USHPRR Base Fuel Qualification Plan and Requirements

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Outline

- Program level goals and requirements
- Regulatory framework for research reactor fuel
- Fuel qualification plan
- Fuel performance requirements
- Fuel testing program
Outline

• Program level goals and conversion requirements
• Regulatory framework for research reactor fuel
• Fuel qualification plan
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• Fuel testing program
Program Level Requirements

- Documented in USHPRR Functions and Requirements, Rev.1, August 2014

  - F 0: Convert to LEU fuel, or verify the shutdown of approximately 200 HEU research reactors by 2030
    - F 0.1.1—Convert USHPRRs to LEU

  - F 1.0: Develop and qualify an alternative LEU fuel

  - F 2.0: Convert Research Reactors to Use Alternative LEU Fuel
Program Level Goals

USHPRR Functions and Requirements (Rev.1, August 2014) states: “To be successful, the USHPRR Conversion Program must develop LEU fuels that are:”

• QUALIFIED
  – fuel that has been successfully irradiation tested and is licensable from the point of view of fuel irradiation behavior
  – integrity and performance of the fuel has been demonstrated through analysis and testing

• COMMERCIALLY AVAILABLE
  – fuel that is available from a commercial manufacturer

• SUITABLE
  – safety criteria are satisfied
  – performance criteria are satisfied
  – fabrication criteria are satisfied
• R 0.8: Safety shall not be adversely affected by conversion and subsequent operation
• R 1.0.3: Design features shall be selected to ensure that the fuel and cladding operate safely under all credible environmental and operating conditions….
• R 1.0.4: Fuel qualification and safety analysis information shall be valid, applicable, and supported by referenced tests, measurements, and operating experience
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Research Reactor Fuel Licensing

- There is not a NRC defined process for Research and Test Reactor Fuel Qualification
- Fuel is licensed as part of the reactor
  - NUREG-1537 provides guidance for reactor licensing
- Most recent precedent for fuel is NUREG-1313
  - Safety Evaluation Report for generic acceptance of U$_3$Si$_2$ fuel in 1988
- IAEA Guide NF-T-5.2
  - Good Practices for Qualification of High Density Low Enriched Uranium Research Reactor Fuels
  - Developed with input from U.S. program
- USHPRR documents
Reactor Licensing

- Non power reactors (including research and test reactors) are licensed using the process outlined in NUREG-1537, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors (1996)
  - Part 1: Format and content guidance for applicants and licensees
  - Part 2: Standard review plan and acceptance criteria for reviewers
  - Scope includes construction permit, initial operating license, license renewal, license amendment, decommissioning and license termination, and highly enriched to low-enriched uranium core conversions

- NUREG-1537 was written as an alternative to LWR licensing regulations
  - ...These documents <RG 1.70, NUREG-0800> were developed specifically for LWR nuclear power plants. Applicants who would use these documents to prepare SARs for non-power reactor facilities and NRC staff who would use them to review these SARs may find it very cumbersome because of the great difference in complexity and hazards between non-power reactors and nuclear power plants....The guidance herein is based on...10CFR50.34, which describes the information to be supplied in a SAR.
NUREG-1537 Section 4.2.1: Reactor Fuel

...the applicant should describe the reactor fuel system. Included should be the design features selected to ensure that the fuel and cladding can withstand all credible environmental and irradiation conditions during their life cycle at the reactor site. The discussions should address the in core fuel operating conditions.

- Chemical composition, enrichment, uranium loading, and important metallurgical features of the fissile material in the basic fuel unit....
- Description of the basic fuel unit, including plates, rods, pins, or pellets. This information should include dimensions, fabrication methods, and cladding or encapsulation methods....
- Material and structural information such as dimensions, spacings, fabrication methods, compatibility of materials, and specifications with tolerances....
- Information on material parameters that could affect fuel integrity, such as melting, softening, or blistering temperatures; corrosion; erosion; and mechanical factors, such as swelling, bending, twisting, compression, and shearing.
- Physical properties with significance in regard to safety and fuel integrity that are important for the thermal-hydraulic analyses, such as heat capacity, thermal conductivity, gas evolution or diffusion, occluded or encapsulated void volume, fuel burnup limits, capability to retain fission products, swelling resistance, and build up of oxides.
NUREG-1537 Section 4.2.1: Reactor Fuel (continued)

- A brief history of the fuel type, with references to the fuel development program, including summaries of performance tests, qualification, and operating history.

- Mechanical forces and stresses, hydraulic forces, thermal changes and temperature gradients, internal pressures including that from fission products and gas evolution, and radiation effects including the maximum fission densities and fission rates that the fuel units and elements are designed to accommodate.

- Limits on operating conditions for the fuel should be supported by information and analyses. These limits are specified to ensure that the integrity of the fuel elements and their cladding or fission product barrier will not be impaired. They should form the design bases for this and other chapters of the SAR, for the reactor safety limits, and for other fuel-related technical specifications.
Other Miscellaneous NUREG-1537 Guidance

• Section 4.5.3, Operating Limits:
  – A transient analysis assuming that an instrumentation malfunction… It should show that the reactor is not damaged and fuel integrity is not lost.

• Section 6, Engineered Safety Features:
  – Licensees analyze a maximum hypothetical accident that assumes an incredible failure that leads to breach of the fuel cladding or a fueled experiment containment.

• Chapter 14, Appendix 14.1, Technical Specifications:
  – To prevent fuel swelling there should be burnup limitations on the fuel. Aluminum-clad aluminum-matrix MTR-type fuel plate non-power reactors should have technical specifications that limit uranium-235 burnup or fission density…..NRC is specifically concerned with the maximum burnup limit for plate-type fuels because of the buildup of oxide on the fuel cladding.

• Chapter 18:
  – …If NRC has previously reviewed and accepted the proposed fuel, reference should be made to the acceptance document (e.g., NUREG-1281, -1282, or -1313).
NUREG-1313

- Most recent/relevant precedent for acceptance of fuel by NRC
  - This evaluation is based primarily on reports issued by ANL that discuss and summarize the developmental tests and experiments, including postirradiation examinations, of both miniature and full-sized plates of prototypical fuel compositions. This evaluation concludes that plate-type fuels suitable and acceptable for use in research and test reactors can be fabricated with $\text{U}_3\text{Si}_2$-Al dispersion compacts with uranium densities up to 4.8 g/cm$^3$
  - These reports, which have been reviewed and evaluated by the Idaho National Engineering Laboratory (INEL), provide the principal bases for the U.S. Nuclear Regulatory Commission’s (NRC’s) acceptance of the use of this new fuel type.... R. R. Hobbins (INEL) conducted the principal technical review under contract to the NRC.
  - The two ANL reports are included as Appendices A and B in this evaluation report.
NUREG-1313 (continued)

• Precedent for ‘split’ submittal of Base Fuel Qualification Report
  – Most of the irradiations were performed in the ORR, where essentially a full-core irradiation program also was conducted. No results of the latter are discussed in the ANL reports. ANL will report on the full-core irradiation program and on any observations or results from the full-core test that conflict with or shed more light on the individual plate and fuel element tests .... discussions with ANL staff indicate that no fuel failure or unpredicted behavior occurred....

• Scope of NRC review
  – The results presented are confined to characteristics of the fuel itself and were not intended to constitute a full safety review of the use of the U₃Si₂–Al fuel system in operating reactors.

• Specification
  – ...acceptance specifications should be developed and required ...to ensure that the fuel samples tested were representative of the fuel elements to be produced under future industrial production-type conditions.
  – Unqualified approval of the U₃Si₂–Al fuel is contingent on the following two conditions: (1) acceptance specifications and (2) evaluations of the results of the full-core tests in the ORR.
IAEA Guidance: NFT-T-5.2

- Good Practices for Qualification of High Density Low Enrichment Uranium Research Reactor Fuels
- PHASE 1: FUEL RESEARCH AND DEVELOPMENT
  - Fuel concept design
  - Fuel manufacturing development
  - Out-of-pile testing
  - Irradiation testing and post-irradiation examination, and
  - Decision point.
- PHASE 2: FUEL PERFORMANCE QUALIFICATION
  - Detailed design
  - Technical specification
  - Prototype manufacturing assessment and development
  - Prototype fuel element (FE) and fuel assembly (FA) manufacturing
  - Qualification test planning
  - Prototype full size FA irradiation testing, including post-irradiation examinations
  - Fuel qualification report, and
  - Fuel licensing
IAEA Guidance: NFT-T-5.2

- Basic properties of unirradiated fuel
  - Fuel-material chemical and phase compositions
  - Fuel-material heat capacity
  - Fuel-material thermal properties
  - Fuel-foil properties (for monolithic fuel)

- Fuel meat and fuel element as-manufactured properties
  - Fuel-meat volume and constituent volume
  - Fuel-meat (element) heat capacity
  - Fuel-meat and cladding thermal conductivities
  - Fuel-meat (element) thermal expansion coefficient
  - Exothermic energy release upon heating
  - Fuel-element mechanical properties
IAEA Guidance: NFT-T-5.2

- Fuel-meat and fuel-element irradiation properties
  - Fission density distribution
  - Fuel element swelling
  - Fuel meat swelling
  - Fuel meat and fuel particle microstructures
  - Fuel element mechanical integrity
  - Blister threshold temperature
  - Cladding corrosion behavior
  - Fission product release
  - Fuel-assembly properties
  - Hydraulic and mechanical behavior
  - Fuel-assembly irradiation behavior
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Fuel Qualification Plan

- Introduction
- Requirements for Qualification
- Approach to Fuel Development and Qualification
  - Design improvement
  - Fuel Irradiation Testing
  - Post-irradiation Examination
  - Out-of-pile Testing
- Fuel Qualification and Demonstration Testing (purpose of and brief description of tests)
  - MP-1, FSP-1, MP-2, ET-1, ET-2, DDEs
- Data Quality Planning and Quality Assurance
- Separate sections for HFIR and ATR were added in FY14

Base Monolithic Fuel: Research, Development, and Qualification Plan

K. Daum, Carla Miller, Brian Durtschi

December 2014
USHPRR Fuel Qualification Process

- Select Design Features
- Develop Requirements for Fuel Qualification
- Develop Fuel Specification
- Demonstrate Fabrication
- Generate Data and Analysis that Prove Qualification Requirements are Met
- Submit Base Fuel Qualification Report
- Demonstrate Reactor Specific Features (DDEs)
Base Fuel Qualification Flowchart

 USSPRR Conversion Requirements F&ORs

 FFC
 FFC R&D Plan
 Fabrication Requirements

 FD
 Base Fuel Qualification Plan
 FD Test Planning and Execution T&FRs

 RC
 Conversion Analysis (Reactor Requirements)
 Testing Envelope Requirements

 Fuel Performance Data Collection and Analysis

 Fuel Performance Data Collection and Analysis

 DA & Fuel Product Specification
 Commercial Fabrication

 Base Fuel Qualification Report
 Accept Generic Fuel

 DDEs
 Reactor Licensing
 Reactor Conversion

 Reactor Conversion
Base Fuel Qualification Report

- Major revision in FY15 to align with F&Rs and Base Fuel Qualification Plan (and add new data)
- Contents
  - Fuel design
  - Fuel fabrication
  - Microstructural attributes (fuel, cladding, diffusion barrier)
  - Fuel properties (mechanical, thermal)
  - Fuel-to-cladding and cladding-to-cladding bonding
  - Irradiation behavior
  - Off-normal behavior
  - Fission product retention
- Submittal to NRC based on completion of ET-1 irradiation and non-destructive PIE
- NRC approval based on completion of ET-1 PIE
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Fuel Requirements

Focus of Fuel Development data generation and analyses

Focus of Fuel Development irradiation testing

F 1.0
Develop and Qualify Alternative LEU Fuel

F 1.1
Mechanical Integrity

F 1.2
Geometric Stability

F 1.3
Stable & Predicable Behavior

F 1.4
Mission Envelope

F 1.5
Tests to Verify

F 1.6
Fabrication Development

Reactor Operation

Fuel Performance

Fabrication
Summary of Fuel Performance Requirements

Mechanical Integrity
- Ensure no delamination during normal operation and anticipated transients
- Mechanical response of the fuel meat, cladding, and interlayers is established

Geometric Stability
- Plate movement caused by pressure differential does not compromise ability to cool the fuel
- Geometry is maintained during normal operation and anticipated transients
- Irradiation–induced degradation of properties does not lead to conditions that result in loss of coolability

Stable and Predictable Behavior
- Fuel performance shall be known and predictable
- Fuel swelling is within a stable regime
- U-Mo corrosion behavior after breach is known
- Irradiation behavior on scale up is predictable
Mechanical Integrity

- Fuel is tested in steady state with margin beyond the normal operating regime
- Testing envelope is determined by conversion element design

No delamination has been found during normal operation and anticipated transients
High power density region of design space driven by HFIR and ATR
No delamination during normal operation and \textit{anticipated transients}
Mechanical Integrity

Mechanical response of the fuel meat, cladding, and interlayers shall be established

- Finite element-based modeling is the primary tool used to understand mechanical response
  - Failure analysis
  - Parametric studies that define sensitivity to specific properties and irradiation conditions

- Reliable data on properties are important
Fuel Properties

- Irradiated fuel properties as a function of burnup
  - U-Mo strength and modulus (~ 30 measurements)
  - Fuel/cladding and cladding/cladding bond strength
  - Residual stress
  - Thermal properties (thermal conductivity)
- Unirradiated properties
Summary of Fuel Performance Requirements

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**Geometric Stability**

Geometry is maintained during *normal operation* and anticipated transients

- Channel gap probe used to verify coolant channel gap dimensions in fuel elements between irradiation cycles
  - Completed: AFIP-7 element assembly (4 plates)
  - ET-1, ET-2, MURR-DDE, MITR-DDE, NBSR-DDE (total of 13 more elements)
  - Neutron tomography being developed (channel gap + fuel meat examination)
Geometric Stability

- Geometric stability during normal operation is also demonstrated through postirradiation dimensional inspection of fuel plates.
- Geometric stability during off-normal conditions is demonstrated through blister testing (~50% of full-size plates, >100 blister tests).

Geometry is maintained during **normal operation and anticipated transients**
Geometric Stability

Plate movement caused by pressure differential does not compromise ability to cool the fuel

Pressure differential between the large channel and the small channel under flow causes the U-Mo/Al test plate to deflect

GTRI Hydro-Mechanical Flow Test Facility at Oregon State University

Testing begins in 2015
Summary of Fuel Performance Requirements

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Stable and Predictable Behavior

- RERTR-12 test data
- Fuel failed at high burnup in peak fission density region
- No fission product release to coolant
Stable and Predictable Behavior

Fission gas bubble superlattice is a key indicator of stability against gas-driven breakaway swelling.

Fuel swelling is within a stable regime.

- 6.2x10^{21} f/cm^3 (79% LEU BU)
- 8.4x10^{21} f/cm^3 (107% LEU BU)
- 9.5x10^{21} f/cm^3 (122% LEU BU)
Corrosion Behavior

• In reactor cladding breaches
• RERTR-7 L1T020
  – Transient liquid phase bonding
• RERTR-10A L1P145
  – Delamination/corrosion induced failure

• L1T020 fuel cladding bond-line crack over 30% of fuel plate Al/Al bond line
• Fission density \( \sim 4 \times 10^{21} \text{ f/cm}^3 \) (~50% BU)
• Operation for 16 days following detection of fission gas at stack monitor
• 53% of fuel eroded from plate (~3 g)
• Total fuel plate swelling \( \sim 30\% \) (~0.4 mm)

U-Mo corrosion behavior after breach is known
Stable and Predictable Behavior

- Irradiation testing completed on fuel at 4 cm to 1 m scale
- Both fuel plate and fuel element configurations

Irradiation behavior is predictable on scale up
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Fuel Testing Program

- Reactor Conversions
  - MITR DDE
  - NBSR DDE
  - MURR DDE

- Fuel Qualification Report to U.S.N.R.C.

- Element Test-1
- Element Test-2
- Full-size plate-1

- Fuel Fabrication Process Selection
  - MP-1
  - MP-2

Note: there are additional ATR and HFIR Specific Tests
Summary

• Monolithic U-Mo fuel has been demonstrated to meet basic fuel performance requirements for qualification
  – Mechanical Integrity
  – Geometric Stability
  – Stable and Predictable Behavior

• Still much to be done. Current fuel performance work focused on fuel properties, fuel specification, fuel performance modeling, flow testing, and irradiation test design

• Fabrication process development and scaleup is proceeding
  – Fabrication process will be selected based on MP-1 irradiation test results (2017 – 2020)

• Preliminary Fuel Development Report to NRC in 2017
  – Intended to confirm fuel behavior is suitable for qualification

• Monolithic Fuel Qualification report to NRC in 2023
QUESTIONS?