MOX Project:
Codes & Methods Development

AREVA's MOX Fuel Database:
Benchmarking Overview

Opening Remarks

Len Newman
AREVA MOX Program Manager

AREVA

Meeting Objectives

Familiarize the NRC with AREVA's MOX benchmarking data

- Fuel Rod Database and Operational Experience

Discuss benchmarking plans for AREVA's MOX code models

- Validation is across a wide range of material and operational parameters and conditions

Demonstrate a successful conclusion to the Catawba MOX LTA Program

- Achievement of operational program objectives
- Demonstrate ability to accurately predict weapons origin (WG) MOX in-reactor performance using AREVA reactor origin (RG) MOX models

Receive NRC feedback and identify next steps

- May require additional meetings to allow the NRC to fully review this data at a sufficient level of detail

» ***AREVA concludes that sufficient data exists to fully qualify BWR and PWR MOX licensing methodologies***

MOX Project:
Codes & Methods Development

AREVA's MOX Fuel Database: Benchmarking Overview

Public Session

Chris Lewis
PWR MOX Project Manager

AREVA

MOX Project: Codes & Methods Benchmarking Overview

Agenda

- **Discussion of AREVA's MOX Fuel Experience**
  - MOX Operational Experience
  - MOX Fuel Rod Database
  - Catawba Lead Test Assembly (LTA) Program Overview
- **Conclusions**

AREVA's MOX Operating Experience

AREVA has almost 40 years of operating experience with MOX fuel

- 532 Cycles of PWR operating experience
- 32 Cycles of BWR operating experience
- MOX core loadings up to ~40% (Licensed to 50% in Germany and EPR designed to handle up to 100% MOX)

No fuel rod issues or failures have ever been identified related to MOX

- MOX and UO_2 fuel performance are equivalent

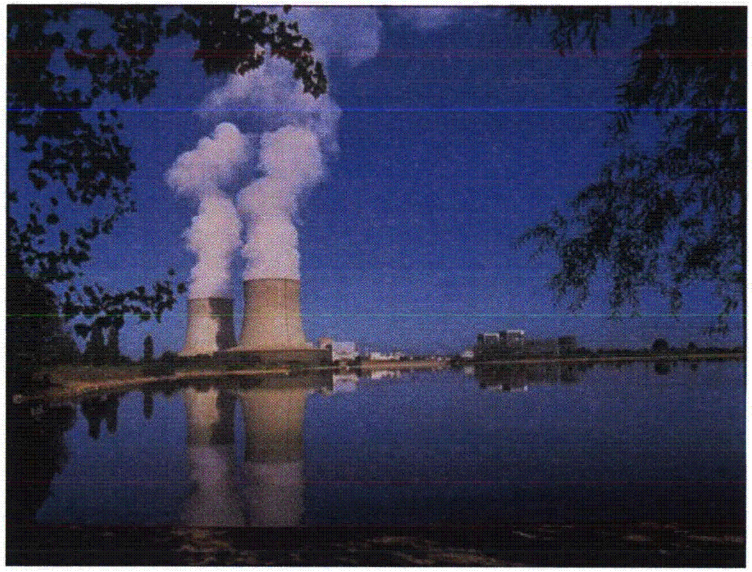
This data will be used to validate the physics codes capabilities

» ***MOX is a mature fuel type whose behavior has been characterized over a number of years***

AREVA's PWR MOX Operating Experience

Since 1972, more than 5050* PWR MOX fuel assemblies, delivered by AREVA NP and its subsidiaries, have been loaded in Belgian, French, German, Swiss, and US PWR units:

- 144 in two Belgian units,
- >3500 in 21 French nuclear plants
- >1330 in 10 German plants and
- 312 in 3 Swiss plants
- 4 in US plants (Catawba)
- >195,000 fuel rods with M5™ Cladding



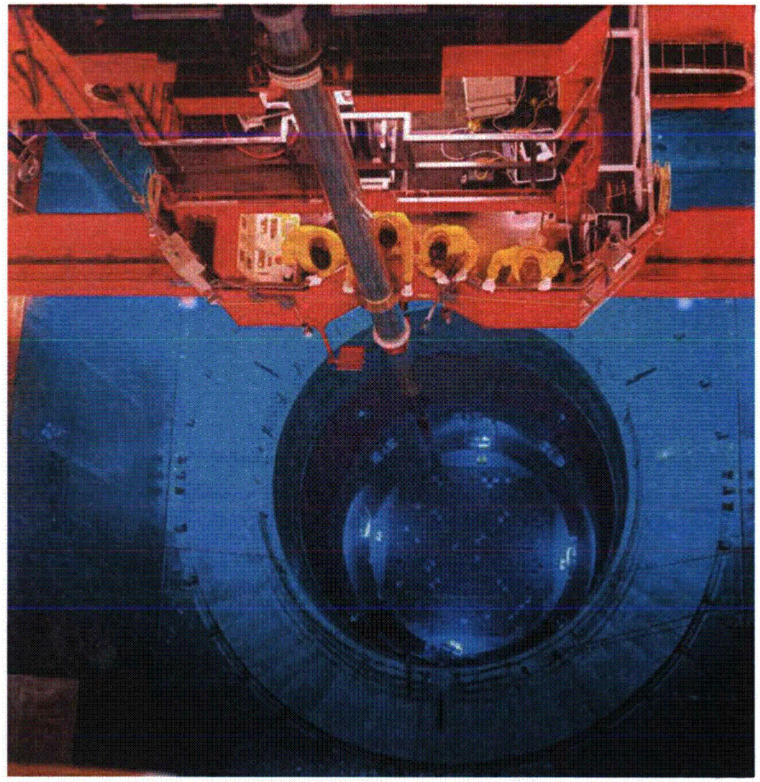
France's St. Laurent B PWR plants started using MOX in 1987.

* Data through 2011

AREVA's BWR MOX Operating Experience

Since 1974, more than 972* BWR MOX or MOX-Gd fuel assemblies, delivered by AREVA NP and its subsidiaries, have been loaded in three German BWR units:

- Gundremmingen A from 1974 to 1997,
- Gundremmingen B from 1995 to 2009,
- Gundremmingen C from 1995 to present



Germany's Gundremmingen plants have operated BWR MOX fuel since 1974

* Data through 2011

AREVA's MOX Operating Experience

MOX Core Loading

Belgium	20.40%
France	30.60%
German PWR	39.40%
German BWR	38.30%
Switzerland	36.20%

Total Plutonium Content	up to 8.65% (assembly avg.) 9.77% peak rod
Pu Fissile Content	63% to 70%
FA Avg Burnups	to 62.2 GWd/tHM

Cycles of Operation

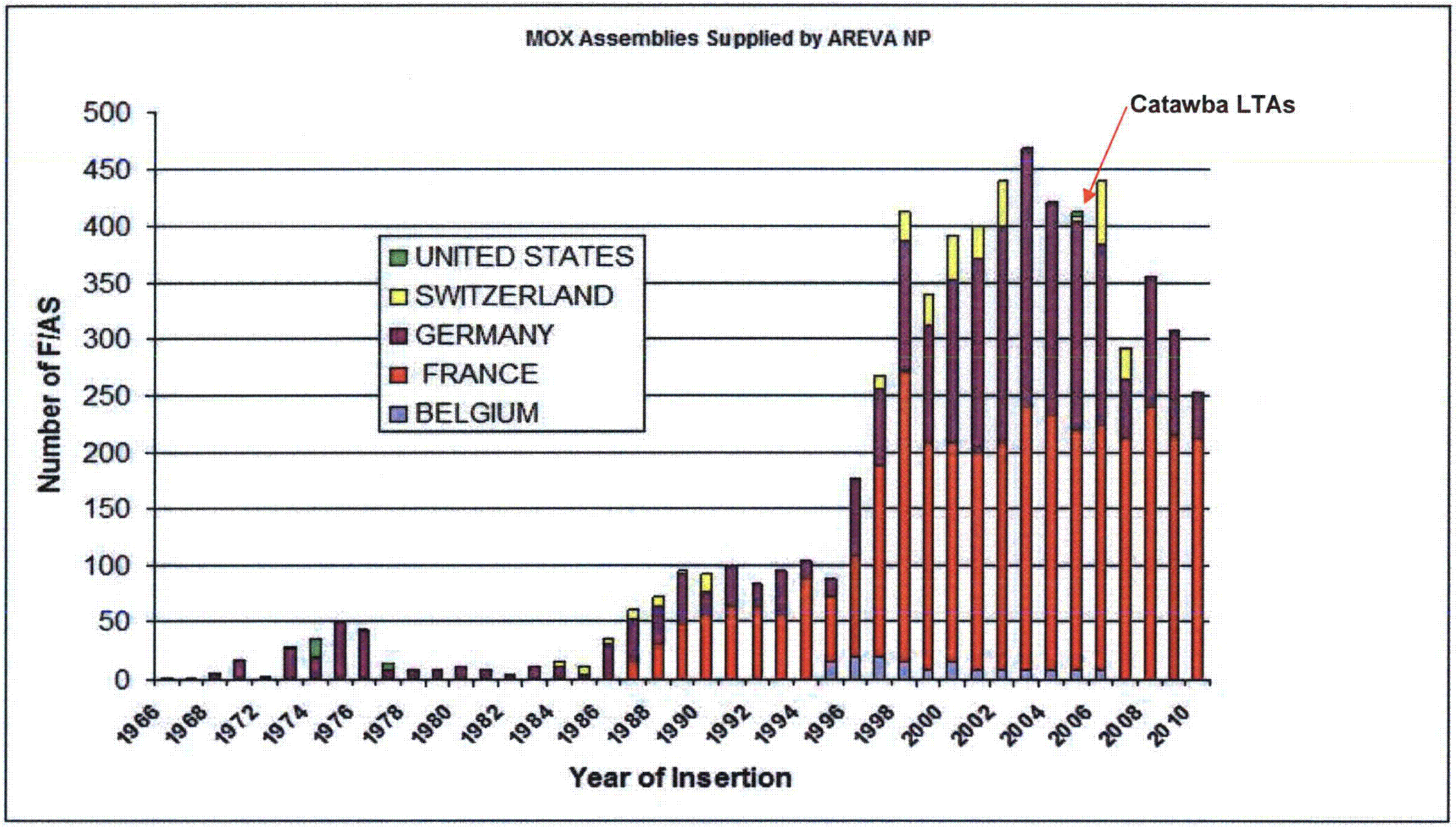
PWRs	# Cycles	FA Array	Core Size
Blayais 1	12	17x17	157
Blayais 2	16	17x17	157
Chinon B1	10	17x17	157
Chinon B2	11	17x17	157
Chinon B3	11	17x17	157
Chinon B4	11	17x17	157
Dampierre 1	19	17x17	157
Dampierre 2	15	17x17	157
Dampierre 3	12	17x17	157
Dampierre 4	11	17x17	157
Gravelines 1	13	17x17	157
Gravelines 2	12	17x17	157
Gravelines 3	20	17x17	157
Gravelines 4	20	17x17	157
Gravelines 6	2	17x17	157
St-Laurent B1	21	17x17	157
St-Laurent B2	20	17x17	157
Tricastin 1	13	17x17	157
Tricastin 2	14	17x17	157
Tricastin 3	13	17x17	157
Tricastin 4	13	17x17	157

PWRs	# Cycles	FA Array	Core Size
Doel 3	15	17x17	157
Tihange 3	7	17x17	157
Obrigheim	26	14x14	121
Neckarwestheim 1	11	15x15	177
Brokdorf	20	16x16	193
Grafenrheinfeld	23	16x16	193
Grohnde	18	16x16	193
Phillipsburg 2	22	16x16	193
Unterweser	23	16x16	193
Emsland	6	18x18	193
Isar 2	12	18x18	193
Neckarwestheim 2	13	18x18	193
Beznau 1	12	14x14	121
Beznau 2	22	14x14	121
Goesgen	13	15x15	177

BWRs	# Cycles	FA Array	Core Size
Gundremmingen A	3	ATRIUM-10A	368
Gundremmingen B	14	ATRIUM-10A/XP	784
Gundremmingen C	15	ATRIUM-10A/XP	784

» ***AREVA brings several hundred reactor years of design, manufacturing and operating experience (BWR and PWR) with MOX fuel which will be drawn upon***

AREVA's MOX Operating Experience



» ***AREVA has worked with MOX fuel since the 1970's and has amassed significant experience in the last 15 years***

AREVA's MOX Operating Experience

BWR/PWR MOX experience is extensive

- **More than 6400 BWR and PWR fuel assemblies**
  - France — 3500 FAs in 21 units since1987
  - Germany — 2450 FAs in 12 units since1972
  - Switzerland — 312 FAs in 3 units since1984
  - Belgium — 144 FAs in Doel 3 and Tihange 2 since1995
  - US — 4 FAs in Catawba since 2005
- **Variety of Plant Management Schemes**
  - Baseload
  - Load Follow
  - Extended Reduced Power (ERPO)
- **Maximum plutonium content up to 8.65% for RG MOX fuel**
  - Maximum plutonium content for WG MOX fuel will be <6%
- **Maximum fuel assembly average burnups exceeding 63 GWd/MThm**
  - Peak rod burnups exceeding 65 GWd/MThm
  - More than 1000 fuel assemblies have been irradiated to burnups exceeding those achieved in the Catawba LTA program

AREVA's MOX Fuel Rod Database

Provides the basis for qualification of AREVA's Fuel Rod Performance Code (GALILEO)

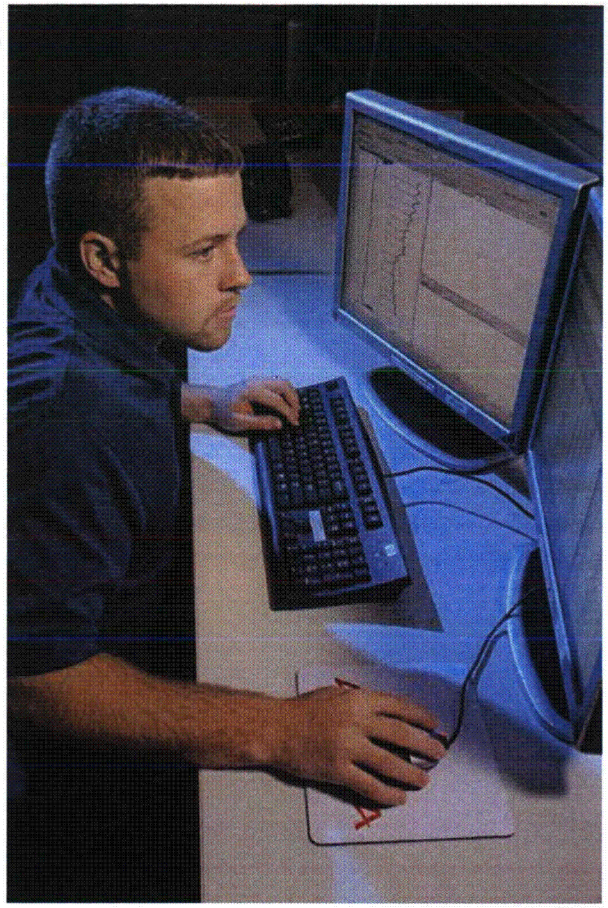
120 MOX rods (PWR and BWR) characterized and evaluated in hot cells

Includes steady-state and transient data

- International Programs
- Bilateral Programs
- Commercial database

Major code models were evaluated for performance against this database

- Centerline temperature, fission gas release (FGR), helium production, etc.
- Variety of cladding types
- Numerous lattice configurations (BWR and PWR)
- Range of fissile content



AREVA's MOX Fuel Rod Database

Numerous International and Bilateral programs have been conducted to evaluate MOX behavior

- Evaluate physical phenomena occurring inside the fuel rod
- Include a number of transient tests (PCI, RIA)

Program	Year	Fuel	Investigated Phenomena	PWR Rods	BWR Rods
Halden [3]	1970's - Present	UO_2, UO_2-Gd, MOX	Fuel Temperature, FGR[1], Free Volume, Int. Press.	10 (HBWR)	
GRIMOX	1993-1995	UO_2, MOX	Fuel Temperature	2	
GERONIMO/TOP-GUN	1990's	MOX	FGR, RDC[2], Rod Length, Free Volume, Int. Press.		16
PRIMO	1987-1989	MOX	FGR, Free Volume, Int. Press.	9	
BR3 Irradiations	1980's	UO_2, MOX	FGR	3	
CAP Irradiations	1980's	UO_2, MOX	FGR, PCI Ramp, Free Volume, Int. Press.	6	
FIGARO	1993 – 1998	MOX	FGR, Free Volume, Int. Press.	2	
REGATE He	2006	MOX	Transient Helium	1	
PROMOX	1990's	MOX	FGR, Pellet Clad Interaction, Ramp Tests	6	
			Total Integral Test MOX Rods	39	16
			Total Integral Test Rods (UO_2, UO_2-Gd, MOX)	405 [4]	61

[1] FGR = Fission Gas Release [2] RDC = Rod Diameter Change [3] HBWR rods [4] PWR+HBWR

» ***Represents a significant amount of data across a large range of operating parameters and includes modern data***

AREVA's MOX Fuel Rod Database

AREVA's Proprietary Database

- **Supplements the International and Bilateral Data**
- **Provide additional mechanical performance data**
  - Assembly & Rod Growth
  - Creep
  - Corrosion
  - Bow and Distortion
- **Confirms FA hardware performance**

Reactor Code	Assembly Type	# of MOX Rods	Cladding
D19	PWR 17x17	12	M5™
D24	PWR 15x15	9	Zr-4
D42	PWR 17x17	18	Zr-4 SR[2]
D55	PWR 17x17	26	Zr-4 SR
D62	PWR 17x17	16	Zr-4 SR
D63	PWR 17x17	16	Zr-4 SR
	Total	97 [1]	

[1] Many of these rods are also provided to the International and Bilateral MOX Programs for further evaluation
[2] SR = Stress-Relieved

» ***Further supplements the International data and provides a strong database of AREVA specific designs***

Catawba LTA Program Objectives

MOX Fuel Design Report, BAW-10238(NP)

- **In Section 1.0, NRC approval was sought for:**
  - Using this fuel design in a confirmatory demonstration of two or four MOX LTA's irradiated for two cycles conditional upon receipt of required regulatory authorizations…
  - Batch implementation of the MOX fuel design to a max. rod burnup limit of 50 GWd/MThm conditional upon receipt of required regulatory authorizations…
- **Furthermore in Section 8.1**
  - "The primary purpose of the lead assembly program is to provide operational experience to demonstrate the acceptability of the MOX fuel design."
- **This led to development of performance criteria necessary for batch certification of MOX fuel (Table 8.2)**

Measurement	Criteria
Fuel assembly growth	Cold measurements of fuel assembly growth shall be consistent with a positive clearance between the fuel assembly and reactor internals under both hot and cold conditions at a maximum rod burnup of 50,000 MWd/MThm.
Shoulder gap	Cold measurements of shoulder gap shall be consistent with a positive clearance between the fuel rods and top nozzle under both hot and cold conditions at a maximum rod burnup of 50,000 MWd/MThm.
Fuel assembly RCCA drag force	Drag force shall not exceed: • 100 lbf in dashpot and • 60 lbf above dashpot.
Fuel rod integrity	No fuel rods in the lead assemblies shall fail from MOX fuel-related causes.
Fuel rod oxide thickness	Peak oxide thickness (using moving average over 1 inch) shall not exceed 50 μm.

Catawba LTA Program Objectives

Final irradiation results provided in:

- ANP-10280NP, Revision 2, Poolside Post-irradiation Examination of MOX Lead Assemblies
- ANP-10320NP, Revision 0, Summary Report on Post-irradiation Examinations of MOX Lead Assemblies

Fuel Assembly Growth

- Cold measurements of fuel assembly growth shall be consistent with a positive clearance between the fuel assembly and reactor internals under both hot and cold conditions at a maximum rod burnup of 50,000 MWd/MThm
- Criteria satisfied

Shoulder Gap

- Cold measurements of shoulder gap shall be consistent with a positive clearance between the fuel rods and top nozzle under both hot and cold conditions at a maximum rod burnup of 50,000 MWd/MThm
- Criteria satisfied

Catawba LTA Program Objectives

RCCA Drag Force

- Drag force shall not exceed
  100 lbf in dashpot and,
  60 lbf above dashpot
- Criteria Satisfied

Fuel Rod Integrity

- No fuel rods in the lead assemblies shall fail from MOX fuel-related causes
- Criteria satisfied

Fuel rod oxide thickness

- Peak oxide thickness (using moving average over 1 inch) shall not exceed 50 µm
- Criteria satisfied

» ***All Catawba MOX LTA's program performance criteria supporting batch certification were met***

Secondary Objectives
Catawba MOX LTA's

MOX Fuel Design Report, BAW-10238(NP), Section 1.0

- **In addition, approval sought for extending irradiation of one or more LTAs for a third cycle (beyond 50 but not exceeding 60 GWd/MThm)**
  - Results from the third cycle of irradiation are not necessary to support approval for batch implementation
  - They will be used to establish a database demonstrating successful operation beyond the approved burnup limit for MOX fuel
  - Results may potentially be used in future submittals to support an increased burnup limit for MOX fuel
- **This option led to the development of conservative reinsertion criteria (Table 8.3)**
  - Ensures that abundant margin is available to accommodate unanticipated operational issues

Measurement	Criteria
Fuel assembly growth	Cold measurements of fuel assembly growth shall be consistent with a positive clearance between the fuel assembly and reactor internals under both hot and cold conditions at the maximum rod burnup allowed in the fuel cycle design.
Shoulder gap	Cold measurements of shoulder gap shall be consistent with a positive clearance between the fuel rods and top nozzle under both hot and cold conditions at the maximum rod burnup allowed in the fuel cycle design.

» ***Third cycle irradiation was not a program requirement, but an option to supplement high burnup MOX data***

Secondary Objectives Catawba MOX LTA's

Fuel Assembly Growth

- **Cold measurements of fuel assembly growth shall be consistent with a positive clearance between the fuel assembly and reactor internals under both hot and cold conditions at the maximum rod burnup allowed in the fuel cycle design**
- **One assembly in four satisfied the reinsertion criteria**
  - One assembly was available for reinsertion
  - Excess fuel assembly growth in other three FA's amounted to the thickness of a dime
  - The other three would have required rework to conservatively ensure availability of additional margin for growth during third cycle of irradiation

Shoulder Gap

- **Cold measurements of shoulder gap shall be consistent with a positive clearance between the fuel assembly and reactor internals under both hot and cold conditions at the maximum rod burnup allowed in the fuel cycle design**
- **Reinsertion criteria satisfied**

» ***The decision was made by the utility not to pursue additional irradiation. This decision was unrelated to the FA growth***

Catawba LTA Program Overview

Summary of Post-irradiation Examinations of MOX Lead Assemblies, ANP-10320NP

- Focused on SRP In-Reactor phenomena
- Used to validate use of RG MOX fuel models for WG MOX

Results:

- Fuel provided acceptable performance,
- Advanced neutronic methods can reduce the calc. uncertainties for peripheral rods, and
- Performance of WG MOX fuel materials is accurately predicted using RG fuel models

SRP In-Reactor Phenomenon	Section Number and Examination
Fuel and burnable poison rod growth	
	3.4 Fuel Rod Growth (Poolside Measurements)
	4.2 Fuel Rod Growth (Hot Cell Measurements)
Fuel rod bowing	
	3.2 Fuel Rod Visual Examinations (Poolside)
	3.8 Water Channels
	4.1 Fuel Rod Visual Examinations (Hot Cell)
Fuel rod and spacer grid oxidation and hydride levels	
	3.1 Fuel Assembly Visual Examinations
	3.2 Fuel Rod Visual Examinations (Poolside)
	3.7 Fuel Rod Oxide Thickness
	4.1 Fuel Rod Visual Examinations (Hot Cell)
	4.7 Optical Microscopy of Fuel and Cladding
Fuel rod fretting	
	4.1 Fuel Rod Visual Examinations (Hot Cell)
	4.17 Inspection of Wear Marks
Fuel assembly growth	
	3.3 Fuel Assembly Growth
Fuel assembly bowing	
	3.5 Fuel Assembly Bow
Channel box wear and distortion	
	(not applicable to pressurized water reactor fuel)
Fuel rod ridging (PCI)	
	4.5 Fuel Rod Profilometry
Crud formation	
	3.2 Fuel Rod Visual Examinations (Poolside)
	4.1 Fuel Rod Visual Examinations (Hot Cell)
Fuel rod integrity	
	3.2 Fuel Rod Visual Examinations (Poolside)
	4.1 Fuel Rod Visual Examinations (Hot Cell)
	4.4 Eddy Current Testing
Holddown spring relaxation	
	3.10 Holddown Spring Height
	3.11 Holddown Spring Stiffness
Spacer grid spring relaxation	
	(not relevant to qualification of MOX fuel)
Guide tube wear characteristics	
	(not relevant to qualification of MOX fuel)

Catawba LTA Program Overview

Further evaluations of hot cell data will be presented in the proprietary session

- **Based on GALILEO code predictions of poolside and hot cell measurements**
- **Evaluations continue to show that WG and RG MOX fuel behave the same thermo-mechanically and both are accurately predicted**
- **Primary differences between RG and WG MOX are in neutronic behavior**
  - RG MOX fuel has more ^{240}Pu, ^{241}Pu and ^{242}Pu which requires higher Pu loadings to compensate for the negative reactivity effects
  - WG MOX is predominately composed of ^{239}Pu making it simpler to model
  - Standard UO_2 fuel builds up Pu immediately upon the start of irradiation such that by end of life, WG and Std. UO_2 fuel have comparable isotopics
  - Modern physics codes accurately predict standard UO_2, WG MOX, and the more complex RG MOX

» ***AREVA's RG MOX fuel models accurately predict WG MOX behavior***

Catawba LTA Program Overview

Once UO_2 fuel starts to burn it basically becomes MOX

- **Only difference is in % Fissile (or Total) Pu**

AREVA's UO_2 and RG MOX experience bound expectations for WG MOX

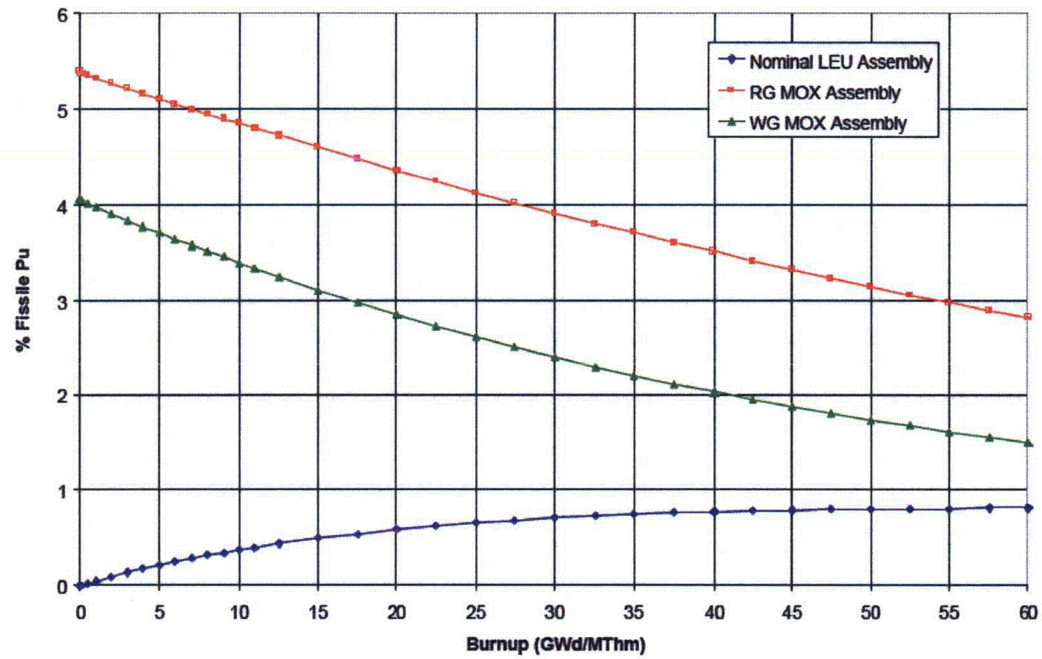


Figure 3.3 Fissile Plutonium as a Fraction of Total Heavy Metal

At higher burnups, MOX, and particularly WG MOX, is similar to UO_2 fuel composition.

Conclusions

AREVA's has almost 40 years of technical expertise in the design, manufacturing, and irradiation of MOX fuel

AREVA's MOX fuel rod database comprises the most extensive set of MOX qualification data available worldwide

Validation of AREVA codes & methods against this database demonstrates performance across the expected range of MOX applications in the US

AREVA's RG MOX fuel models accurately predict WG MOX behavior (i.e. RG and WG MOX behave the same)

Additional LTA test data is not needed to validate AREVA's MOX models for BWR/PWR batch licensing applications

» ***AREVA expects and will support additional meetings with the staff to review this data in the detail required to satisfy all safety and regulatory expectations***

MOX Project:
Codes & Methods Development

AREVA's MOX Fuel Database: Benchmarking Overview

Proprietary Session

AREVA

MOX Project:
Codes & Methods Development

GALILEO- AREVA
MOX Model Benchmarking

Patrick Blanpain
AREVA Fellow – Fuel Thermal Mechanics

AREVA

MOX Model Benchmarking

Objective

- Show that the European Reactor Grade (RG) MOX data used to benchmark AREVA's codes & methods is sufficient to justify their use for all steady-state and transient design and analysis necessary to license a MOX reload in both US PWR and BWR reactors.

Content

Code Overview

Global Validation Database & Range of Applicability

Validation Results

- Burnups
- PWRs and BWRs
- Steady-state and transient conditions

Conclusion

GALILEO Code Overview

GALILEO Database (1/2)

GALILEO predictive capability is supported by the extent and the representativeness of the database which includes

- Bilateral and International integral test programs
- Separate effects experiments
- Irradiation programs covering high burnup
- Low and high duty conditions
- Both BWR and PWR
- Recent data (bilateral, international & commercial irradiations)

A representative sample of the PWR and BWR MOX rods have undergone an extensive characterization program and been included in the MOX Fuel Rod Database.

Major code models were evaluated for performance against this database

- Centerline temperature, fission gas release, helium production, etc.
- Variety of cladding types
- Numerous lattice configurations (BWR and PWR)
- Range of fissile content

GALILEO Database (2/2)

AREVA's MOX Fuel Rod Database

Numerous International and Bilateral programs have been conducted to evaluate MOX behavior

- Evaluate physical phenomena occurring inside the fuel rod
- Include a number of transient tests (PCI, RIA)

Program	Year	Fuel	Investigated Phenomena	PWR Rods	BWR Rods
Halden [3]	1970's - Present	UO_2, UO_2-Gd, MOX	Fuel Temperature, FGR[1], Free Volume, Int. Press.	10 (HBWR)	
GRIMOX	1993-1995	UO_2, MOX	Fuel Temperature	2	
GERONIMO/TOP-GUN	1990's	MOX	FGR, RDC[2], Rod Length, Free Volume, Int. Press.		16
PRIMO	1987-1989	MOX	FGR, Free Volume, Int. Press.	9	
BR3 Irradiations	1980's	UO_2, MOX	FGR	3	
CAP Irradiations	1980's	UO_2, MOX	FGR, PCI Ramp, Free Volume, Int. Press.	6	
FIGARO	1993 – 1998	MOX	FGR, Free Volume, Int. Press.	2	
REGATE He	2006	MOX	Transient Helium	1	
PROMOX	1990's	MOX	FGR, Pellet Clad Interaction, Ramp Tests	6	
			Total Integral Test MOX Rods	39	16
			Total Integral Test Rods (UO_2, UO_2-Gd, MOX)	405 [4]	61

[1] FGR = Fission Gas Release [2] RDC = Rod Diameter Change [3] HBWR rods [4] PWR+HBWR

» *Represents a significant amount of data across a large range of operating parameters and includes modern data*

AREVA's MOX Fuel Rod Database

AREVA's Proprietary Database

- **Supplements the International and Bilateral Data**
- **Provides additional mechanical performance data**
  - Assembly & Rod Growth
  - Creep
  - Corrosion
  - Bow and Distortion
- **Confirms FA hardware performance**

Reactor Code	Assembly Type	# of MOX Rods	Cladding
D19	PWR 17x17	12	M5
D24	PWR 15x15	9	Zr-4
D42	PWR 17x17	18	Zr-4 SR[2]
D55	PWR 17x17	25	Zr-4 SR
D62	PWR 17x17	16	Zr-4 SR
D63	PWR 17x17	16	Zr-4 SR
	Total	96[1]	

[1] Many of these rods are also provided to the International and Bilateral MOX Programs for further evaluation
[2] SR = Stress-Relieved

» ***Further supplements the International data and provides a strong database of AREVA specific designs***

Large Validation Database Covering Entire Burnup Range of Interest

Code Range of Applicability

Reactor Type	PWR and BWR
Operation Type	Class 1 and Class 2 conditions
Fuel Type	UO_2, UO_2-Gd_2O_3 and MOX
Fuel Rod Burnup	
Cladding Type	
Fuel Temperature	Up to fuel melting

Characteristics of MOX vs. UO_2

MOX in-pile behavior differences are:

- Higher fuel temperature (for equivalent power conditions) due to:
  - Lower thermal conductivity
  - Higher reactivity
- Higher rod internal pressure at end of life due to:
  - Higher fission gas release (FGR) due to:
    - Higher fuel temperature
    - Heterogeneity of the fission rate density (fuel microstructure)
  - Additional helium production and release (HeR), mainly related to α – decay of Minor Actinides

Presentation is focused on fuel centerline temperature, FGR and densification/swelling

GALILEO Validation
Fuel Centerline Temperature (1/2)

» **Excellent temperature predictive capability**

GALILEO Validation
Fuel Centerline Temperature (2/2)

[ ]

» No bias versus burnup or LHGR

Fuel Centerline Temperature - MOX

Fuel Centerline Temperature - MOX

GALILEO Validation
Fission Gas Release Results (1/5)

» **Large spectrum of burnups and LHGRs**

GALILEO Validation
Fission Gas Release Results (2/5)

[redacted]

» **Accurate FGR predictive capabilities for all fuels**

GALILEO Validation
Fission Gas Release Results (3/5)

» **Accurate FGR predictive capabilities for PWR and BWR**

GALILEO Validation
Fission Gas Release Results (4/5)

[

]

Accurate FGR predictive capabilities for PWR and BWR

GALILEO Validation Fission Gas Release Results (5/5)

Accurate FGR predictive capabilities in transient conditions

GALILEO Predictions Rod Free Volume

[ ]

» Good overall predictions

GALILEO Predictions
Rod Internal Pressure

» Good overall predictions

MOX: Helium Production & Release (1/3)

MOX: Helium Production & Release (2/3)

Reliable He production calculations

MOX: Helium Production & Release (3/3)

Satisfactory predictive capability

MOX Fuel Densification & Solid Swelling

Predicted values well within the measurement range

Rod Elongation (1/3)

Zy4: No MOX specificity

Rod Elongation (2/3)

M5: No MOX specificity

BWR Rod Elongation (3/3)

» **Recrystallized Zr-2**

GALILEO Conclusion

The European MOX benchmarking data (both hot cell and reactor operating experience) are sufficient to demonstrate the ability of AREVA fuel rod design code to handle:

- **steady-state and transient licensing analyses**
- **for both PWRs and BWRs**
- **up to high burnups**

MOX Project:
Codes & Methods Development

Operational Performance of WG MOX Fuel

Kevin McCoy
Advisory Engineer
PWR Fuel Thermal Mechanics

AREVA

Performance of WG MOX Fuel Is Predicted by Available Models

Why would we expect that conclusion to be true?

What tests were done to confirm that conclusion?

What do the data tell us?

Performance of WG MOX Fuel Is Predicted by Available Models

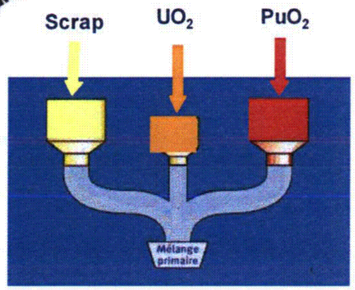
WG MOX and RG MOX are both mixtures of UO_2 and PuO_2

Processing (milling, blending, sieving, etc.) is the same, so pellet microstructure is the same

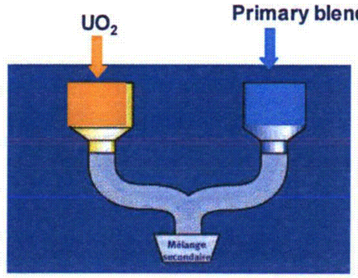
Models for MOX properties cover a range of compositions, including those for WG MOX

Density of fissile nuclei in agglomerates is similar

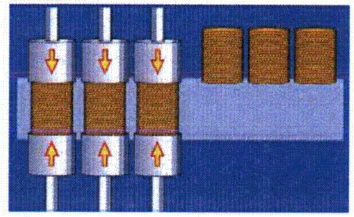
MOX MIMAS Fabrication Process
WG MOX Fuel = RG MOX Fuel



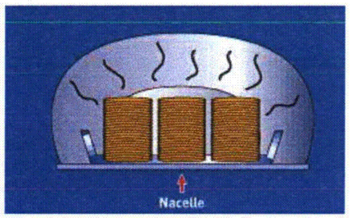
1 *Preparation of primary blend*



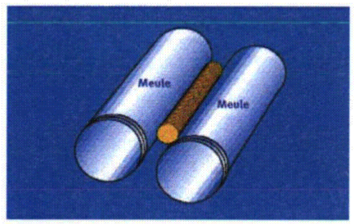
2 *Preparation of secondary blend*



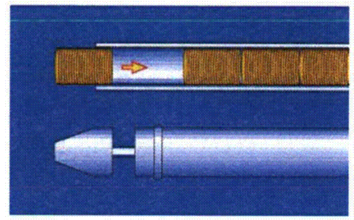
3 *Pressing or pelletizing*



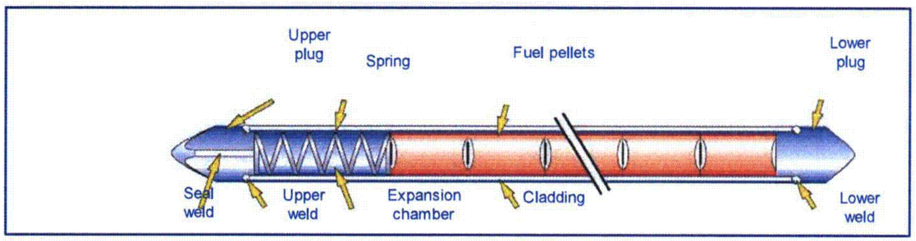
4 *Sintering*



5 *Grinding*



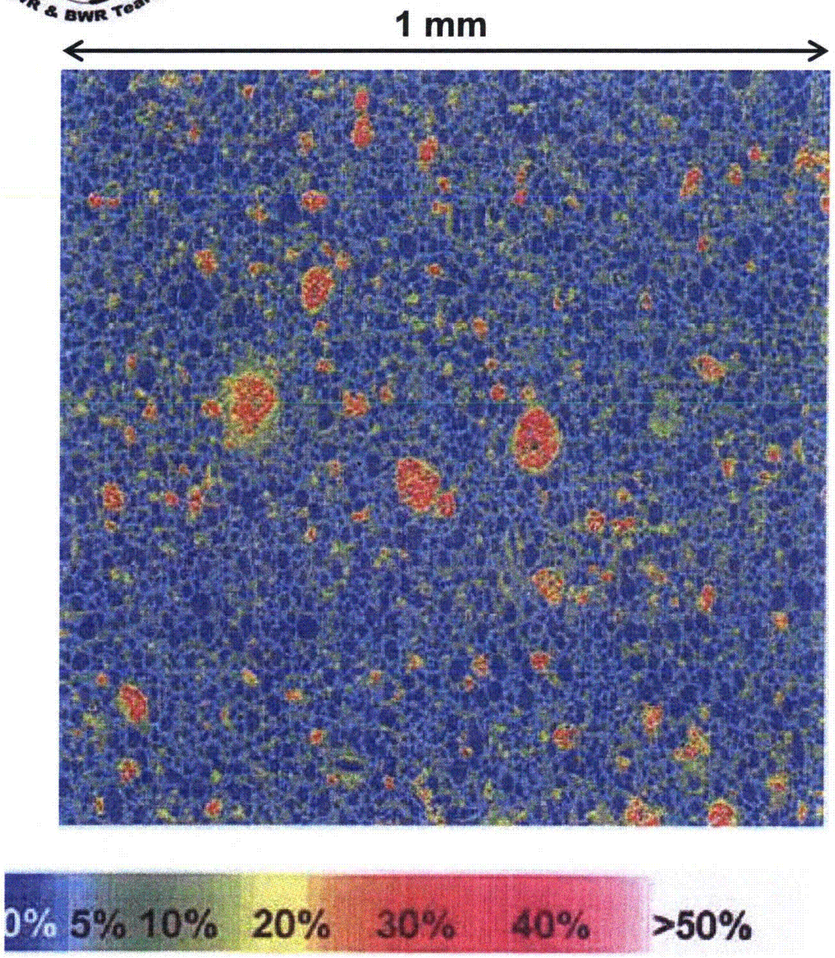
6 *Rod cladding*

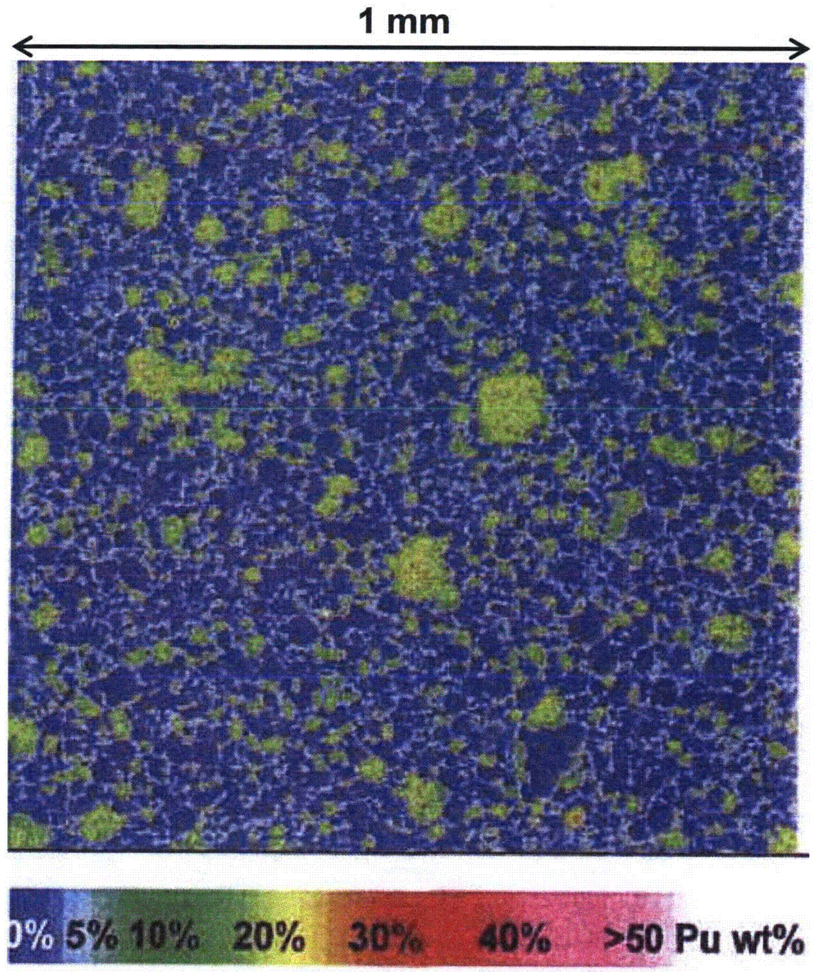


Light water reactor fuel rod

7 *Assembly fabrication*

RG and WG MOX: Pu X-Ray Maps





(Note that the color scales differ slightly.)

Models for MOX Properties Reflect Pu Content

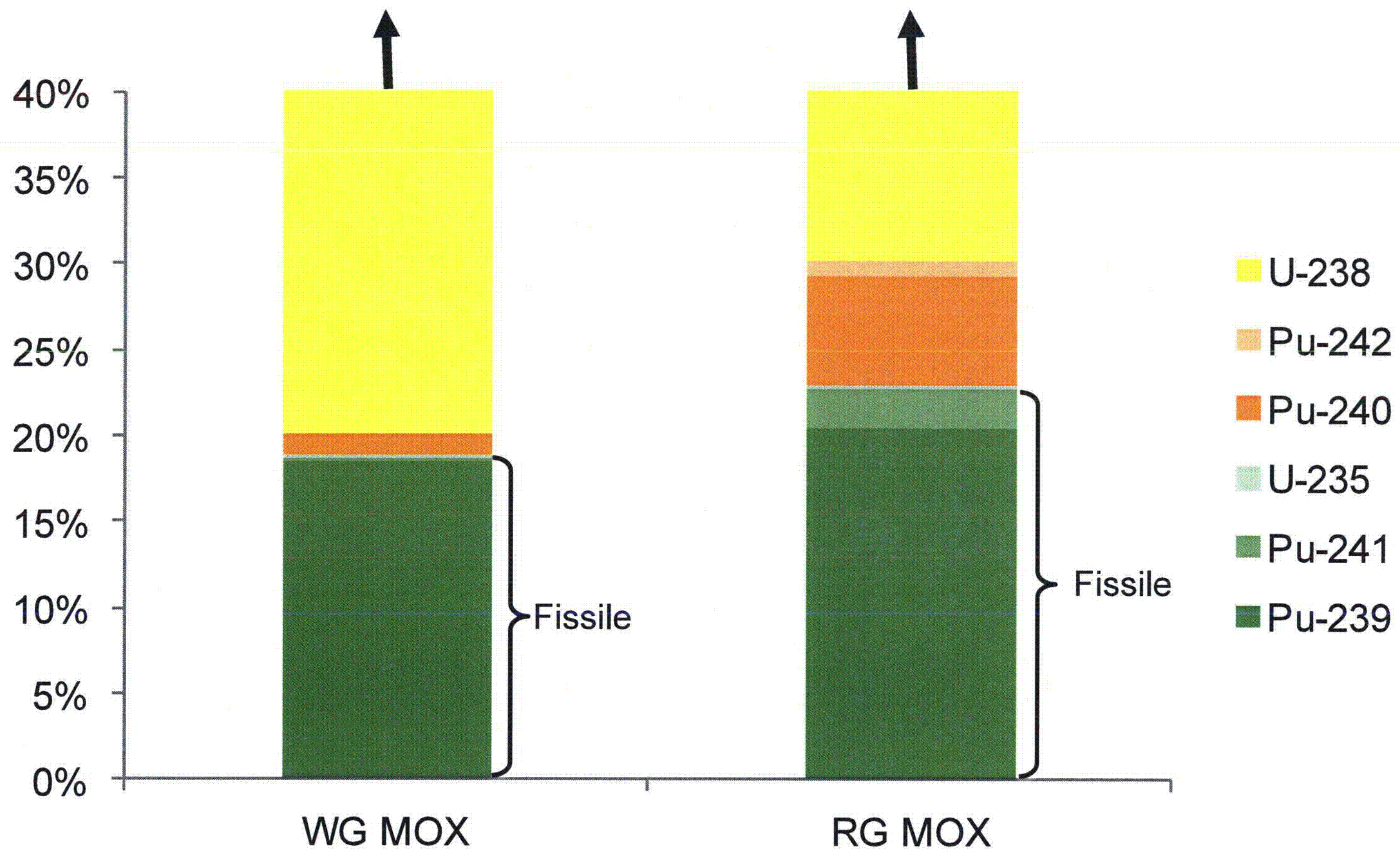
Thermal conductivity depends on Pu content, oxygen to metal ratio, etc.

Melting point depends on Pu content, etc.

...

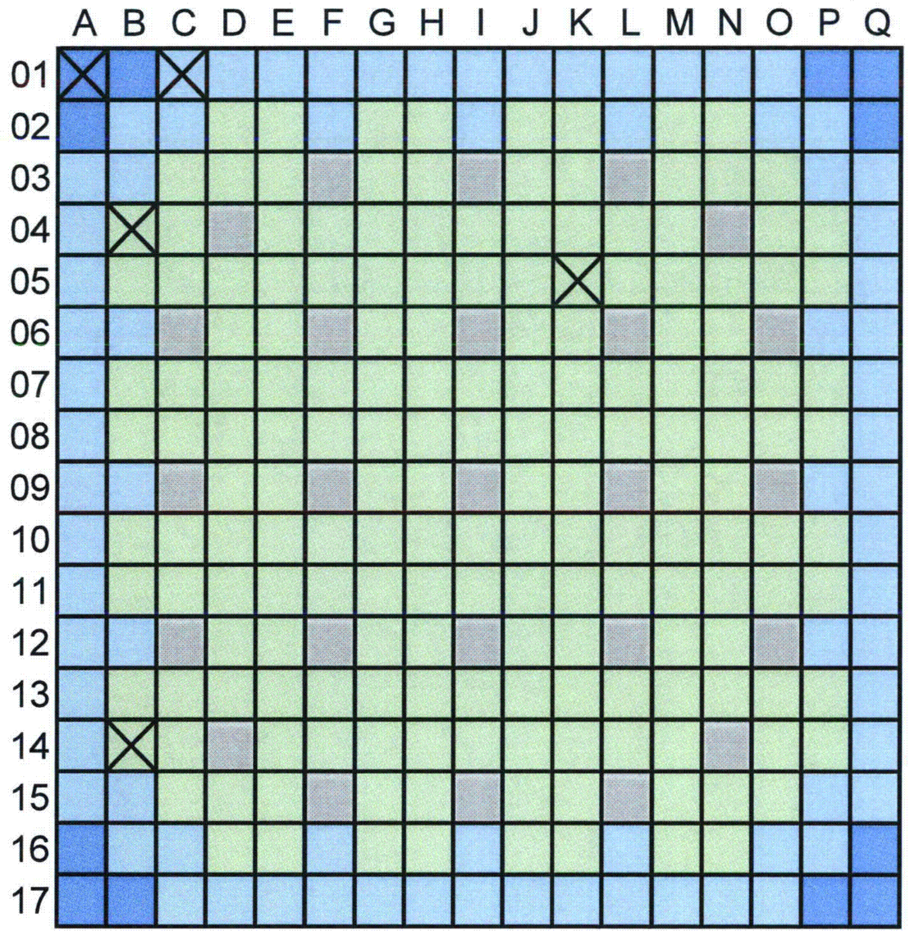
» **Pu content of WG MOX is within the range of Pu contents used in RG MOX**

RG and WG MOX Have Similar Fissile Nuclei Densities in Agglomerates



Typical Isotopics of Agglomerates

Diverse Fuel Rods Were Selected for Hot Cell Examination



☒ = Selected for hot cell exam
= Unfueled location
= High-Pu location (4.94%)
= Medium-Pu location (3.30%)
= Low-Pu location (2.40%)

Rod-average burnups were 40 to 47 GWd/MT

Examinations Were Detailed and Thorough

Nondestructive exams

- Visual examination
- Fuel rod length
- Gamma scanning
- Eddy current testing
- Fuel rod profilometry

Examinations Were Detailed and Thorough

Destructive exams

- Gas pressure, void volume, and gas analysis
- Optical microscopy of fuel and cladding
- Transmission electron microscopy of cladding
- Scanning electron microscopy of fuel and cladding, radial burnup profile
- Burnup determination
- Isotopic analysis of fuel
- Gallium analysis
- Cladding hydrogen analysis
- Mechanical testing of cladding (in progress)
- Pellet density
- Inspection of wear marks
- Cladding surface microscopy

Fuel Rod Visual Examination

Significance: provides general information on fuel rod performance and condition

[ ]

Fuel Rod Visual Examination

[ ]

Fuel Rod Visual Examination

Gamma Scanning

Significance: provides information on axial power shape, stack growth, stack gaps, and end peaking

[ ]

Gamma Scanning

Gamma Scanning

0

Gamma Scanning

Fuel Stack Growth

Gas Pressure, Void Volume, and Gas Analysis

Significance: provides information on fission gas release, gas pressure in spent fuel pool

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Gas Pressure, Void Volume, and Gas Analysis

Void Volume

Scanning Electron Microscopy

Significance: provides information on fuel pellet microstructure, cladding oxidation, gallium-cladding reaction, radial burnup profile

[ ]

Scanning Electron Microscopy

Summary

[ ]

Scanning Electron Microscopy

Scanning Electron Microscopy

Burnup Determination

Significance: provides information on accuracy of neutronic calculations

[ ]

Burnup Determination

AREVA

Burnup Determination

0

Gallium Analysis

Significance: provides information on postulated cladding degradation due to gallium

Gallium Analysis

Summary and Conclusions

Performance of WG MOX fuel is predicted by available models

- Similarity of RG MOX and WG MOX is expected
- Lead assemblies have been irradiated, and detailed, thorough hot cell exams were performed to confirm that expectation
- Exams showed no significant difference between RG MOX and WG MOX

The hot cell exams indicated safe operational performance

MOX Project:
Codes & Methods Development

PWR Neutronics MOX Benchmarks

Kevin Segard
Supervisor, PWR Neutronics Methods & Licensing
PWR MOX Project Technical Lead

AREVA

Agenda

Introduction

APOLLO2-A Validation

- Critical Experiments
- Spent Fuel Analysis

ARTEMIS / Core Operations Validation

Uncertainty Analysis

Transient Validation

Gd/UO_2 Rods in MOX Assemblies

Introduction

ARCADIA® Code System Topical Report (ANP-10297P)

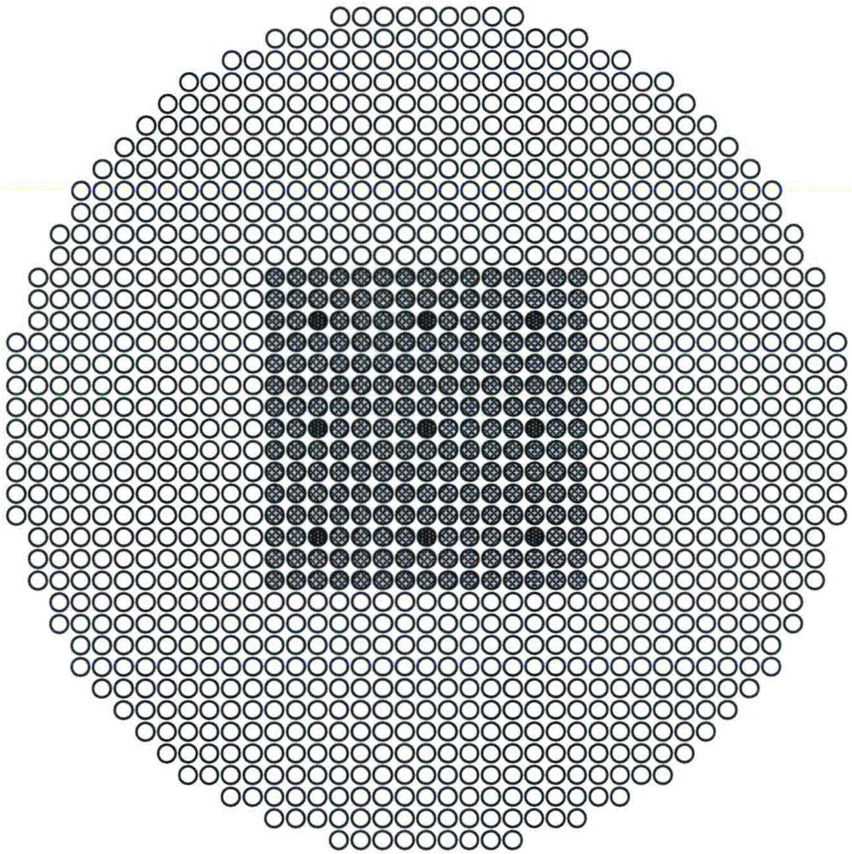
- Submitted for review in March 2010
- Draft SER reviewed and comments provided by AREVA in July 2012
- This TR addresses the use of ARCADIA for UO_2 cores

Supplemental information will be provided to license the ARCADIA® system for use with MOX

APOLLO2-A Validation

APOLLO2-A Validation Suite

APOLLO2-A Validation - PRCF



O UO_2 fuel rod

⊗ PuO_2 fuel rod (4 wt% PuO_2 / 18 wt% Pu^{240}) for Configuration III)
(2 wt% PuO_2 / 24 wt% Pu^{240}) for Configuration VIII)

● PuO_2, water hole, BP Glass, AIC, or B_4C rod

APOLLO2-A Validation EPICURE

APOLLO2-A Validation

[ ]

ARTEMIS Validation

ARTEMIS Validation Suite

ARTEMIS Validation

ARTEMIS Validation Suite

ARTEMIS Validation

ARTEMIS Validation Suite

Uncertainty Analysis

[ ]

Transient Validation

Gd/UO_2 Rods in MOX

AREVA has experience with Gd/UO_2 in BWR MOX fuel.

[ ]

Conclusions

The validation cases chosen for both APOLLO2-A and ARTEMIS™ demonstrate that the ACARDIA® code system is capable of handling MOX.

The transient validation cases demonstrate that the ARCADIA® is capable of accurately analyzing transient events.

The proposed treatment of gad/UO_2 rods in MOX will provide an acceptable uncertainty factor for use in the uncertainty analysis.

MOX Project:
Codes & Methods Development

BWR Neutronics MOX Benchmarks

Ralph Grummer
Supervisor
BWR Neutronics Methods & Codes

Agenda

Differences between UO_2 and MOX fuel

MOX Experience Base

MICROBURN-B2 Benchmarks

CASMO-4 Benchmarks

Differences between UO_2 and MOX fuel

The primary difference between UO_2 and MOX fuel from the neutronics perspective is the concentration of the heavy metal isotopics

UO_2 fuel produces all of the Pu isotopics from neutron absorption and associated decays.

MOX fuel initially has high concentrations of Pu isotopes

MOX Benchmark Data

MOX Benchmark Data

Comparison of Specific Lattice Designs

Equilibrium Cycle for all UO_2 design

- ATRIUM-10 XM 4.44 w/o 12 Gd Rods 8.0%

Equilibrium Cycle for UO_2 / MOX design

- ATRIUM-10 XM 4.19 w/o 18 Gd Rods 2.2%

Operating data for UO_2 / MOX Designs

- ATRIUM-10 XP 4.56 w/o 4 Gd 1.5%

U-238

U-235

Pu-239

Pu-240

Pu-241

Pu-242

Gd-155

CASMO-4 VALIDATION DATABASE

CASMO-4 validation includes an existing database that is documented in the following references from the code developer, Studsvik:

- ***CASMO-4 Benchmark Against Critical Experiments (Proprietary SOA-94/13)***
- ***CASMO-4 Benchmark Against MCNP (Proprietary SOA-94/12)***
- ***CASMO-4 Benchmark Against Yankee Rowe Isotopic Measurements (STUDSVIK/SCOAB-96/5)***

Benchmark of CASMO-4

[ ]

Colorset

[ ]

Benchmark of CASMO-4

MICROBURN-B2 Validation database

MICROBURN-B2 Validation database

CASMO-4/MICROBURN-B2 Validation Database

CASMO-4/MICROBURN-B2 Validation Database

Conclusions

AREVA Concludes:

There is sufficient data available to demonstrate the adequacy of the models to predict the behavior of WG MOX fuel

Additional Lead Use Assemblies will not provide any more information than is already available.

Meeting Wrap Up

AREVA has developed a substantial benchmarking database over the last few decades

- Includes a significant amount of MOX data (BWR and PWR)
- Addresses steady-state and transient operation
- Addresses operational range of applicability (e.g. burnup, enrichment, etc.)
- Significantly expands on validation data presented in previous AREVA submittals

The CAT LTA program provides a further validation point confirming:

- MOX can be successfully manufactured, loaded, and burned in US reactor's
- AREVA's codes and methods accurately predict MOX behavior

AREVA concludes that additional LTA data are not necessary for understanding of the codes & methods and their associated uncertainties