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

Meeting Objectives

- Present a summary of the GALILEO topical report
- Present in depth a sub-set of key topics
  - Models applicable to both 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

Proprietary Meeting

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:
  - < [ ]
  - < [ ]

▶ Cladding oxidation, hydriding, and crud buildup

- Calculated oxidation shall be less than:
  - [ ]
- Hydrogen shall be less than:
  - [ ]
- 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)

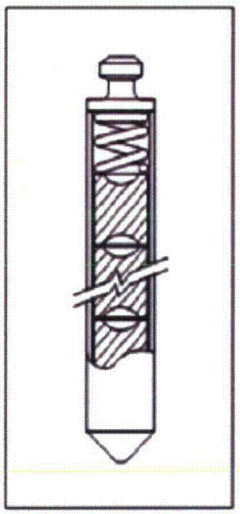
- **A separate analysis is performed using GALILEO on the hot node to determine an allowable overpower factor based on the maximum allowed cladding strain and fuel temperature. This method is used for BWR slow transients and PWR transients.**
  - The overpower factor result is used in conjunction with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

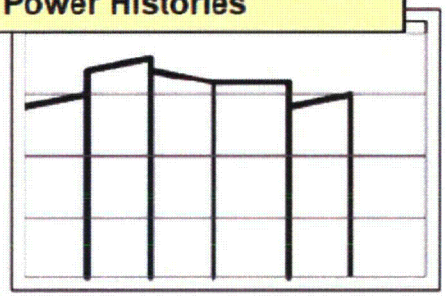
Requirements and Capabilities
GALILEO Fuel Rod Code

INPUT DATA

Rod Characteristics
Pellet & Cladding Geometry
Material

Irradiation Conditions
Thermal-Hydraulic Conditions
Power Histories





Pellet and Cladding Thermics Clad Corrosion

GALILEO

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

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

Model		Comes from:			New features
		RODEX4	COP2	CARO-E	
THERMAL	Fuel Pellet Radial Power Profile	Y		Y	Use of the sophisticated pin cell code CIRTHE and interpolation techniques
	Coolant model	Y	Y	Y	IAPWS-IF97 tables for water and steam
	Pellet-cladding gap conductance		Y		New contact conductance model Interface smoothing model
	Fuel Thermal conductivity		(Lucuta's radiation damage)		Kinetic radiation damage Improved conductivity modeling at high temperature (Fink correlation)
	Rim model	Partly			Temperature threshold Impact on density and pellet strain
	Pellet relocation			Partly	
GAS	Fission Gas Release		Partly	Partly	High burnup release enhancement model considering Xe concentration limit and bubble interlinkage Grain growth
	Helium models				He producion and release modeling for MOX fuel (from CEA)
	Rod free volume and inner pressure	(open porosity)	Y		Contribution of a fraction of the gaseous porosity to the open porosity Lower plenum temperature correlation

Requirements and Capabilities GALILEO Highlights

Model		Comes from:			New features
		RODEX4	COP2	CARO-E	
PELLET STRAINS	Densification	Y			
	Solid-Swelling	Y			
	Gaseous Swelling		Partly		AREVA model
	Fuel creep				CEA model
	Pellet Relocation			Y	
	Pellet cracking	Y			
	GLOVD				New AREVA model
CLAD STRAINS	Zr4 low stress creep		Y		
	Zr4 high stress creep		Y		
	Zr4 plastic strain		Y		
	Zr4 free growth		Partly		New AREVA model after contact
	M5 low stress creep		Partly		Creep anisotropy modeling
	M5 high stress creep		Y		
	M5 plastic strain		Y		
	M5 free growth				New AREVA model
	SR and RX Zr2 creep	Partly			Creep anisotropy modeling
	SR and RX Zr2 free growth	Partly			
MULTI-DIMENSIONAL MODELS	Hourglassing model	Partly			Improved RODEX4 model
	Clad shell model				new AREVA model
	Cladding ridging	Partly			Improved RODEX4 model
	Cladding ovality	Y			
	CROVINC		(CROV)		
	Dish filling	Partly			Improved RODEX4 model
CORROSION	Zr4 corrosion		Y		
	Zr4 H2 pick-up model		Y		
	M5 corrosion		Y		
	M5 H2 pick-up model				New AREVA model
	Zr2 corrosion	Y			

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

Reactor types	PWR and BWR reactors
Fuel types	UO_2, UO_2-Gd_2O_3 and MOX (NP and RG)
Manufacturing processes	Dry conversion and ADU
Cladding types	Zircaloy-4, M5®, Zircaloy-2 (SR and RX)
Rod diameters	All current and past designs
Fuel rod burnup (all fuel types)	Up to 62 GWd/tM for full-length rod and equivalent for part-length rods
Fuel rod power	Up to LHGR resulting in fuel melt over entire burnup range

GALILEO - Selected Topics

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

Fuel TCD
General Background, Phenomenology

Fuel TCD
UO_2 Model Formulation

▶ **Fully dense 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)

Fuel TCD

[ ]

- Satisfactory UO_2 fuel temperature predictions up to very high burnup (102 GWd/tM)

Fuel TCD

[ ]

- Satisfactory UO_2 fuel temperature predictions at high burnup (62 GWd/tM) for LHGR ranging from 11 to 31 kW/m

Fuel TCD

[ ]

- Satisfactory UO_2 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.

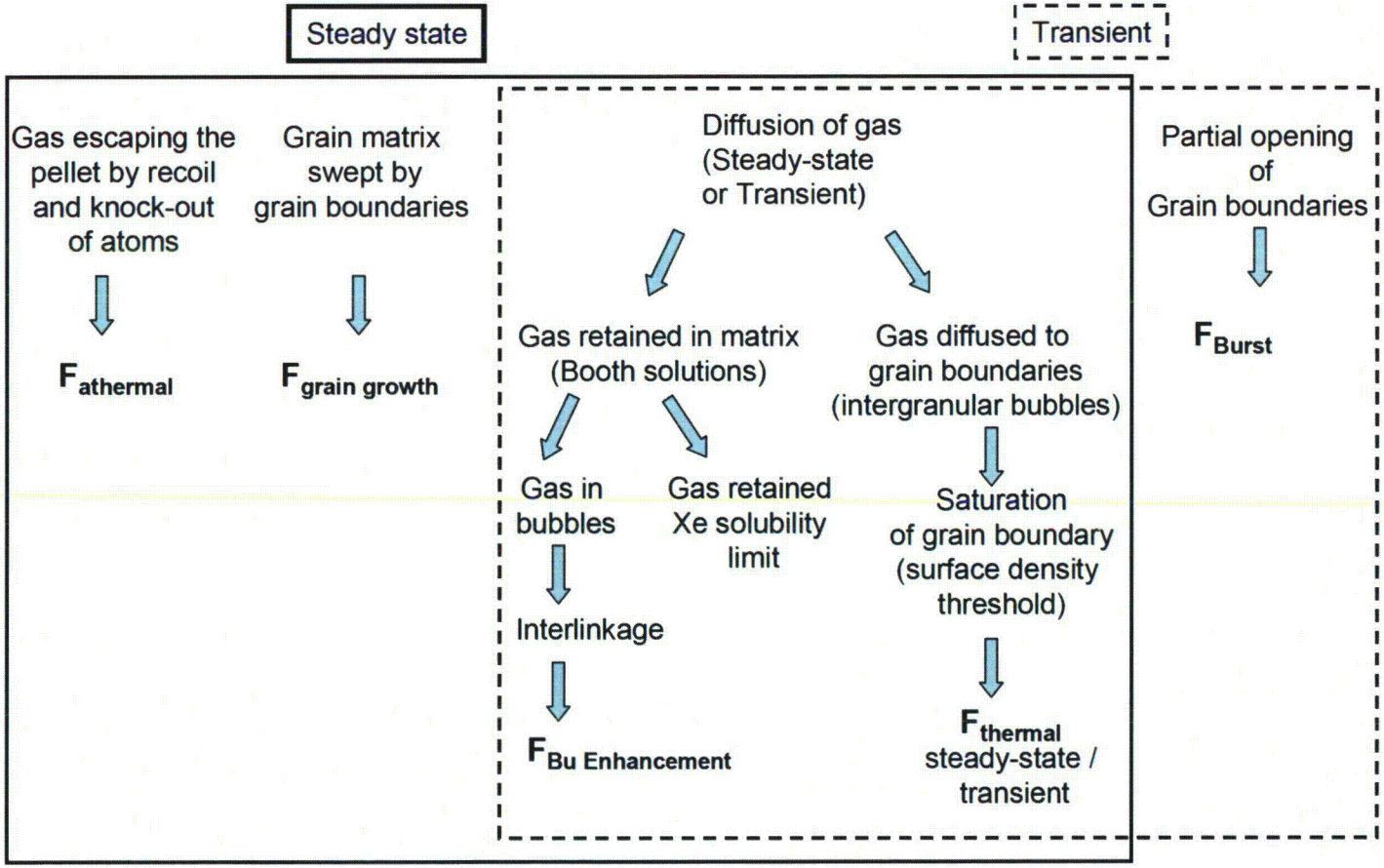
FGR
Mechanisms: Thermal Release (I)

FGR
Mechanisms: Thermal Release (II)

FGR
Mechanisms: Enhanced Release

FGR
Mechanisms: Additional Remarks

FGR
Mechanisms: Schematic Overview



FGR
Enhanced Release – Results (I)

FGR
Enhanced Release – Results (II)

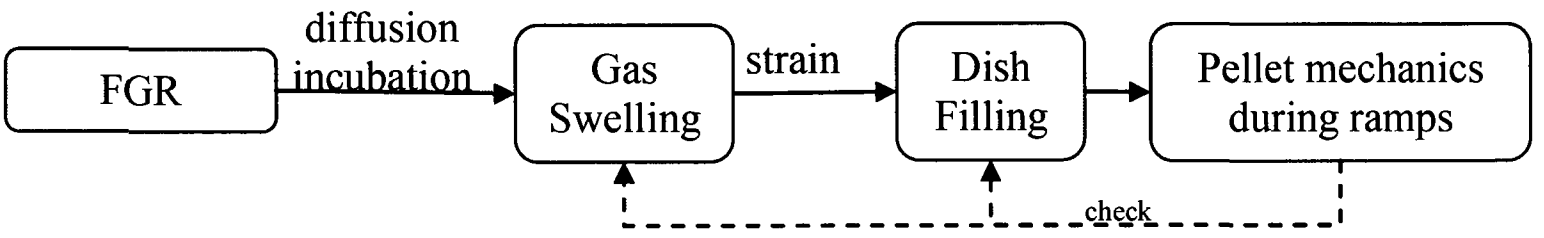
=> Measured EPMA profiles are well reproduced by GALILEO FGR model.

FGR Validation

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



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

Gaseous Swelling Results

Dish Filling

Pellet Mechanical Model

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
- [

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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.

Zircaloy-2 Cladding Corrosion Model Formulation

BWR Zy-2 Uniform Corrosion Validation

- 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.**

Cladding type	Oxidation limit, µm	Hydrogen limit, wppm
BWR Zry-2 SRA	[ ]	[ ]
BWR Zry-2 RXA	[ ]	[ ]
PWR Zry-4 SRA	[ ]	[ ]
PWR M5 RXA	[ ]	[ ]

Oxidation and Hydriding: Design Criteria Background

▶ 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

[ ]

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
  - α decay of some of the actinides
  - (n, α) reactions on ^{16}O
  - Ternary fissions

  ↓ Decreasing amount

- α decay is a continuous process, depending on calendar elapsed time, whereas (n, α) 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 (UO_2, UO_2-Gd_2O_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 Mechanisms (2/2)

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**

[ ]

1) K. Yamamoto, T. Hirosawa, K. Yoshikawa, K. Mrozumi and S. Nomura, "Melting temperature and thermal conductivity of irradiated mixed oxide fuel", Journal of Nuclear Materials 204 (1993) 85-92

Applicability to NP MOX

2014

AREVA

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.

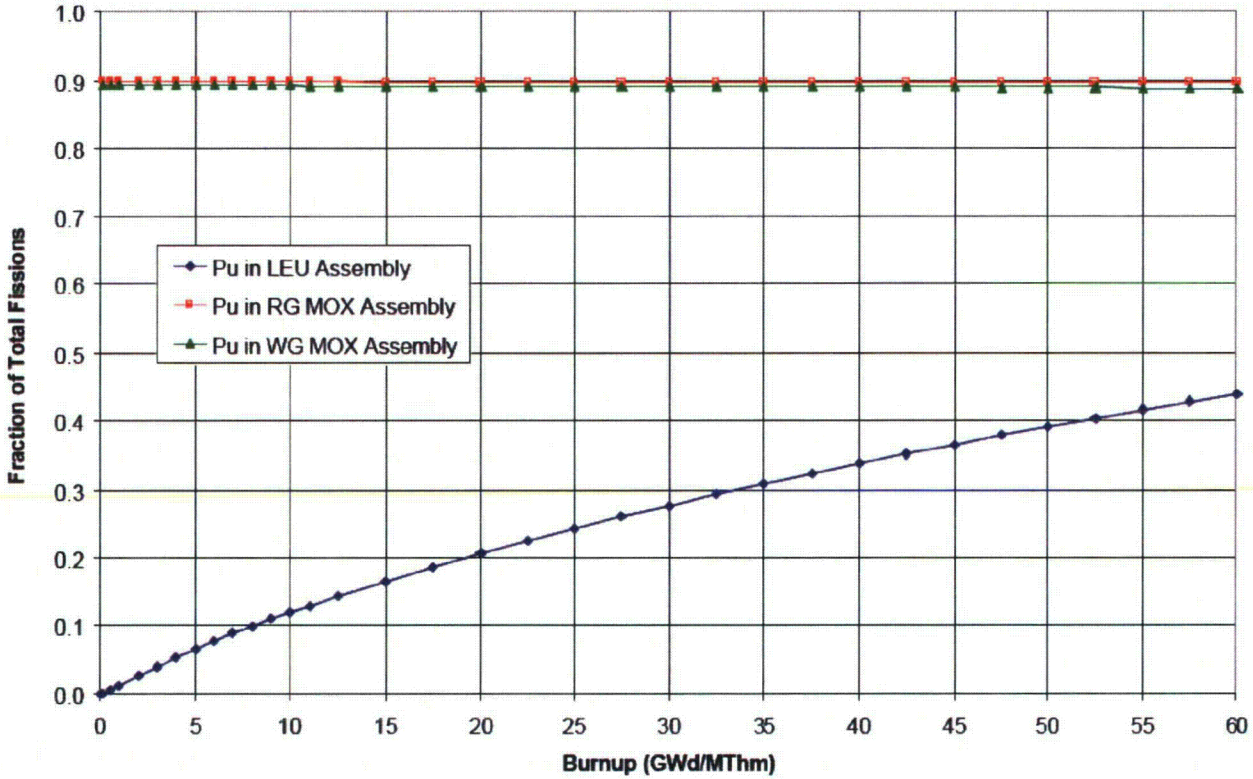
◇ **Approach**

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 Un-irradiated Fuel Isotopic

For information: Plutonium Fissions as a Fraction of Total Fissions



Difference and Approach

▶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

US NP MOX LTA Measurements

NP MOX LTA Performance Prediction

- 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

NP MOX LTA Performance Prediction

[ ]

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 UO_2 feeding powder to DCP (dry conversion process) UO_2 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 UO_2 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 UO_2 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 UO_2 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

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- 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 of a state-of-the-art fuel rod code and methodology
  - Applicable to PWRs and BWRs
  - Applicable to UO_2 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-Irridiation 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