The importance of the Fuel Design

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AREVA Fuel BU Executive Vice President

Atoms for the Future 2012
October 24th, 2012 - Paris
The importance of Fuel Design

Contents

- Fuel Assembly: A highly engineered and technologically specific product
- Fuel Assembly Design is key for Performance
- Fuel Assembly Design is decisive to ensure Fuel Reliability and optimized Operation
- Modeling is essential for Design optimization
- What the Future of Designing might be…
Fuel Assembly: A highly engineered and technologically specific product
Fuel Assembly: Just a set of sticks?

PWR Fuel

BWR Fuel
**No! Fuel Assembly is the Oil and the Engine**

**The Oil**
- Enriched uranium pellets (or Mixed Oxide or Enriched Reprocessed Uranium pellets) loaded into zirconium rods
- ~ 200 W / cm

**The Engine**
- A ~4 m structure made of guide tubes bundled together with grids
- Flow and geometry control
  - Nozzles Allow coolant flow outlet/inlet and Bottom nozzle stop debris
  - Spacer grids ensure the positioning of the fuel rods
- Insertion of Rod Cluster Control Assembly (RCCA) for reactivity control
- ~ 700 kg (PWR FA)
No! Nuclear Fuel is a highly engineered product

- 1st barrier against nuclear contamination
  - Integrity of the fuel rod under extreme conditions of temperature, pressure and flow (PWR conditions: ~155 bar / ~350 °C / 5m/s water flow)
  - Maintained geometry under normal and accidental conditions

- Long time to market due to extensive testing
  - ~10 to 15 years for a new product
  - One type of product per type of reactor

- Highly challenging requirements
  - Utilities expect 0 issues / 0 defaults with their fuel
  - Excellence in manufacturing is decisive
A large set of tests to support the Fuel Assembly Design activities (1/2)

Tests before irradiation in hydraulic facilities (Kathy, Hermes, Peter)

- Thermal hydraulic Testing in the Kathy loop
  Karlstein, Germany
  - BWR bundle for Dry Out tests
  - Campaign of CHF tests for a new PWR grid

- Mechanical endurance test to assess FA behavior under vibration
  - Hermes, CEA test loop for wear evaluation
  - Peter loop, Erlangen for vibration mode identification

Design Qualification and Licensing
A large set of tests to support the Fuel Assembly Design activities (2/2)

- **Tests on irradiated components**
  - Hot cell examinations
  - Ramp tests in experimental reactors
    - Characterization of mechanical behavior of irradiated material

- Design option validation / Modeling Database / Investigation on failed fuel
A complex and parcelled Fuel Market

### PWR Plants

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<th>FRA</th>
<th>KWU</th>
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### BWR Plants

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- **Wide range of operating conditions**
  - Cycle lengths and loading patterns
    - 6 to 24 months
    - 1/2 to 1/5 fuel management
  - Coolant temperature and chemistry
    - Li up to 5 ppm / Zn injection
  - Linear heat rate
    - From 130 to 240 W/cm

- **Almost always at least 2 international suppliers are able to provide any specific FA design**

- **A wide variety of plants requiring specific fuel assembly designs**
  - Over 136,000 AREVA PWR fuel assemblies supplied in 140 PWRs worldwide
  - Almost 74,000 AREVA BWR fuel assemblies supplied in 60 BWRs worldwide
A small Cost for a Great Stake

Relative breakdown Generation Cost

- Operating and maintenance: 56%
- Front-end: 28%
- Back-end: 6%
- Depreciation: 10%

- Design-Fabrication: ~15%
- Enrichment
- Conversion
- Natural Uranium

~85%
Fuel Assembly Design is key for Performance
Constant concern to match utility needs by increasing performance through …

- Improved fuel cycle economy and reparable
  - Improved T/H performance and reliability
  - Enhanced Performance, Reliability and Handling
  - Enhanced Robustness
M5®: A Breakthrough Cladding Supporting PWR Fuel Rod Performance

- High corrosion resistance
  - Impressive gain vs. Zircaloy-4 allowing high BU applications
- Extremely low hydrogen uptake
  - EOL hydrogen content < solubility limit in operation
- PCI technological limit pushed higher
  - Allows extension of plant operating diagram and relaxation of PCI induced limitations

M5® cladding provides margins for fuel management upgrades and flexibility in operation compared to Zircaloy 4
Performance
25 year Increasing Discharge Burnups

Average Discharge Burnup - PWR [MWd/kgU]

Year of Discharge


Worldwide Experience

Burnup of Peak Reload Batch

Average of All Fuel Assemblies Discharged Each Year

25 30 35 40 45 50 55 60

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Fuel Assembly Design is decisive to ensure Fuel Reliability and smooth Operation

Some examples
Beginning of the 2000’s, AREVA experienced grid-to-rod fretting of AFA 2G fuel assemblies in some 17x17 14 ft

- GTRF issue occurred after GEMMES fuel management implementation in the 14ft 4 loop plants (Fuel assembly burnup Increase)
- Higher axial flow rate (+14%) and higher transverse flow (+60%) in the first span of the fuel assembly in a 14ft 4 loop plant
- Only at the bottom grid level

Grid To Rod Fretting

Development and Implementation of the “twin grid” concept on the 14 ft designs in 2002

- 14 ft AFA 3G design has not been concerned any more by GTRF
- As of May 2012, more than 8,300 fuel assemblies were irradiated in 23 14 ft plants
Resistance to FA deformation: Monobloc® Guide Tube and Hold Down system Optimization

- Mid of the 90’s, AREVA experienced severe fuel assembly distortions of AFA 2G fuel assemblies with 17x17 designs
  - Extensive fuel assembly bow measurements (14,000 available as of December 2010) to support understanding program and modeling
  - Systematic rod drop time measurements at end of each cycle

- Prompt implementation of a thick MONOBLOC® guide tube with appropriate Hold Down spring force reduction
  - As of May 2012, more than 26,500 fuel assemblies are made of MONOBLOC® guide tubes
  - These improvements reduced the in-core deformation by about a factor 2

RCCA Drop Time Abnormality Indicator Value

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900 MW
1300 MW
Modeling is essential for Design optimization
FA deformation Modeling

► Development launched in 1993
  ◆ Mechanical and hydraulic modeling
  ◆ A large FA deformation measurement database

► Accelerated in 2002
  ◆ Fluid Structure Interaction modeling
  ◆ STAR CD Hydraulic calculation
  ◆ More powerful computation

Schematic Visualization of FA Bow in a PWR core
Complex collective phenomena can be reproduced and design changes assessed with confidence.
What the Future of Designing might be…
Three main drivers

- **Highest safety standards**
  - Training for awareness
  - Advanced codes & methods

- **Human Performance**
  - Decisive for securely achieve right design

- **Knowledge Management**
  - A main stake for all actors of the nuclear fuel industry

A step forward in Performance and Achievements
Safety will remain the first objective

The safety principles rationale (re-)explained

- A specific Safety course
  - Understanding the rationale behind the criteria
  - Knowledge of the underlying assumptions
  - Radiological impact root criteria
- Real accidents and their 3 simultaneous root causes
  - Programmatic, Material and Human

A Governance Giving Priority to Training and People Development

- Benchmark of technical and quality training investments in all regions
  - Mentoring, technical courses, quality system mastering,…
- Planning quantitative competency building individually (600 plans)

Acting with the highest level of awareness
Implementation of advanced Codes & Methods

**ARCADIA® / ARGOS**
- Full core 3D T/H calculations with subchannel by subchannel
- Mechanical and T/H fuel and core design codes: A step forward
  - FA bow simulation including mechanical and FSI effects
  - Fuel Rod bow and Fuel Assembly growth simulations
  - CFD tools to select the best solutions for new and improved products

**GALILEO**
- 1400 fuel rod worldwide database, including MOX
- Conservative Thermal mechanical assessment in all operating conditions
- Implementation of advanced Codes & Methods
  - FA bow simulation including mechanical and FSI effects
  - Fuel Rod bow and Fuel Assembly growth simulations
  - CFD tools to select the best solutions for new and improved products

**XEDOR™**
- Unique on-line PCI risk monitoring for BWR
- XEDOR™ implementation

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Always more cooperation between Utilities and Fuel Suppliers

The fuel rod is the first safety barrier

FUEL

Safety

Reliability

Performance

Fuel is a technically specific product

Quality of interaction between the 3 actors will remain the best guarantee of Safety, Reliability and Performance
Take Away

- Fuel Assembly is a highly engineered and technologically specific product

- Capitalizing 25 years of continuous improvement

- Leading to Enhanced Performance & Reliability in Operation

- Going forward with….
  - R&D focused on modeling
  - Safety culture orientation
  - Secured knowledge management
  - Active collaboration between all actors
Thank you for your attention!

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AFA fuel assembly (first generation)

*Bi-metallic grid design implementation*

- Move from all Alloy 718 grids to AFA bi metallic grid in 1985
  - Need to decrease Alloy 718 content of the fuel assembly
  - Keep acting grid spring forces as long as possible to prevent grid to rod fretting (GTRF)

- Implementation of screwed connections to the upper and lower nozzles
  - Not to get anymore fuel assemblies definitely discharged because of a leaking fuel rod
AFA second generation fuel assembly
Enhanced performance and reliability

- Move to the AFA 2G grid design
  - Improvement of the vane size and pattern
  - Capability to meet higher CHF performance request

- Move to Zy4 low tin cladding and anti-debris nozzle from 1991
  - Increased burn-up and high duty conditions required cladding with higher performances with regard to corrosion
  - At that time, debris fretting brought about most of the cladding failures
AFA third generation fuel assembly

Enhanced robustness

- Implementation of a thick MONOBLOC® guide tube with appropriate holddown spring force reduction

- Implementation of the “twin grid” concept on the 14 ft designs to avoid GTRF

- Improved AFA 3G grid against handling hazard

- Implementation of the anti-debris Trapper bottom nozzle

- Move to M5® material for cladding and structure components
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Back-Up Slides
GAIA fuel rod features offer a variety of benefits for maximum flexibility in PWR fuel managements.
Mitigation of PCI-induced stress

PCI Critical area - BU : 20-50 GWd/tU

- M5® / UO₂ safe zone
- M5® / Cr₂O₃-doped fuel benefit zone
- Zy-4/UO₂ - Non-Failed
- Zy-4/UO₂ - Failed
- M5/UO₂ - Non-Failed
- M5/UO₂ - Failed
- Zy-4/Cr₂O₃-doped UO₂ - Non-Failed
- M5/Cr₂O₃-doped UO₂ - Failed
- M5/Cr₂O₃-doped UO₂ - Non-Failed

\( \Delta P_{\text{max}} \) (W/cm)
A Robust Fuel Rod Welding Process

- AREVA fuel experienced some fuel failures due to weld defects in 2005 (Root cause: Pollutant contamination)

- Best Practice Study launched
  - French and Belgian manufacturing facilities using laser and TIG welding
  - German and US facilities using upset shape welding (USW)

- USW determined Best Practice
  - AREVA facilities transitioned to USW by 2007

More than 5 000 000 leak proof welds
A smooth loading of the AFA 3G fuel rods

- AFA 3G fuel experienced early leakages (small holes in the cladding)
  - Root cause: Harmful shavings created during loading of fuel rods in the fuel assembly structures

- Decisive corrective actions
  - Corrective actions in fuel manufacturing plants to ensure a smooth loading of the fuel rods into the fuel assembly structure
  - Implementation of loading of fuel rods lubrication in manufacturing plants

- AFA 3G early leaking rate divided by a factor ~ 10

Back to high reliability records
A step forward in Mechanical Modeling

- Secured resistance to grid-to-rod fretting ensured by analytical and experimental means from AREVA and CEA
  - CFD/LES simulations, Peter loop test, autoclave tests, HERMES P loop test

- Tools to support enhancement of fuel assembly resistance to lateral deformation
  - Fluid structure interaction (Peter loop), Network modeling
A step forward in Thermal Hydraulic and Neutronics Modeling

- CFD tools and AREVA facilities (KATHY loop) to secure and speed up the Design improvement process
  - Easier Grid vane Design Optimization

- AREVA started implementing a new generation of advanced Codes & Methods integrating state of the art physics
  - Full 3D information for entire core
  - → more precise analysis
  - → more insight / understanding
Human Performance at the heart of the Design Activities

Instilling Safety-Quality Culture and Adequate Behaviors

- A set of easy-to-use support tools
- Based on
  - Systematic questioning of calculations, assumptions ➔ Questioning Attitude, Peer Reviews…
  - Avoiding misunderstanding in the transmission of information between individuals ➔ Pre-job briefing, turnover…
  - Systematic analysis of deviations
  - Generalization of good-catches
  - ...
- And a quarterly review process closely involving the managers

Documented methods and continuous controlling process to achieve the right mindset and performance in a sustainable way

A global approach HU / Safety with practical examples: numerous small deviations can lead to 1 main safety issue
Knowledge Management: A main Stake

A Fuel Design Organization Leveraging all assets

Global and Local: exhaustive and responsive

An Organization making all AREVA Knowledge available to our Customers for the Sake of the Public