)

Comprehensive plan developed to support product designs

PWR Test Assembly Programs

[ ]

Augmentation of database beyond current limit

PWR Test Assembly Programs (Continued)

[ ]

Well defined LTA program for advanced products

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PWR Test Assembly Programs (Continued)

[ ]

Provides data for benchmarking models

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CE Zr-4 Assembly Growth Summary

[ ]

Assembly growth continues on linear trend

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CE M5® Assembly Growth Summary

[ ]

Assembly growth consistent with historical trends

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Mark-B-HTP Assembly Growth Summary

[ ]

Assembly growth consistent with historical trends

Mark-BW Assembly Growth Summary

[

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]

Assembly growth consistent with historical trends

M5® Fuel Rod Growth Summary

[ ]

Assembly growth consistent with historical trends

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M5® Grid Growth Summary

[ ]

Grid growth consistent with historical trends

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Zircaloy-4 Grid Growth Summary

[ ]

Grid growth consistent with historical trends

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Fuel Assembly Bow Summary

[ ]

Fuel assembly distortion within previous experience

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Zr-4 Fuel Assembly Bow Summary

[ ]

Fuel assembly distortion within previous experience

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Holddown Spring Inspections

[ ]

No new spring failures observed since implementation of manufacturing process improvements

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PWR Crud Assessments in 2011

Background

- Heavy Crud deposits have been observed at CR3, D-B, and TMI-1
  - At D-B 2 rods were observed to have eddy current evidence of wall thinning (maximum of 23%)
- Ultrasonic Fuel Cleaning was employed at both CR3 and D-B to reduce the impact of the crud inventory on future cycles
- No unusual crud has been observed anywhere else
- RCA Completed in 2010 and corrective actions implemented

What have we learned?

- Visual inspections at TMI and Davis-Besse indicated crud condition improved as a result of corrective actions implemented

Future Plans

- Perform risk assessment using Level III and IV tools – Establish adequate benchmarks and establish CIPS and CILC criteria
- Continue to monitor crud condition with visual inspections
- Monitor Oconee transition to 24-month cycles for impact on crud

» *Goal is to maintain a crud safe environment*

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Summary

Elimination of spacer grid fretting failures

- All plants experiencing GTRF failures have transitioned to fretting-resistant HTP designs
- Sequoyah also plans to transition to HTP

The B&W plants have observed an improvement in fuel assembly distortion as they implemented HTP

All fuel assembly growth measurements remain within design limits

Grid width measurements collected in 2011 and 2012 was lower than historical data

Rod growth remains within the design limits

Inspections of hold-down springs have not identified any failures in springs manufactured under the new process

Crud is at low levels owing to management of coolant chemistry and detailed local temperature evaluations

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PWR Mechanical Faulted (Seismic and LOCA) Analysis Methodology

Brett T. Matthews
Supervisor, Fuel Mechanical Dynamic Analysis

AREVA

Agenda

- Background on faulted analysis methods
- Overview of AREVA's faulted methods
  - Focus on BAW-10133PA
- Goals of new accident analysis topical
- Plans for topical submittal and interim licensing approach
- Plan for advanced faulted methods

Background
General PWR Fuel Faulted Methods

- **PWR fuel faulted methods and NRC framework were developed in the 70's and have evolved since then:**
  - **NRC Framework established by Appendix A of Chapter 4.2 of SRP, NUREG/CR-1018, NUREG/CR-1019, and NUREG/CR-1020**
  - **Framework places a large emphasis on the grid integrity under lateral loading:**
    - Two fundamental safety requirements relating to grid integrity
      - Maintain acceptable rod pitch to ensure proper coolability,
      - Maintain the guide tubes array geometry to ensure control rod insertion.
  - **PWR assemblies are also evaluated for vertical loads generated by lift-off and subsequent set back**
  - **Mechanical models aim at calculating appropriate (accurate or conservative) impact loads (both horizontal and vertical)**
  - **Non-grid components are evaluated with combined horizontal and vertical loads to protect against structural failure (e.g. fragmentation of fuel rods)**

Spectrum of AREVA's Faulted Methods

Originating Company	Topical	Comments
B&W / Framatome	BAW-10133PA	• Original version written in late 1970s (B&W) • Amendment approved in 2000 (Framatome) • STARS / CASAC Code • Primary method applied for U.S. PWR fuel
Exxon Nuclear	XN-76-47PA	• Approved in 1981 • ANSYS Code
Exxon Nuclear	XN-NF-696PA	• Approved in 1985 • Referenced in EMF-92-116PA (approved in 1999) • NASTRAN Code
Siemens	EMF-93-177PA	• Approved in 1995 • KWUSTOSS code verified with NRC sample problem for PWR fuel

Going Forward: Optimize methodology based on combination of best practices

Building a New Methodology

- Best platform for future method progression is BAW-10133PA
  - Actively used
  - Forms the basis for the bulk of AREVA's PWR fuel in the U.S
  - Adequately tested across a broad array of fuel types
    - B&W 15x15, CE 14x14, CE 16x16, W 17x17
  - Platform for licensing fuel for new plants
    - U.S. EPR
    - Bellefonte
  - CASAC is an AREVA global standard in France and the U.S.
    - Benefits from global operating experience and global R&D efforts
  - Consistent testing specifications with AREVA methods in France

Overview of BAW-10133PA

- BAW-10133PA, Revision 1
  - Submitted to the NRC in May 1979
  - Approved in October 1982
- Addenda 1 and 2 to BAW-10133PA, Revision 1
  - Submitted to the NRC in September 1997 and May 1999, respectively
  - Approved in October 2000
  - Amended to upgrade methodology to update spacer grid dynamic model (CASAC introduced), hydrodynamic coupling model, and fuel assembly damping values
- BAW-10133PA has been successfully applied for the bulk of AREVAs PWR fuel supply in the U.S.:
  - All B&W 15x15 plants
  - Some W plants
  - Some CE plants

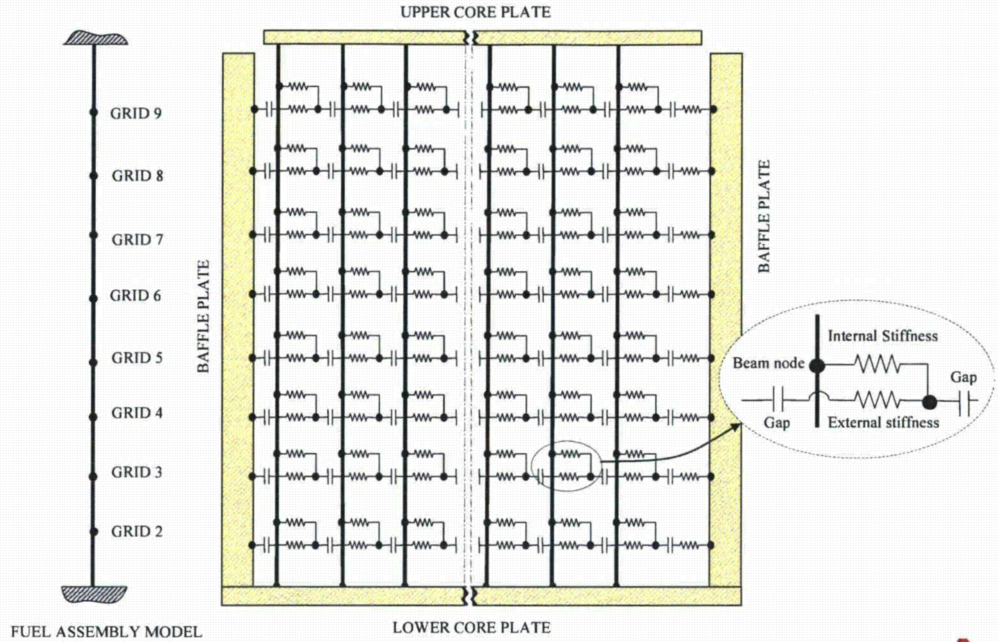
Overview of BAW-10133PA: Inputs

- BAW-10133PA relies on inputs resulting from structural analysis of the primary coolant system and reactor internals
- Time history motions of the core and baffle plates are provided for both seismic and LOCA events
  - Time history analysis is used to capture non-linear fuel assembly response
- LOCA evaluations also consider direct transient pressure loads

Overview of BAW-10133PA: Code

- CASAC is the computer code used for PWR fuel seismic and LOCA mechanical analyses:
  - Code used to support both French and U.S. PWR fuel faulted analyses
  - Dynamic analysis uses direct integration together with an explicit integration algorithm
  - CASAC row models implement a single beam representation of the PWR fuel assemblies

Overview of BAW-10133PA: Lateral Model



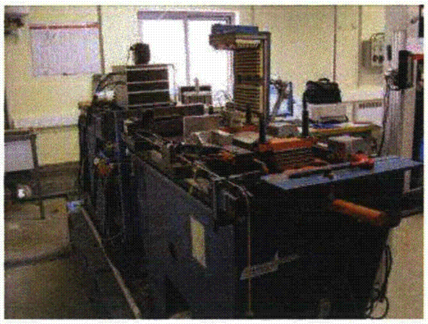
Overview of BAW-10133PA: Lateral Testing

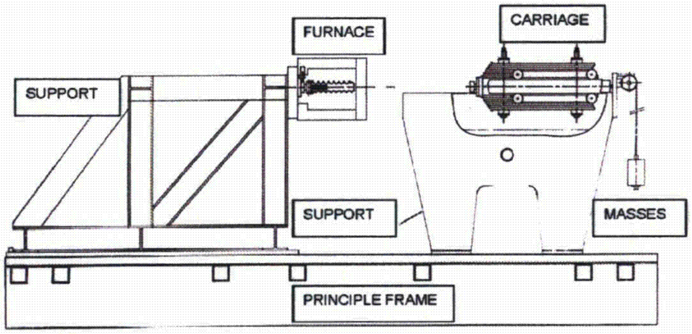
Fuel Assembly Tests Used in Developing Lateral Models

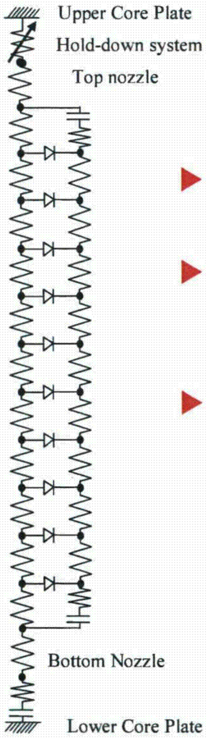
Test	Used in Developing Analytical Model
1. Pluck	- Obtain 1st mode natural frequency at target amplitude - Higher order target frequencies are obtained by the ratio of the higher order and the 1st frequencies obtained from the forced vibration tests.
2. Forced Vibration	- Obtain the natural frequencies of the first fuel assembly modes of vibration - Determine higher order mode frequencies scaling ratio.
3. Static Stiffness	Obtain fuel assembly static stiffness
4. Dynamic Grid Crush	See next slide. Obtain through-grid spacer grid stiffness, damping, and allowable impact load
5. Lateral Impact	Derive internal spacer grid stiffness

Overview of BAW-10133PA: Grid Testing

- Obtain spacer grid through-grid stiffness, damping, and allowable impact load
  - Grid to be impact tested is loaded with cladding segments in all the rod cells and equipped with GT segments welded to the tabs
  - Grid is secured against an anvil in the furnace
  - Impacts are generated by the carriage featuring the average span mass
  - Carriage is given increasing velocities until instability occurs
  - Force/deflection values are continuously recorded during impacts







Overview of BAW-10133PA: Vertical Model

- Accounts for potential lift-off and set-back during seismic and LOCA events
- Model benchmarked to axial static and drop tests performed with BOL and simulated EOL test bundles at RT and extrapolated to OT in water
- No vertical interaction between Fuel assemblies; hence a single one dimensional structural model is used

Overview of BAW-10133PA: Vertical Testing

Fuel Assembly Test Used in Developing Vertical Models

Fuel Assembly Vertical Tests	
Test	**Used in Developing Analytical Model for**
Axial Stiffness Tests and Fuel Assembly Drop Tests	- Obtaining the fuel assembly axial stiffness and drop impact loads for various drop heights. - Numerically simulate the drop in the test conditions (RT in air) with the analytical model. - Lower End Fitting stiffness and damping tuned to match the impact loads time history recorded during the test.

Overview of BAW-10133PA: Summary

- **Method defined in BAW-10133PA is**
  - . . . still applicable
  - . . . consistent with current industry technology
  - . . . consistent with NRC guidance
  - . . .requires too many RAIs
- **Method progression is desired**
  - . . . minimize need for RAIs
  - . . . leverage best practices
  - . . . better document critical thinking

Submittal of a new topical is planned

Goals of New Methods Topical (1/2)

- Generic applicability to PWR fuel designs
- Streamline and consolidate content from BAW-10133PA
  - Merge base document, Addenda 1 and 2, SERs, and RAI responses
  - Facilitate AREVA application and NRC reviews
  - Minimize likelihood of human performance errors
- Consolidate relevant information from previous Exxon and Siemens topicals
- Clarification on appropriate combination of horizontal and vertical loads
  - Highlight rules for application of Reg. Guide 1.92 versus plant FSARs

Goals of New Methods Topical (2/2)

- Clarification and refinement of mechanical testing protocols
- Clarification on definition of faulted stress allowables for non-grid components
- Clarification on treatment of fuel assembly dynamic characteristics (e.g. stiffness, frequency, damping, etc.) in the irradiated condition
- Definition of test protocol for simulated-irradiated spacer grids
  - In response to pending Information Notice from NRC
- Clarification on the definition of "P(crit)" for spacer grids

New topical will be an evolution from BAW-10133PA

Plans for Topical Submittal and Interim Licensing Approach

- Submittal of new topical by the end of 2013 to NRC for review and approval
- Until new topical is approved. . .
  - Continue to use approved topicals to license fuel transitions, design changes, and new plants
  - As necessary, clarifications or definitions beyond approved topicals (e.g. P(crit) definition, simulated-EOL grid testing, etc.) will be discussed within licensing amendment requests or technical reports

Plans for Advanced Faulted Methods

- Beyond the upcoming planned submittal, AREVA is investing to further advance faulted methods
  - Advanced Fuel Assembly Mechanical Models
    - Multi-beam (separate guide tube and fuel rod structures) modeling
    - Non-linear modeling
  - Fluid Structure Interaction and Damping
  - Spacer grid deformation modeling

Maintain engagement with the NRC on future efforts

BWR Fuel Performance Update

Norman L. Garner
Technical Sales Manager – BWR Fuel

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AREVA BWR Fuel Performance Topics

- **BWR PIE Update**
  - **Healthy Fuel Surveillance**
  - **Failed Fuel Examinations**
- **Elevated Corrosion Under Spacer Grids**
  - **Recent examinations at an EU BWR**

2011 BWR Surveillance PIE Campaigns

[ ]

BWR PIE Campaign Results

- In general, 2011 BWR PIE campaigns revealed healthy fuel
  - ATRIUM 10XM LTA performance within historical database
  - Zry-BWR fuel channel performance within historical database
  - No unusual rod or assembly length changes (growth) observed
  - Crud scrapes successful at Columbia, Browns Ferry, and Susquehanna
- Challenges for quality poolside liftoff data were encountered
  - Eddy current liftoff measurements are sensitive to coolant chemistry:
  - Requires compensation for ferromagnetism (permeability) typically associated with Zn precipitation in crud layers
  - Dual frequency compensation is not sufficient in high Zn-injection plants
  - Coolant conductivity (e.g. elevated Cu levels) may also skew liftoff data
  - Condition Report 2011-6428 issued to track resolution of liftoff capability
  - Alternate poolside measurement techniques are being sought

2012 BWR Surveillance PIE Campaigns

[ ]

US/Taiwan BWRs with AREVA Fuel - 10 year failed rod history

[ ]

Corrective actions to eliminate failed rods due to PCI/Missing Pellet Surface have been effective

Failed Fuel Rod Exam Update
(US/Taiwan BWR Plants with AREVA Fuel)

[ ]

Elevated Corrosion Under Spacer Grids

Recent examinations at an EU BWR

Elevated corrosion at an EU BWR - Background

[ ]

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Elevated corrosion at an EU BWR - Status and Observations

[ ]

Preponderance of data to date indicates this corrosion issue is unique to recent cycles at Plants C04 & C05

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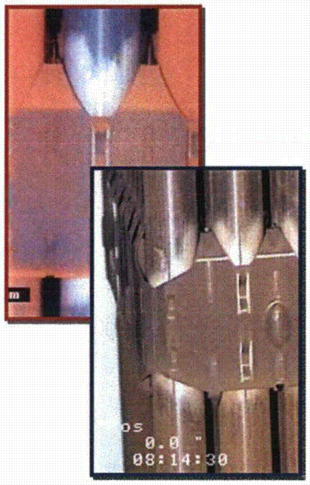
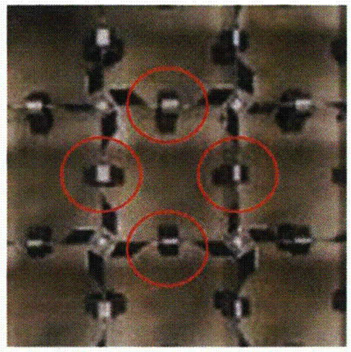
Shadow corrosion on AREVA BWR fuel rods under ULTRAFLOW™ spacer grids

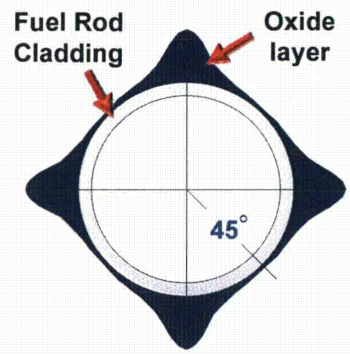
Shadowing can be observed to a distance of ~1/4" from Ni-alloy





Alloy-718 clip springs are used on both the ATRIUM 10 Zircaloy grids and the all alloy-718 ATRIUM 10XM/XP spacer grids

Typical 4-lobe corrosion pattern with peaks under spring clip contact lines



Peak thickness is ~the same for ATRIUM 10 and ATRIUM 10XM/XP

Note: Thickness of oxide exaggerated for illustration purposes

Typical shadow corrosion on fuel rods under all Ni-alloy grids

[ ]

Note: Thickness of oxide exaggerated for illustration purposes

Measurements of elevated corrosion under spacer grids at Plant C04

[ ]

Note: Thickness of oxide exaggerated for illustration purposes

Unique characteristics of water conditions at Plants C04/C05

[ ]

A distinct visual difference between C04/05 and most other BWRs has always been clear

Preliminary conclusions

[ ]

- There is no immediate concern for corrosion in other BWRs

Root cause developments will continue to be evaluated for any lessons for US BWR coolant chemistry guidance

Continuing investigation and response to elevated corrosion observations

[ ]

AREVA Burnup Extension Program

NRC Primer

June 14, 2012

AREVA

Agenda

- Program Objective
- Feasibility Review
- Licensing Approach
- Overview of AREVA High Burnup Data
- Q&A

Program Objective and Context

- **AREVA's objective is to extend burnup beyond 62GWd/mtU per EPRI guideline (EPRI-TR-1013278)**
  - The industry has significantly reduced fuel failure rates since 2005
  - Utilities are interested in operational flexibility provided by a higher fuel rod burnup limit
  - Global operating experience and industry data supports performance up to 75GWd/mtU

Feasibility Review

- **AREVA's preliminary feasibility review of licensed burnup extension to date has considered:**
  - **Licensing**
    - EPRI Industry Guideline
    - Topical Report review
    - Applicability of licensed codes/methods
  - **Regulatory Environment**
    - Data Requirements
    - Review Readiness
    - External Factors (TCD, Fukushima, SMR, etc.)
  - **AREVA's High Burnup Operating Experience**
    - US High Burnup Program (North Anna PIE)
    - Global Database
- **No significant technical barriers to rod BU > 62GWd/mtU**
  - **Open communication with NRC and Utilities on a preferred Licensing Approach is vital to program success**

Licensing Approach

- **Currently available data may not fulfill the compliance requirements up to specified upper bound of 75 or cover all fuel types**
  - AREVA is reviewing data to establish applicability limits of US and global high burnup data
  - AREVA is exploring ways of obtaining additional compliance data from US fuel to increase density of data and validate applicability of global OE
- **AREVA is considering a phased approach (e.g. 65->70->75)**
  - Establishes data requirements for vendor compliance per EPRI guideline at various BU levels for a given fuel design family (e.g. 15x15 HTP)
  - Allows NRC to begin review in parallel with data collection at higher BU and/or lead programs for other fuel types
  - Eliminates need for separate Licensing Topical Report for each design or BU increment

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Brief Overview of Global High Burnup Database

- **Fuel performance at BU > 62 Gwd/mtU has been demonstrated worldwide**
  - **E.g. German M5 fuel assembly burnup limit is 70 Gwd/mtU**
- **Includes extensive AREVA experience with M5 clad fuel**
  - **Cladding Corrosion (oxide)**
    - Data up to 80 GWd/mtU
  - **Cladding Hydriding**
    - Strong linear trend in data out to ~76 GWd/mtu
  - **Rod Growth**
    - Global data expressed vs. fast fluence E>1MeV, data out to ~17E21 n/cm^2
  - **Fuel Assembly growth**
    - Strong dependence on fuel assembly type, PIE ongoing at higher BU
  - **Guide tube and grid corrosion and hydriding performance**
    - Has been demonstrated to be acceptable up to 68 GWd/mtU (FA)
- **Large GALILEO fuel rod database supports fuel rod performance out to 75GWd/mtU (65 for Gad, MOX)**

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US High Burnup Data
North Anna M5 LTAs

- **Hot cell exam of a fuel rod at 71.2 Gwd/mtU (FA BU of 67.6 Gwd/mtU)**
  - **Non Destructive Examinations**
    - Visual Appearance and Length Measurement
    - Rod Diameter
    - Neutron Radiography and Gamma Scan - Pellet-Pellet Interface Gaps
    - Eddy Current Oxide
  - **Destructive Examinations**
    - Isotopic and Burnup Analyses
    - Fuel Rod Pressure and Fission Gas Release
    - Fuel Ceramography and Radial Isotopic Profile
    - Corrosion and Hydriding
    - Fuel Perimeter Zone
  - **Mechanical Properties**
    - Uniaxial Longitudinal or Axial (AX and SAX) Direction
    - Uniaxial Transverse or Hoop (UNI) Direction
    - Biaxial or Plain Strain (PS) Direction
- **Guide tubes sent to hot cell as well**

Questions or Comments?

LOCA 50.46 Process

Graydon Uyeda
Engineering & Projects, Nuclear Analysis
Manager, LOCA, ECCS & BWR Analysis

Gayle Elliott
Manager, Product Licensing

AREVA

50.46 Reporting Engineering Process

- **Issue identified (entered into WebCAP)**
  - **Issue screened across organization for general applicability of error**
- **Extent of applicability evaluated within LOCA group**
  - **All plants (operating and planned)**
- **Decision made as to how to determine error estimate**
  - **Engineering judgment**
  - **Sensitivity calculations**
    - General plant design
      - W3, W4, EPR
      - CE
      - B&W (raised-, lowered-loop)
    - Plant-specific

50.46 Reporting
Engineering Process

- Error assessment provided to applicable Fuel and EPR Project Managers
  - Penalty, credit, no impact
- Calculation file (Analysis of Record) updated
  - Document amendment released to track 50.46 assessments prior to reanalysis
- Project Managers provide Customer notification of errors and technical summary

Annual 50.46 Reporting

- Annual 50.46 Reports Submitted to NRC
  - Operating Plants
    - Summary of ECCS evaluation model and application changes/errors implemented for customers whose plants were licensed under 10 CFR 50
    - Informational submittal
  - U.S. EPR
    - Summary of ECCS evaluation model and application changes/errors implemented for the U.S. EPR Standard Design
    - Regulatory submittal

PWR Fuel Assembly Distortion

Tom Gardner
Supervisor, Fuel Assembly Structural Design

AREVA

Agenda

- Background on Fuel Assembly Distortion
- Performance Improvements Observed
- Plant Status

Fuel Assembly Distortion

- **Impact of Fuel Assembly Distortion**
  - Increased Control Rod Drag Forces / Drop Times
  - Fuel Assembly Handling Damage
  - Difficult Core Loading
- **Distortion Performance**
  - Design Specific
  - Linked to Lateral Stiffness

Progressive Improvement

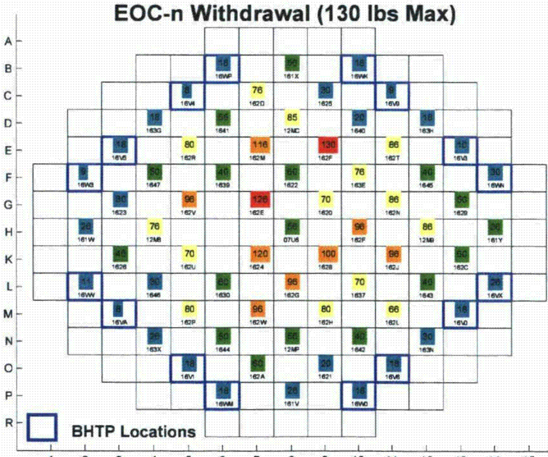
- **Fuel Design Changes**
  - Lateral Stiffness Increase (Welded Structure)
  - Reduced Axial Hold-down Forces
  - Standardized HTP Fuel Assembly Design
- **Core Design Management**

Design Changes For B&W Fuel

- **Previous Design - Mark-B Fuel Assembly**
  - **Floating Structure (non-welded)**
  - **Mark-BZ Grids**
- **New Design - Mark-B-HTP Fuel Assembly**
  - **Welded Structure – Increased Lateral Stiffness**
  - **HTP Grids**
  - **Reduced Hold-down Forces Through-out Life**

B&W Plant Control Rod Drag

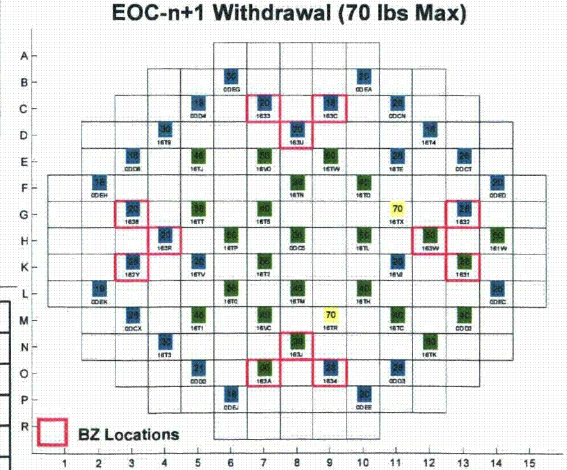
EOC-n Withdrawal (130 lbs Max)



Color	Drag Load (lbf)
light blue	< 30
dark green	30 to 60
yellow	60 to 90
orange	90 to 120
red	> 120

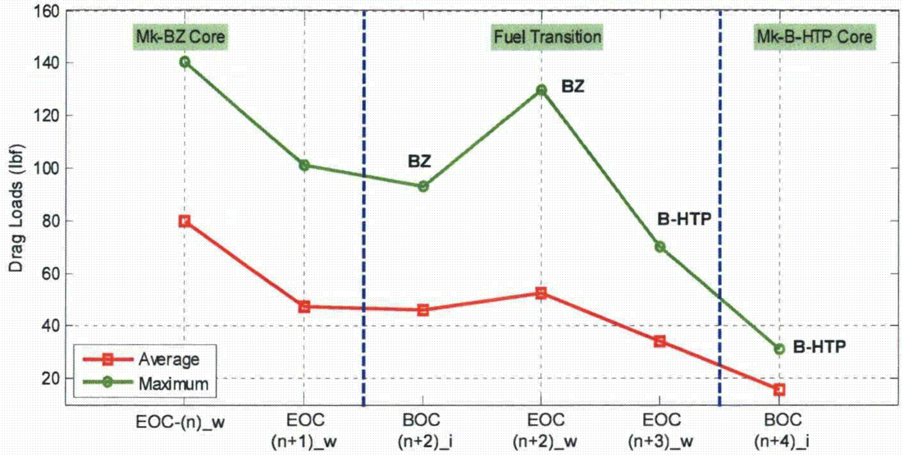
- **Significant reduction in control rod drag observed with Mark-B-HTP transition**

EOC-n+1 Withdrawal (70 lbs Max)



Control Rod Drag
Average and Maximum

- Significant reduction in control rod drag observed with Mark-B-HTP transition to full core
  - Data obtained during component shuffles by utility staff



B&W Plants

▶HTP Implementation Status

- All 7 Plants Adopted Mark-B-HTP
- 5 Plants Fully Transitioned (First Batch in 2003)
- 2 Plants Are In Transition

▶Results

- Improvement in Control Rod Drag and Bow
- Reduced Occurrence of Fuel Assembly Handling Damage
- Improvement in Core Loading Time
- Informal Feedback – "Core is Straighter Than Ever Before"

Westinghouse Plants

▶HTP Implementation Status

- All 4 Plants Adopted HTP
- 2 Plants Fully Transitioned (since 1990's)
- 2 Plants Beginning Transition in 2012-2013

▶Results

- Operational Experience Indicative of Minimal Distortion
- Expect Continued Good Performance of HTP Design in all Plants

CE Plants

▶HTP Implementation Status

- All 6 Plants Adopted HTP
- 4 Plants Fully Transitioned (early 2000's)
- 2 Plants Are In Transition

▶Results

- Operational Experience Indicative of Minimal Distortion
- Expect Continued Good Performance of HTP Design in all Plants