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AREVA's Enhanced Accident Tolerant Fuel (EATF) Program

AREVA/NRC Meeting
Rockville
March 2017

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Introduction

Jerry Holm
AREVA Licensing Engineer

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Agenda

- Introduction
  - Program Organization and Background
  - Program Goals
  - AREVA Approach
- Near Term Focus
  - Chromia Doped Fuel
  - Chromium Coated Cladding
  - Licensing Approach
- Long Term Focus
  - Silicon Carbide Cladding
- Summary

Objectives

- Introduce AREVA's EATF concepts to NRC
- Introduce program goals
- Present AREVA's current status and future activities
- Obtain NRC feedback

Introduction
Program Organization and Background

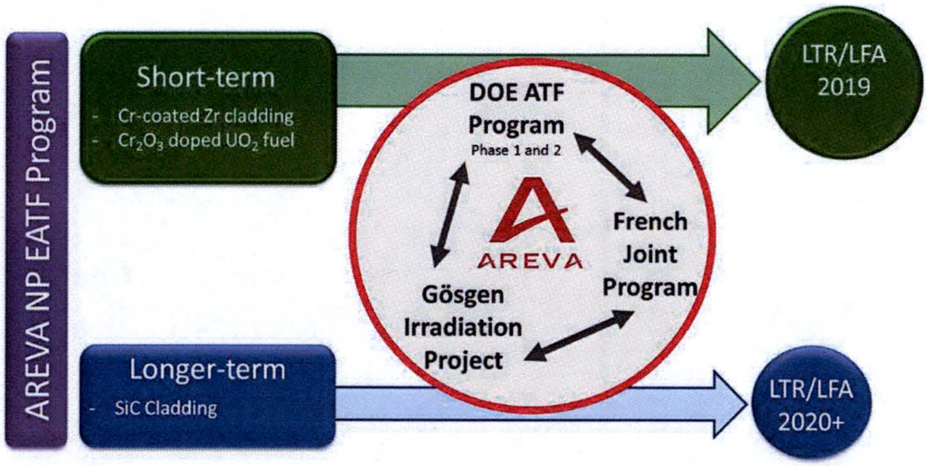
- Department of Energy funded program
- Multiple vendors involved
  - Each with individual design concepts
- Support from others
  - U.S. National Laboratories
  - European facilities
  - Operating plant licensees
- Congress authorized the program in 2012

Introduction
Program Goals

- **Enhanced Accident Tolerant Fuel**
  - Can tolerate loss of active cooling in the reactor core for a considerable longer period of time than conventional fuel
  - Maintains or improves fuel performance during normal operations, operational transients, design basis events and beyond design basis events
- **Congressional mandate**
  - Initiate aggressive research and development program for enhanced accident tolerant LWR fuels with the goal of inserting lead fuel rods (LFRs) or lead fuel assemblies (LFAs) into a commercial LWR by the end of FY 2022
- **Industry goal**
  - Lead fuel rods insertion by 2019 and batch implementation by 2023

Introduction
AREVA Role

- ▶ Design, test, and license EATF concepts
- ▶ Support insertion of lead test assemblies or lead test rods
- ▶ Provide reloads of EATF
- ▶ Near term concepts
  - ◆ Chromia doped fuel
  - ◆ Chromium coated cladding
- ▶ Long term concept
  - ◆ Silicon Carbide (SiC) Cladding



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EATF Concepts

Jacqueline Stevens
Engineering Supervisor

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EATF Program Goal - DOE

Improved Clad Reaction Kinetics with Steam

- Heat of oxidation
- Oxidation rate
- Hydrogen bubble and explosion
- Hydrogen embrittlement of the clad

Improved Cladding Properties

- Clad fracture
- Geometric stability
- Thermal shock resistance
- Melting of the cladding

Improved Fuel Properties

- Lower operating temperatures
- Clad internal oxidation
- Fuel relocation/dispersion
- Fuel melting

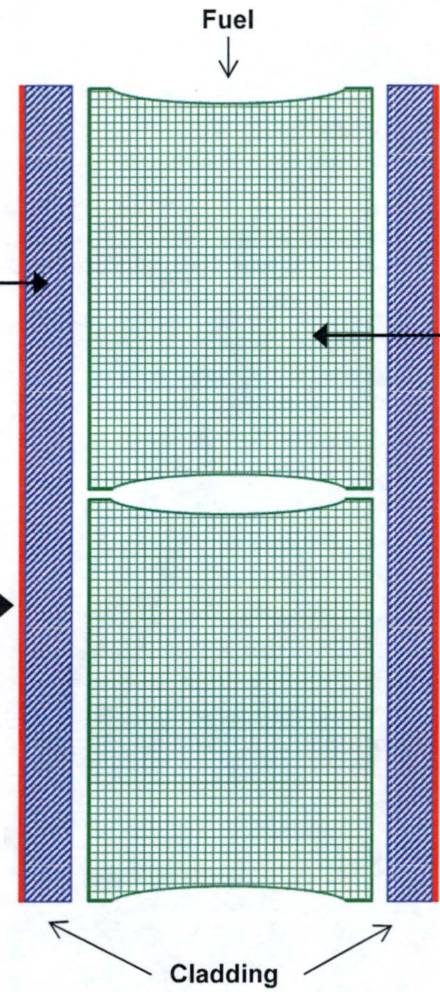
Enhanced Retention of Fission Products

- Gaseous fission products
- Solid/liquid fission products

NEAR TERM SOLUTION

Chromia-doped pellets
Chromium-coated cladding

Near Term Solution
AREVA Concept



Base M5® cladding

- No change to properties or dimensions

Cr-coating

- 10-20 µm
- Insignificant impact to base M5® properties or performance
- Improved oxidation resistance
- Improved wear resistance

Chromia-doped UO_2 Pellets

- BWR Licensing: Under NRC review
- Improved FGR
- Improved fragmentation behavior
- Improved PCI performance

** Figure not to scale*

Near Term Solution
Cr-Coated Cladding / Cr_2O_3-Doped Fuel

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CHROMIA-DOPED PELLETS

Overview
Chromia (Cr_2O_3)-Doped Pellets

Cr_2O_3-doping UO_2 improves:

- Fission gas retention
- Pellet-clad interaction resistance

AREVA Optimized Cr_2O_3-Doped Fuel

- Optimum addition of [ ] Cr_2O_3
- [ ]
- [ ]
- High fuel viscoplasticity
- Enhanced wash-out behavior
- Reduced susceptibility to chipping

Benefits include:

- Improved reliability and robustness
- Reduced pin pressure
- Greater operating flexibility

Initial Development
Conclusions of Basic Studies

- **Fuel pellets with large grain microstructure and viscoplastic behavior improve fuel performance**

[ ]

Cr_2O_3

- Achieves the targeted fuel microstructural evolutions
- No degradation of the fuel fundamental properties (e.g. thermal behavior, neutronic absorption)
- Compatible with current UO_2 manufacturing conditions
- No environmental consequences
- Reprocessing ability

Maximum improvement with [ ]

» **Optimizes pellet microstructure & performance**

Fuel Behavior Operating Experience

- **Irradiation in both PWR and BWR Reactors allows investigation into a wide range of operating conditions to high burnup:**
  - **From high duty operation to moderate or low power operation followed by ramp testing at various stages of burn-up and initial conditioning states**

[ ] [ ]

Enhanced product performance based on PWR and BWR program results

Fuel Behavior, Operating Conditions Fission Gas Release(1/3)

- Cr_2O_3-doped UO_2 fuel exhibits reduced fission gas release in various operating modes:

[ ]

Greatest benefits are achieved under demanding high power conditions

Fuel Behavior, Operating Conditions
Fission Gas Release(2/3)

- Reduced FGR during power transients

[ ]

Post-Experiment Examinations Reveal:

- **Extensive Accumulation of Gaseous Precipitation in the Cr_2O_3-Doped Large Grains**
- **Low Accumulation of Gases on the Grain Boundaries**

Fuel Behavior, Operating Conditions Fission Gas Release(3/3)

- Favorable change in the transient FGR kinetics with Cr_2O_3-doped UO_2 fuel

[ ]

Cr_2O_3-doped UO_2 fuel is beneficial in reducing the source term

Fuel Behavior, Operating Conditions Thermal Response

- Cr_2O_3 addition [ ]
  - Negligible change in fuel melting point
  - No changes in specific heat
- Fuel temperature measurements show:
  - No significant difference between UO_2 and Cr_2O_3-Doped fuels
  - Negligible on thermal conductivity degradation at high burnup

[ ]

Cr_2O_3-doped UO_2 fuel thermal behavior is similar to UO_2 fuel

Fuel Behavior, Operating Conditions
Pellet-Clad Interaction Resistance

- **Ramp test results confirm significant gains in power ramp capability**

[ ]

- **Investigations revealed the beneficial effects of Cr_2O_3 addition:**
  - Pellet yield under stress over a large volume reduces cladding hoop stress
  - Multiple fine radial cracks at pellet periphery distribute load to minimize stress concentrations on the cladding

Clad stress is reduced in power transient conditions

Fuel Behavior, Operating Conditions
Pellet-Clad Interaction Resistance

[redacted]

Fuel Behavior, Operating Conditions
Washout Behavior

- **Autoclave testing used to simulate ingress of coolant onto fuel pellets operating at representative LWR conditions**

[ ]

Enhanced wash-out behavior lowers activity release in defective rods

Cr_2O_3-Doped Pellets Accident Conditions

- In the context of EATF, Cr_2O_3-doped fuel expected to show improved performance

Limit the consequences of an accident

- Reduce the rod internal pressure
- Reduce FGR during accidents

→ *Limit the balloon size and the risk of burst*

- Reduce the fine fragmentation of the fuel

→ *Limit the risk of fuel dispersal*

[ ]

» **Improved performance over standard UO_2 pellets**

Performance in Accident Conditions Testing Plan

- Analytical experiments to study and model the behavior of the doped fuel under accident conditions

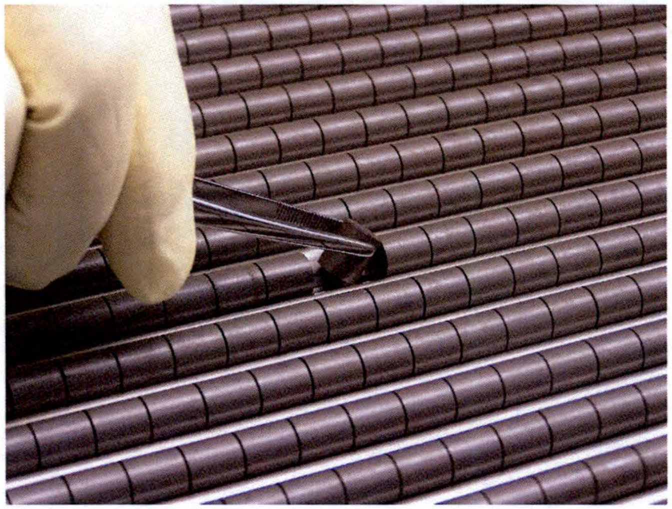
[ ]

Cr_2O_3-Doped Pellets Industrialization Status

- Fully industrialized in Europe

  (completed in 2015)

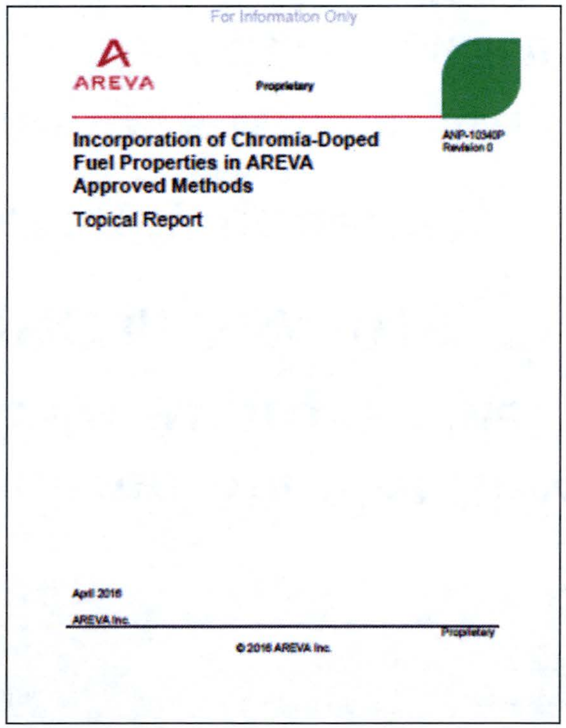
[ ]



AREVA Fuel Rod Mechanical Analysis

Cr_2O_3-Doped fuel performance will be included in both codes

- BWR
  - RODEX4


For Information Only

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Proprietary

Incorporation of Chromia-Doped Fuel Properties in AREVA Approved Methods

ANP-10340P
Revision 0

Topical Report

April 2016

AREVA Inc.

Proprietary

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- PWR
  - GALILEO

BWR Licensing

BAW-10340P, "Incorporation of Chromia-Doped Fuel Properties in AREVA Approved Methods"

- **Submitted to NRC in Apr-2016**
- **NRC review currently underway**
- **Some model changes were needed**
  - **Fuel Rod Growth – low densification and earlier clad contact impact the empirical rod growth correlation (not part of RODEX4 code)**
  - **Thermal Conductivity – RODEX4 model change affects margin to fuel melt**
  - **Gaseous Swelling - RODEX4 model change affects margin to cladding strain limits**

PWR Licensing

- **BAW-10340P, Supplement 1 for PWR with GALILEO**
  - [ ]
  - GALILEO available as part of AREVA Advanced Methods AREA and ARITA
  - Potential GALILEO Model changes: Thermal Conductivity, Gaseous Swelling, and FGR
- **RLBLOCA and SBLOCA – plan is to incorporate GALILEO**
  - Initial step will be an evaluation for best approach
  - RLBLOCA Rev.3 – Currently COPERNIC for initialization
  - SBLOCA – Currently RODEX2 for initialization

CHROMIUM COATED CLADDINGS

Cr-Coated Cladding Definition

PVD process compatible with industrial scale fabrication

Cr-Coated Cladding Incremental Change

- Similar mechanical properties as Uncoated M5®
- No fuel assembly design changes required
- Tensile and radial creep tests at room temperature (RT) and 400°C show no change in mechanical behavior
- Improved wear resistance

Simplified licensing

Cr-Coated Cladding Manufacturing

[ ]

Cr-Coated Cladding Performance in Normal Operation(1/3)

[ ]

- Negligible weight gain for Cr-coated samples
- No delamination observed on sample surface
- No dissolution of Cr in the water

→ Excellent corrosion behavior in normal conditions

Cr-Coated Cladding Performance in Normal Operation(2/3)

» **Cr-coating is protective of underlying cladding**

Cr-Coated Cladding Performance in Normal Operation(3/3)

[ ]

» Improved cladding fretting performance and wear resistance

[ ]

Cr-Coated Cladding Accident Performance (1/2)

Improved high temperature steam oxidation behavior

Cr-Coated Cladding Accident Performance(2/2)

Improved clad swelling and rupture performance

Cr-Coated Cladding USW Process

[ ]

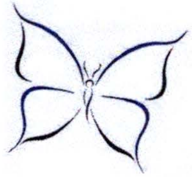
Cr-coating is compatible with current fuel rod manufacturing process

Cr-Coated Cladding Ongoing Irradiations

- CEA reactor – Irradiated to [ ]
  - Cr-coated specimens showed excellent adherence to underlying substrate
  - No Cr diffusion into the substrate and no modification of Cr-Zr interface observed

[ ]

Cr-Coating performs as-expected under irradiation: No diffusion or delamination



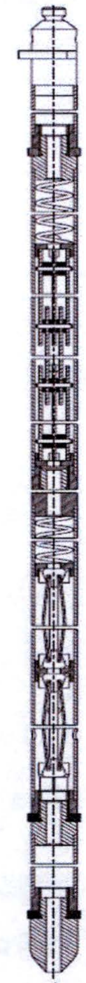
Cr-Coated Cladding IMAGO - Overview

▶ Objectives:

- **Acquire in-reactor material data under representative PWR conditions:**
  - Corrosion kinetics
  - Evolution of microstructure, mechanical, or physical properties under irradiation
- **Obtain in-reactor data for the justification of future fuel rod/assembly irradiations**

▶ Description:

- **EATF samples within Material Test Rods (MTRs) inserted within guide tubes of a fuel assembly:**
  - Cr-coated zirconium alloys
  - SiC composite samples



» **First irradiation cycle began [ ]**

Cr-Coated Cladding IMAGO – Material Description

[ ]

Cr-Coated Cladding
IMAGO – PIE

[ ]

» **Large scope of PIEs through on-site inspections and hot cell examinations at PSI and CEA**

PERFORMANCE ASSESSMENT

Cr-Coated Cladding Codes and Methods

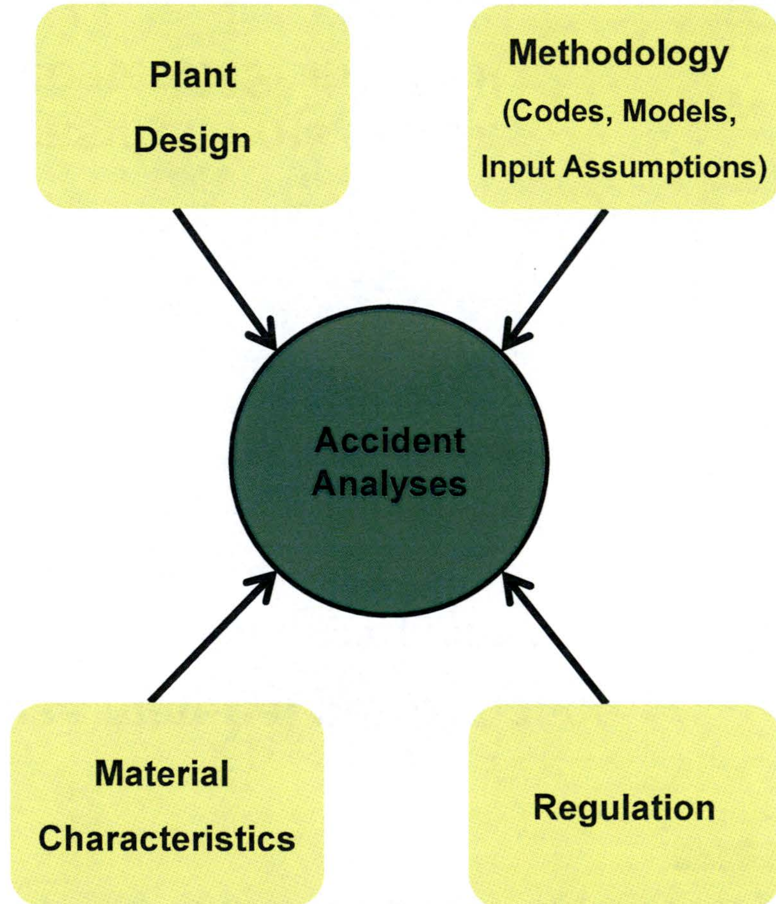
- Thin coating does not change base material performance
  - No modification needed to M5® mechanical or physical properties.
- Expected modeling changes due to coating

[ ]

» Irradiation & hot cell measurements will be performed to verify Cr-coated M5® material properties

Accident Analyses for EATF Concept

- Experiments demonstrate significant improvements in material characteristics which are relevant to safety
  - Pre-transient conditions of the fuel and cladding
  - Transient performance
- Accident analyses demonstrate the overall plant safety



Accident Analyses for EATF Concept

- Primary EATF objective is increased safety in accidents
- Accident analyses translate the experimental results into quantifiable accident performance values
- "Safety improvements" are specific to:
  - Accident and scenario
  - Figure of merit
  - Plant design
- First analyses and assessments provide assurance of no detrimental to current fuel design
  - Limited code modification needed
- Later analyses quantify the safety improvements gained by the EATF concept

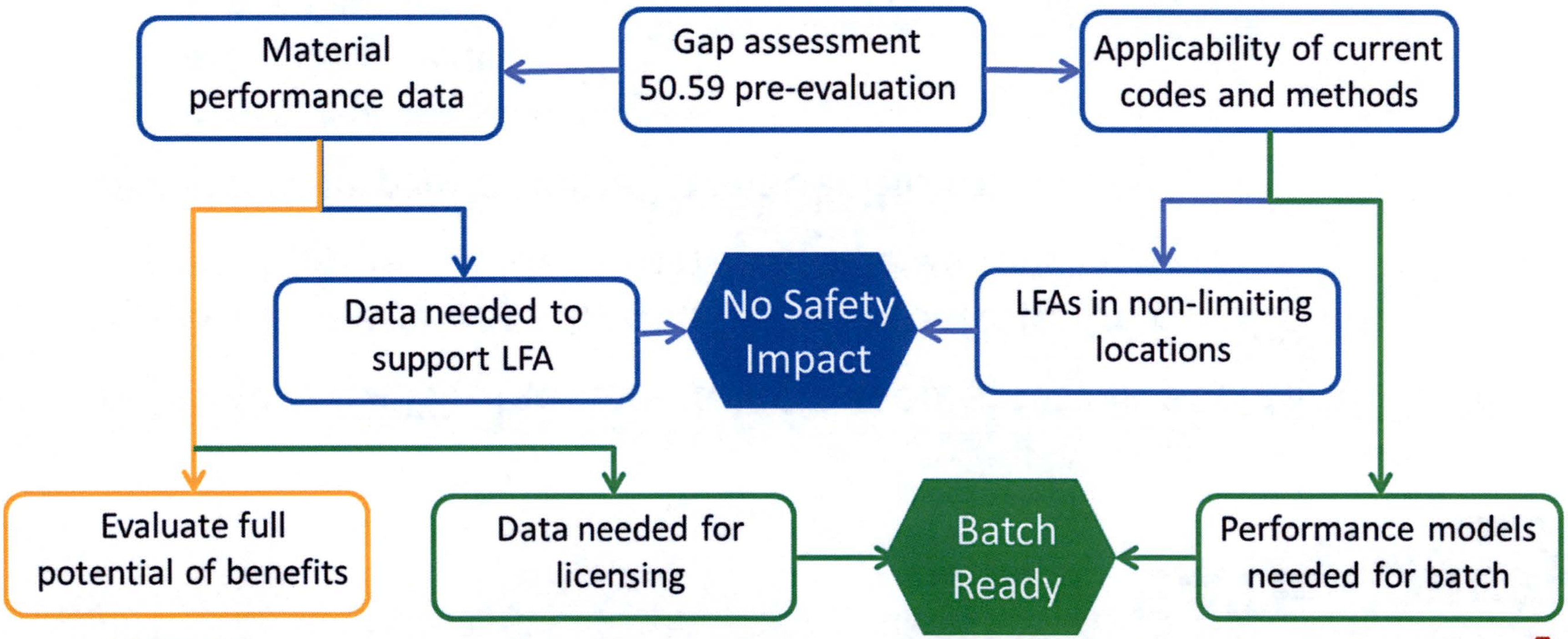
Chromia-Doped Pellets / Cr-Coated Clad Schedule & Feasibility

AREVA EATF Project Goals:

- Demonstrate the performance expectations of the solution

[ ]

- Evaluate full potential of achievable benefits of the concept



Chromia-Doped Pellets / Cr-Coated Clad
Out of Pile Testing

Chromia-Doped Pellets / Cr-Coated Clad Irradiation Program

Investigate Accident Response

Data for Licensing

Performance Confirmation

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Near Term Concept Licensing Approach

Jerry Holm

AREVA Licensing Engineer

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Near Term Solution Topical Reports

BWR contracts ATRIUM™11 with AURORA-B

- ANP-10300 AURORA-B Transient and Accident Scenarios
- BAW-10247 RODEX4 for Recrystallized Zircaloy-2 Cladding
- ANP-10332 AURORA-B LOCA
- ANP-10333 AURORA-B CRDA
- ANP-10335 ACE/ATRIUM™ 11 Critical Power Correlation
- ANP-10340 Chromia-Doped Fuel
- BAW-10247 RODEX-4 Suppl 2, BWR Mechanical Methods
- ANP-103XX RAMONA-5 ATWSI Analysis Methodology
- Best Estimate Long term Stability Solution for BWRs

PWR contracts and VQPs including GAIA

- ANP-10337 PWR Fuel Assembly Structural Response to Externally Applied Dynamic Excitations
- ANP-10334 Q-12 Structural Material
- ANP-10297 Suppl 1 ARCADIA Reactor Analysis System
- ANP-10338 AREA-ARCADIA Rod Ejection Accident
- ANP-10341 ORFEO-GAIA and ORFEO-NMGRID CHF Correlations
- ANP-10342 GAIA Mechanical Design

Advanced C&M, Product Improvements or Regulatory Compliance

- ANP-10336 Z4B Fuel Channel Irradiation Program
- BAW-10192 Suppl BWNT LOCA-Evaluation Model for Once Through Steam Generator Plants
- BAW-10227, M5 Supplement
- ANP-10323 GALILEO
- ANP-10323 GALILEO Update
- BAW-2241 Revision New Fluence Methodology
- BAW-10227, Rev Address Cr-coated M5® cladding
- ANP-10326 Environmentally Assisted Fatigue
- BAW-10179, Rev 9 Safety Criteria and Methodology for Acceptable Cycle Reload Analyses
- ANP-10337 Addendum PWR Fuel Assembly Structural Response ...
- ANP-10339 ARITA Methodology
- ANP-10340 Chromia-Doped Fuel Supplement 1, PWRS
- EMF-93-177, Rev 1, Suppl 2, Z4B Fuel Channels

white boxes – Pending submittal

Colored boxes – Submitted to NRC

- **Priorities discussed during management review meetings remain unchanged.**

Near Term Focus
Licensing Approach

- **Near term designs**
  - **Chromia-doped fuel**
  - **Chromium coated M5® cladding**
- **Lead fuel assemblies**
  - **[ ]**
  - **Target [ ]**
  - **Exemption request**
    - M5®
    - Chromium coating on cladding
  - **Implement under 50.59**
- **Topical Reports to support batch implementation**
  - **Target [ ]**
- **Batch Implementation**
  - **Target [ ]**
  - **[ ]**

Topical Reports

- **BWR focused Chromia doped fuel topical report**
  - **BAW-10340P**
  - **Submitted April 29, 2016**
  - **Approval requested [ ]**
- **Topical Report Submittals [ ]**
  - **PWR Chromia doped fuel** [ ]
    - RLBLOCA (GALILEO)
    - SBLOCA (GALILEO)
  - **Chromium coated cladding** [ ]

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Long Term Solution

Silicon Carbide Cladding

Jacqueline Stevens
Engineering Supervisor

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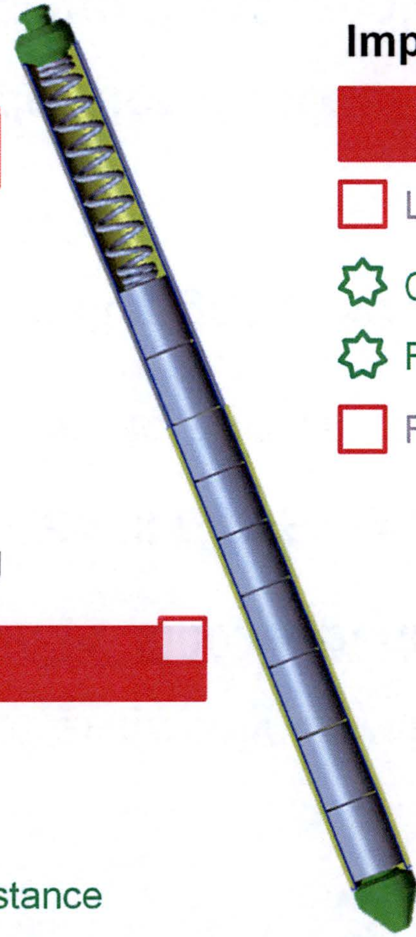
Why Silicon Carbide?

Benefits over Zirconium based cladding

- Smaller neutron absorption cross-section
- Resistance to high temperature oxidation
- Can withstand high burnups and high operation temperatures
- Low activation
- Exceptional irradiation resistance
- Stable in nuclear waste

Long Term Solution
SiC Cladding / Cr_2O_3-Doped Fuel



Improved Clad Reaction Kinetics with Steam

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Improved Cladding Properties

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Enhanced Retention of Fission Products

- Gaseous fission products
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Silicon Carbide Development History

- Multilayer SiC concept originally developed for Gen IV reactors (CEA program initiated in 2000, experimental work in 2002)
- Transitioned to LWR Gen III EATF cladding concept under AREVA-CEA-EDF Tri-Partite agreement
- Significant technical challenges associated with realizing the projected benefits of SiC
- AREVA's focus is to develop a robust SiC concept by systematically addressing the technological gaps

Silicon Carbide Cladding Mechanical Properties(1/2)

[redacted]

▶ **Mechanical properties**

- Different braided preforms have been tested
- Filament winding – minimal roughness of the inner surface

▶ **3D braiding – Interlock**

- Thermal conductivity
- Resistance to interlaminar shear

[ ]

» Mechanical properties can be tailored by appropriate braiding

Silicon Carbide Cladding Mechanical Properties (2/2)

[redacted]

- **Surface treatment**
  - Significant reduction in sample roughness
  - No effect on mechanical properties
- **After long-term exposure under representative LWR Conditions**
  - No degradation in mechanical properties

» **Excellent retention of the mechanical behavior [ ] exposure to LWR coolant**

[ ]

Silicon Carbide Cladding Accident Performance

[

]

- Following exposure to [ ], slight weight gain
- Strength maintained at high temperatures, high T_M
- Reduced cladding deformation
- Reduced hydrogen and heat generation

Silicon Carbide Cladding Key Challenges(1/3)

[redacted]

[ ]

[ ]

Innovative solutions are being examined

Silicon Carbide Cladding
Key Challenges (2/3)

[redacted]

Silicon Carbide Cladding Key Challenges (3/3)

SiC concepts must be proven through neutron irradiation studies

Silicon Carbide Development Plan

[ ]

AREVA EATF Program Summary

- **Near-term solution – Cr-coated M5® with Cr_2O_3-doped pellets**
  - Improved performance in normal operation
  - Improved performance in accident conditions
  - Simplified licensing
- **Revolutionary solution – SiC cladding**
  - Significant gains in severe accident scenarios
  - Higher risk, technical challenges remain
  - Require significant changes in regulatory framework