GALILEO Fuel Rod Performance Code and Methodology for BWRs and PWRs

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Agenda

- Objectives
- Introduction
- GALILEO - Selected Topics
  - Thermal Conductivity Degradation (TCD) with Burnup
  - Fission Gas Release (FGR)
  - Gaseous Swelling and Advanced Mechanical Models
  - Crud, Corrosion and Hydrogen Pickup
- GALILEO MOX
  - Fuel Modeling
  - Non-Proliferation (NP) vs. Reactor Grade (RG)
  - Applicability to Dry Conversion Process
  - Impact on Margin
- Summary
- Next steps

2014 June 24th - GALILEO post-submittal meeting
Meeting Objectives

- Present a summary of the GALILEO topical report
- Present in depth a sub-set of key topics
  - Models applicable to both $\text{UO}_2$ (with and without gadolinium) and MOX
  - MOX key models and considerations
- Discuss the NRC review and approval process for the GALILEO topical report
  - Goal is an SER by December 31, 2015
GALILEO Topical Report

Objectives

▸ Produce state-of-the-art design code and methods to license AREVA fuel
  ◆ Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR)
  ◆ All AREVA cladding and fuel types
  ◆ Address all observed phenomena, including fuel thermal conductivity reduction with burnup
  ◆ Code backed by extensive calibration and validation database
  ◆ Statistical methodology

▸ Replace legacy codes RODEX2/2A, TACO3, GDTACO
  ◆ Incorporate modern fuel thermal conductivity models
  ◆ Add hydrogen models to address future NRC changes to loss of coolant accident (LOCA) and control rod ejection criteria

▸ Provide a means to transition to a single fuel performance code
Requirements and Capabilities

Criteria to be evaluated (NUREG-0800, Section 4.2)

- Fuel temperature for anticipated operational occurrences (AOOs)
- Cladding transient strain (AOOs)
- Rod internal pressure
- Cladding corrosion
- Cladding hydrogen uptake
- Cladding collapse
- Cladding fatigue

LOCA criteria

- GALILEO will be used to generate LOCA initialization data
- Implementation in LOCA methodology will be addressed in separate topical reports
This concludes the public portion of AREVA’s presentation.
Requirements and Capabilities
AOO Criteria

- **Fuel temperature**
  - Calculated maximum fuel temperature shall remain less than the fuel melt temperature
  - Lower bound melting temperature includes effect of gadolinia, Pu content of MOX, and is a function of exposure

- **Cladding transient strain**
  - Transient-induced tangential outside diameter (OD) strain, elastic + plastic, excluding irradiation growth and steady-state creep down, shall not exceed 1%
  - Hydrogen limits established to preserve adequate ductility at higher exposures
Requirements and Capabilities
Normal Operation Criteria

- Rod internal pressure
  - Rod internal pressure limited to prevent unstable increase in the pellet-clad gap, i.e., the outward cladding creep shall not exceed fuel swelling rate
  - To avoid hydride reorientation, rod pressure is restricted to:
    - $< [\text{C}]$
    - $< [\text{C}]$

- Cladding oxidation, hydriding, and crud buildup
  - Calculated oxidation shall be less than:
    - $[\text{C}]$
  - Hydrogen shall be less than:
    - $[\text{C}]$
  - The thermal effect of crud is taken into account
Requirements and Capabilities
Normal Operation Criteria

- **Cladding cyclic fatigue**
  - Cladding fatigue usage factor shall not exceed 1.0. The fatigue design curve (O'Donnell & Langer) includes a factor of safety of either 2 on stress, or a factor of 20 on the number of cycles, whichever is more conservative.

- **Cladding creep collapse**
  - Axial gap formation [ ] to provide adequate support to the cladding (RODEX4 methodology).
  - If greater than [ ] to show the following sub-criteria are satisfied (CROV methodology):
    - [ ]
Requirements and Capabilities
Normal Operation Criteria

- Hydrogen uptake criterion for Zry-2 cladding
  - Hydrogen uptake model developed for RODEX4
  - RAI response with model submitted in November 2013
  - The GALILEO topical report refers to the separate submittal
  - AREVA plans to update GALILEO topical report to include this model following NRC approval for use in RODEX4
  - This allows for a single model
    - Review of implementation in GALILEO will be required
Requirements and Capabilities
Statistical Methodology

▸ Follows the same statistical methodology described in BAW-10247PA for RODEX4

◊ GALILEO was calibrated to provide a best-estimate response with a minimum of bias and no significant local bias over the range of applicability

◊ Fuel rods (power histories) and uncertainties are sampled and propagated through the code using known statistical variances of the input variables

◊ [ ]
Requirements and Capabilities
Reactor Operations Scenarios

Normal Operation

- Analysis is made separately for each reload (batch) of fuel in the core
  - Power histories for the reload are calculated using current neutronic core simulator codes for BWRs and PWRs
- BWR and PWR normal operations scenarios are evaluated in a very similar manner
Requirements and Capabilities
Reactor Operations Scenarios

AOOs

- Effort was made to consolidate BWR and PWR methods to the extent feasible – some differences continue to exist
  - BWRs and PWRs use different methods for power monitoring, and the fuel rod power limits are not defined in the same way
  - Historical differences exist in the treatment of strain between BWRs and PWRs

- The BWR AOO method with GALILEO was derived from the RODEX4 methodology
  - The same types of transients are evaluated, and GALILEO was substituted for RODEX4

- The PWR AOO method is based on the COPERNIC methodology
  - The PWR AOO methodology accounts for uncertainties, as with the RODEX4 methodology
Requirements and Capabilities
Reactor Operations Scenarios

Evaluation of AOOs

- For BWRs, slow transients are embedded in the steady-state power histories for the evaluation of the transient strain criteria (cladding strain and fuel melt). Additionally, the transients are included to account for their effect on rod internal pressure.

- For PWRs, transient power spikes are included in the steady-state power histories only for their effect on rod pressure. The transient strain criteria for PWRs are evaluated separately from the power history analysis.

- Compared to the COPERNIC methodology, uncertainties are taken into account in the analysis of AOOs for PWRs, as well as of BWRs.
Requirements and Capabilities
Reactor Operations Scenarios

Evaluation of AOOs (continued)

◊ A separate analysis is performed using GALILEO on the hot node to determine an allowable overpower factor based on the maximum allowed cladding strain and fuel temperature. This method is used for BWR slow transients and PWR transients.

- The overpower factor result is used in conjunction with an approved PWR systems transient code to evaluate setpoint limits to protect the transient criteria.
- The overpower factor result is used for BWRs to establish flow-dependent LHGR multipliers that protect the transient criteria for slow transients.

◊ For BWR fast transients, the power excursions calculated from an approved reactor system transient code (e.g., COTRANSA2) are evaluated by GALILEO for cladding strain and fuel temperature. Linear heat generation rate (LHGR) multipliers are established as a function of power to protect the transient criteria.
Requirements and Capabilities
GALILEO Fuel Rod Code

**INPUT DATA**
- Rod Characteristics
  - Pellet & Cladding Geometry
  - Material
- Irradiation Conditions
  - Thermal-Hydraulic Conditions
  - Power Histories

**GALILEO**
- Pellet and Cladding Thermics
- Clad Corrosion
- Pellet and Cladding Mechanics
- Fission Gas Release
- Helium Balance

**OUTPUT RESULTS**
- Fuel and Clad Temperatures
- Fuel and Clad Stresses and Strains
- Outer Zirconia Thickness and Hydrogen Content
- Fission Gas Release and Helium Balance
- Rod Internal Pressure

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Requirements and Capabilities
GALILEO Highlights

- A single code for both BWR and PWR
  - Cladding models include Zry-4, M5®, and Zry-2, stress-relief (SR) annealed and recrystallized (RX) annealed
- Some models adapted from RODEX4, COPERNIC and CARO-E3, as part of a best practice effort
- New models and model improvements based on research and development programs

GALILEO incorporates modern technology and best practices.
### Requirements and Capabilities

**GALILEO Highlights**

<table>
<thead>
<tr>
<th>Model</th>
<th>Comes from:</th>
<th>New features</th>
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<tbody>
<tr>
<td></td>
<td>RODEX4</td>
<td>COP2</td>
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<tr>
<td><strong>THERMAL</strong></td>
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<td>Fuel Pellet Radial Power Profile</td>
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<td>Pellet relocation</td>
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<td>Helium models</td>
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<td>Rod free volume and inner pressure</td>
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# Requirements and Capabilities

## GALILEO Highlights

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<td>M5 free growth</td>
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<td>Creep anisotropy modeling</td>
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<td>SR and RX Zr2 free growth</td>
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<td><strong>MULTI-DIMENSIONAL MODELS</strong></td>
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<td>Improved RODEX4 model</td>
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<td>Clad shell model</td>
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<td>Improved RODEX4 model</td>
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<td>CROVINC</td>
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<td>Dish filling</td>
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<td>Improved RODEX4 model</td>
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<td><strong>CORROSION</strong></td>
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<td>Zr4 corrosion</td>
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<td>Zr4 H2 pick-up model</td>
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<td>M5 corrosion</td>
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<td>New AREVA model</td>
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<tr>
<td>Zr2 corrosion</td>
<td>Y</td>
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</tbody>
</table>
Database Highlights

Database is composed of 1439 fuel rods selected from over 2000 rods covering high burnups (>75 GWD/MTU) and high duty plants (>35 kW/m)

- PWR vs. BWR
  - Rod Type Breakdown
  - Test reactor vs. commercial reactor data

Extensive and balanced validation database
## Ranges of Applicability

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Reactor types</strong></td>
<td>PWR and BWR reactors</td>
</tr>
<tr>
<td><strong>Fuel types</strong></td>
<td>$\text{UO}_2$, $\text{UO}_2\cdot\text{Gd}_2\text{O}_3$ and MOX (NP and RG)</td>
</tr>
<tr>
<td><strong>Manufacturing processes</strong></td>
<td>Dry conversion and ADU</td>
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<tr>
<td><strong>Cladding types</strong></td>
<td>Zircaloy-4, M5®, Zircaloy-2 (SR and RX)</td>
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<tr>
<td><strong>Rod diameters</strong></td>
<td>All current and past designs</td>
</tr>
<tr>
<td><strong>Fuel rod burnup (all fuel types)</strong></td>
<td>Up to 62 GWd/tM for full-length rod and equivalent for part-length rods</td>
</tr>
<tr>
<td><strong>Fuel rod power</strong></td>
<td>Up to LHGR resulting in fuel melt over entire burnup range</td>
</tr>
</tbody>
</table>
GALILEO - Selected Topics

- Thermal Conductivity Degradation
- Fission Gas Release
- Advanced Pellet Mechanical Models
- Corrosion and Hydrogen Pickup
Fuel TCD

General Background, Phenomenology
Fuel TCD

$\text{UO}_2$ Model Formulation

- Fully dense $\text{UO}_2$ fuel TCD model formulation:
Fuel TCD Calibration Methodology
Fuel TCD
Burnup, Temperature Trends

- Fully dense (100% TD) UO$_2$ fuel thermal conductivity model trends vs. burnup and temperature:
Fuel TCD
Calibration, Validation Results

No bias vs. burnup on the calculated fuel temperature up to very high burnup (102 GWd/tM)
Satisfactory UO₂ fuel temperature predictions up to very high burnup (102 GWd/tM)
Satisfactory UO₂ fuel temperature predictions at high burnup (62 GWd/tM) for LHGR ranging from 11 to 31 kW/m
Satisfactory UO₂ fuel temperature predictions at high burnup (60 GWd/tM) up to fuel melting
Fuel TCD
Mixed Fuels (MOX, Gd)

Satisfactory fuel temperature predictions vs. burnup for mixed fuels (MOX, Gd)
Fission Gas Release

▶ Short overview about the model and the main release mechanisms

▶ Results
  ◆ Enhanced release
  ◆ Validation
FGR Mechanisms: Athermal Release

- Recoil and knockout of fission gas (FG) atoms through free surfaces (cracks, open pores)
- Temperature independent
- Increases with burnup and open porosity
- Remains low with acceleration at high burnup associated with the formation of fuel pellet rim.
Mechanisms: Thermal Release (I)
Mechanisms: Thermal Release (II)
Mechanisms: Enhanced Release
Mechanisms: Additional Remarks
Mechanisms: Schematic Overview

Steady state:
- Gas escaping the pellet by recoil and knock-out of atoms
  - $F_{\text{athermal}}$
- Grain matrix swept by grain boundaries
  - $F_{\text{grain growth}}$

Diffusion of gas (Steady-state or Transient):
- Gas retained in matrix (Booth solutions)
  - Gas in bubbles
    - Interlinkage
    - $F_{\text{Bu Enhancement}}$
  - Gas retained Xe solubility limit
- Gas diffused to grain boundaries (intergranular bubbles)
- Saturation of grain boundary (surface density threshold)
  - $F_{\text{thermal steady-state / transient}}$

Transient:
- Partial opening of Grain boundaries
  - $F_{\text{Burst}}$

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FGR
Enhanced Release – Results (I)
Enhanced Release – Results (II)

=> Measured EPMA profiles are well reproduced by GALILEO FGR model.
Advanced Pellet Mechanical Models

- Gaseous swelling model
- Dish filling model
- Pellet mechanics
- Original model GLOVD developed for transient conditions (driving clad strain)

Calibration process of the pellet deformations

FGR → diffusion → Gas Swelling → strain → Dish Filling → Pellet mechanics during ramps

check
Gaseous Swelling Phenomenology

- Gaseous swelling refers to the portion of fuel swelling linked to porosity induced by fission gases
  - Mainly intergranular bubbles
  - Does not include nanobubbles (included in solid swelling) at macroscopical level

- Closely linked to FGR
  - Evolution governed by FG diffusion towards bubbles
  - Gaseous swelling occurs above the FG incubation threshold

- Mitigated by
  - Strong PCMI (hot pressing)
  - Very high temperature (redensification)
Gaseous Swelling Database

- No direct access to measurements of gaseous swelling
Gaseous Swelling Model Formulation

- Gaseous swelling equation rate
Cracking Model
The GLOVD Model
Clad Strain Validation (1/3)

- Satisfactory results on the whole L/D range
Clad Strain Validation (2/3)

- Satisfactory results for all types of fuel rods
Clad Strain Validation (3/3)

- Satisfactory results for all types of fuel
Corrosion: Model Basis and Databases

- Separate oxidation models for each of the three cladding materials: Zry-4 and M5® for PWR and Zry-2 for BWR
Low Tin SR Zircaloy-4 Corrosion Model Formulation
Low Tin SR Zircaloy-4 Corrosion
Accelerated Oxidation Rate at High Exposure

Validation Database – Measured Values
Low Tin SR Zircaloy-4 Corrosion Model Calibration, Validation
Low Tin SR Zircaloy-4 Hydrogen Pick-Up Model Calibration, Validation
Recrystallized M5® Corrosion Model Formulation
Recrystallized M5® Corrosion Model Calibration, Validation
Recrystallized M5® Hydrogen Pick-Up Model Formulation
Recrystallized M5® Hydrogen Pick-Up Model Calibration, Validation
BWR Corrosion, Hydrogen, Crud

- Modern Zry-2 material has optimized microstructure that minimizes nodular corrosion, however the lift-off database includes older data points with higher nodular corrosion.

- A hydrogen model for Zircaloy-2 has been developed by AREVA separate from the GALILEO code and was submitted to the NRC in Nov. 2013.
BWR Uniform Corrosion

Model validation, as shown later, is based on measurements from (9x9) and (10x10) rods irradiated in various commercial BWRs.

It is applicable to both RXA and CWSR Zry-2 claddings.
Despite the relatively large scatter, which is common for corrosion modeling and which is accounted for by model parameter uncertainties, both figures show an overall balanced result.
Accounting for Crud in BWR Analyses

Typical crud layer thickness is part of the lift-off measurements on fuel rods irradiated in both European and U.S. plants and Zr-2 cladding in both CWSR and RXA metallurgical condition.
Uniform Oxide and Crud Models Show Best-estimate Prediction of Measured Lift-off Data
Oxidation and Hydriding: Design Criteria Background

Oxidation limits were established by considering wall thickness stress analysis constraints and operating experience regarding corrosion-induced failures:

- Corrosion-related failures not observed up to the established limits based on extensive operating experience.
- Stress analyses conservatively support the amount of wall thinning at the oxidation limits. Cyclic fatigue is also considered.
- Corrosion limits coincide approximately with the hydrogen limits.

<table>
<thead>
<tr>
<th>Cladding type</th>
<th>Oxidation limit, μm</th>
<th>Hydrogen limit, wppm</th>
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<tbody>
<tr>
<td>BWR Zry-2 SRA</td>
<td>[ ]</td>
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<tr>
<td>BWR Zry-2 RXA</td>
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<tr>
<td>PWR Zry-4 SRA</td>
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<td>PWR M5 RXA</td>
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Hydrogen limits

[ ] for normal operation and AOOs, as requested by NUREG-0800 SRP4.2

Available mechanical test data were grouped according to metallurgical state - stress-relieved or recrystallized, and environmental conditions - unirradiated or irradiated, room temperature or elevated temperature.

Data sources
- AREVA mechanical test data on M5 cladding
- Test program undertook by AREVA to gain data on RXA Zry-2 cladding: main results described in AREVA paper 8538 at Topfuel 2013
- NFIR data: consists of SRA and RXA Zry-4 samples

Most data include information regarding both uniform and total elongation
Oxidation and Hydriding: Design Criteria Background

Uniform strain, RXA data

- Sharp reduction in ductility observed as a function of irradiation
Oxidation and Hydriding: Design Criteria Background

- Uniform strain, SRA data
Highlights of axial tensile and biaxial tests on irradiated RXA Zry-2 cladding

► Axial tensile tests:
  ◦ All samples failed by ductile shear with the main fracture surface inclined 45° to the loading direction
  ◦ Necking was noticed in all cases, at a higher degree in the low fast fluence samples, as expected
  ◦ The residual strain to failure varied in the range of 4.3 % (HF and high H uptake) to 14.9 % (LF)
  ◦ The ultimate tensile strength (UTS) varied from 413 MPa to 714 MPa

► The results from the hardening and relaxation tests are summarized as follows:
  ◦ A total strain of 1.1% was achieved during the loading
  ◦ At the end of the test after all relaxation steps, a total permanent strain of around 1.5% was accumulated

Ductility is maintained at the levels required by licensing criteria even for this elevated hydrogen uptake level combined with high irradiation embrittlement
Hydrogen Uptake Model for Zry-2

Hydrogen uptake criterion for Zry-2 cladding

- Hydrogen uptake model developed based on most recent data acquired by AREVA and confirmed with non-AREVA data – AREVA paper accepted at Topfuel 2014
- The H uptake model was submitted in November 2013 in the framework of RAI response to RODEX4 RXA Supplement
- The GALILEO topical report makes reference to this separate submittal
- AREVA plans to update GALILEO topical report to include this model following NRC approval for use in RODEX4
- This allows for a single model
  - Review of implementation in GALILEO will be required
GALILEO MOX

- Models
- Applicability to NP MOX
- Conversion
- Impact on Margin
MOX Fuel Modeling
Introduction, Overview

▶ Adapted MOX Fuel Models
  ◆ [ ]

▶ Specific MOX Fuel Models
  ◆ [ ]

▶ Key Material Properties
  ◆ [ ]
MOX Fuel Modeling
MOX Fuel Modeling

He balance = He volume after irradiation – Initial He volume (manufacturing)

STP: (0°C/32°F – 1013.25hPa/14.6959psi)
MOX Fuel Modeling
Helium Production Mechanisms (1/2)

- He production originates from 3 different sources
  - $\alpha$ decay of some of the actinides
  - $(n, \alpha)$ reactions on $^{16}$O
  - Ternary fissions

- $\alpha$ decay is a continuous process, depending on calendar elapsed time, whereas $(n, \alpha)$ reactions on $^{16}$O and ternary fissions only occur under irradiation

- Only MOX fuel can yield a significant amount of He, depending on the initial isotopic composition and more particularly on the $^{241}$Am content (RG vs. NP MOX)

- He production and by extension He behavior can be neglected for other fuel types ($\text{UO}_2$, $\text{UO}_2-\text{Gd}_2\text{O}_3$)
MOX Fuel Modeling
Helium Production Mechanisms (2/2)
MOX Fuel Modeling
Helium Production Validation

- He production calculations are performed through the PRODHEL V2.2 module (CEA, France) embedded in the GALILEO code

- He production calculations have been successfully benchmarked with the ORIGEN-S code (ORNL, US) results
MOX Fuel Modeling

Helium Release Mechanisms (1/2)
MOX Fuel Modeling
Helium Release Multiscale Model
MOX Fuel Modeling
Helium Release Model Calibration
MOX Fuel Modeling
Helium Release Model Validation
MOX Fuel Modeling
Adaptation for Helium Transient Release
MOX Key Material Properties
Fuel Melting Point (1/2)
MOX Key Material Properties
Fuel Melting Point (2/2)

Robustness of the MOX fuel melting temperature model and conservatism of its lower bound limit have been successfully benchmarked against experimental data and reference models set-out from the literature.

Applicability to NP MOX

2014
Introduction

- Difference between NP MOX and RG MOX

- US NP MOX LTA Measurement in Database

- US NP MOX LTA Performance Prediction

The fuel rod design and the fuel assembly design will provide reliable and safe operation, comparable to that of equivalent low-enriched uranium (LEU) designs.
Difference and Solution

1. Isotopics

Difference
NP plutonium has a greater concentration of fissionable isotopes and lower concentration of absorber isotopes.

Approach
The difference in isotopes is modeled explicitly in Galileo fuel performance code.
Primary blend is more dilute for NP MOX to control local heating and fission gas release.
For information: Sample Unirradiated Fuel Isotopic
For information: Plutonium Fissions as a Fraction of Total Fissions

- Pu in LEU Assembly
- Pu in RG MOX Assembly
- Pu in WG MOX Assembly

Fraction of Total Fissions

Burnup (GWh/MTm)

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2. Impurity

**Difference**

NP plutonium will contain small amounts of gallium as a stabilizer.

**Approach**

Manufacturing process: NP plutonium will be polished to remove the gallium prior to the MOX processing stage.

Specification: The design impurity level for gallium for the NP MOX is similar to the current trace levels of gallium in LEU fuel.
Difference and Solution

3. Microstructure

Difference

Very slight difference in thermal conductivity, fission gas release, fuel pellet swelling, and pellet radial power distribution.

Approach

UO$_2$ matrix that establishes the overall pellet microstructure is the same.

NP MOX has a smaller total concentration of plutonium than RG MOX to achieve similar reactivity.

These parameters have been modeled in GALILEO.
US NP MOX LTA Measurements

- 4 lead test assemblies (LTAs) manufactured in France and irradiated at Catawba Unit 1

- Post-irradiation examination (PIE) performed at Oak Ridge National Laboratory

- Non-destructive and destructive tests

- Conclusion: NP MOX Measurements are within the range of the current database
Using GALILEO, predictions for the Catawba MOX LTA fuel rods have been compared with the measurements from the hot cell PIE.

The GALILEO code is found to satisfactorily predict all phenomena. The predicted vs. measured behaviors for the NP MOX are consistent with that of the RG MOX in the verification and validation database.

- Fuel rod growth
- Fuel stack growth
- Fuel rod diameter
- Fission gas release
- Helium Balance
- Free void volume
- Internal gas pressure
- Pellet density
Conclusion: FGR for NP MOX LTA is well predicted by GALILEO. The NP rods are also consistent with the RG MOX data.
Dry Conversion Process MOX
Introduction, Context

► Current MOX manufacturing context:
  ◆ Industrial shift from ADU UO₂ feeding powder to DCP (dry conversion process) UO₂ powder.
  ◆ AREVA experience feedback is mainly based on ADU MOX.

Objective: demonstration of DCP MOX in-pile equal performance level vs. ADU MOX
Dry Conversion Process MOX
DCP MOX vs. ADU MOX

Overall equivalent phases surface distribution than reference ADU MOX. No impact foreseen on in-pile performance.
Dry Conversion Process MOX
DCP MOX vs. ADU MOX

- Same expected in-pile performances:
  - No major microstructural specificities of DCP MOX
  - No foreseen impact of DCP UO₂ feeding powder on:
    - Thermal conductivity
    - Melting point
    - Densification & Swelling
    - Fission gas release
    - Pellet cladding interaction (PCI) behavior
    - Reactivity initiated accident (RIA) behavior

- Positive experience feedback from DCP MOX irradiation follow-up program - no impact of DCP UO₂ feeding powder on base-irradiation performances relative to:
  - Rod and fuel stack dimensional evolution
  - Fuel density
  - FG and helium release

Next objective: demonstration of the ability of GALILEO to predict DCP MOX behavior
Dry Conversion Process MOX
GALILEO Predictions vs. Measurements

- Fuel rods dimensional behavior
Dry Conversion Process MOX
GALILEO Predictions vs. Measurements

Fuel pellet density evolution
Dry Conversion Process MOX
GALILEO Predictions vs. Measurements

» Puncturing results
Dry Conversion Process MOX

Conclusions

- DCP MOX as-fabricated properties and microstructural features are equivalent to those of standard ADU MOX.
  
  Therefore in-pile performances are expected to be the same.

- Results from the DCP MOX irradiation follow-up program lead to the conclusion of the non-impact of DCP UO₂ feeding powder on MOX in-pile performance under base-irradiation conditions.

- GALILEO prediction results of DCP MOX fuel rods are in the same scatter as standard ADU MOX fuel from the experience feedback database.

GALILEO is able to correctly predict the in-pile behavior of DCP MOX fuel rods.
Impact of MOX on Fuel Rod Analyses

Expected Impact of MOX on fuel rod analyses
Impact of MOX on Fuel Rod Analyses

Differences in results from application examples

- For BWRs, an application example for MOX fuel shows similar results to the corresponding UO$_2$ case.

- For PWRs, an application example for MOX fuel also shows similar results to the corresponding UO$_2$ case except for lower margin to the collapse criterion (due to a combined effect of higher L/D and densification for the MOX fuel).

- In general, the MOX fuel is designed by taking into consideration fuel differences.

In summary, the application example cases do not show significant differences in results between MOX and UO$_2$ fuel because of fuel design and core design strategies.
Summary

- The GALILEO topical report presents a state-of-the-art fuel rod code and methodology
  - Applicable to PWRs and BWRs
  - Applicable to UO₂ and MOX
  - Applicable to all AREVA cladding and fuel types
  - Includes all observed phenomena, including fuel thermal conductivity reduction with burnup
  - Code is backed by extensive calibration and validation database
  - Utilizes a realistic methodology
- Replaces legacy codes RODEX2/2A, TACO3, GDTACO
- Adds hydrogen models to address future NRC changes to LOCA and control rod ejection criteria
NRC Review Process

- Audits
- RAIs
Next Steps

- Update of GALILEO topical report to include Zr-2 hydrogen model - upon RODEX4 approval

- Audit(s)
  - One or more audits will facilitate the NRC review

- RAI
  - One round of RAIs would make the review efficient

- SER
  - SER Requested by December 31, 2015
Acronyms/Nomenclature

- ADU: Ammonia Diuranate
- AOO: Anticipated Operational Occurrence
- B&W: Babcock and Wilcox
- BWR: Boiling Water Reactor
- CE: Combustion Engineering
- CEA: French Atomic Energy Commission
- CWSR: Cold Worked Stress Relieved
- DCP: Dry Conversion Process
- EPU: Extended Power Uprate
- FE: Finite Element
- FG: Fission Gas
- FGR: Fission Gas Release
- HPUF: Hydrogen Pick-up Fraction
- ID: Inner Diameter
- L/D: Length/Diameter
- LEU: Low-Enriched Uranium
- LHGR: Linear Heat Generation Rate
- LOCA: Loss of Coolant Accident
- LTA: Lead Test Assembly
- MOX: Mixed Oxide
- NP: Non Proliferation
- NRC: Nuclear Regulatory Commission
- OD: Outer Diameter
- PCI: Pellet Cladding Interaction
- PCMI: Pellet Cladding Mechanical Interaction
- PIE: Post-Irradiation Examination
- PIRT: Phenomena Identification and Ranking Table
- PWR: Pressurized Water Reactor
- RAI: Request for Additional Information
- RG: Reactor Grade
- RIA: Reactivity Insertion Accident
- RX: Recrystallized
- RXA: Recrystallized
- SRA: Stress Relieved Annealed
- TCD: Thermal Conductivity Degradation
- TD: Theoretical Density

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