Bringing the Back-End Forward in Fuel Design

Opportunities and Challenges

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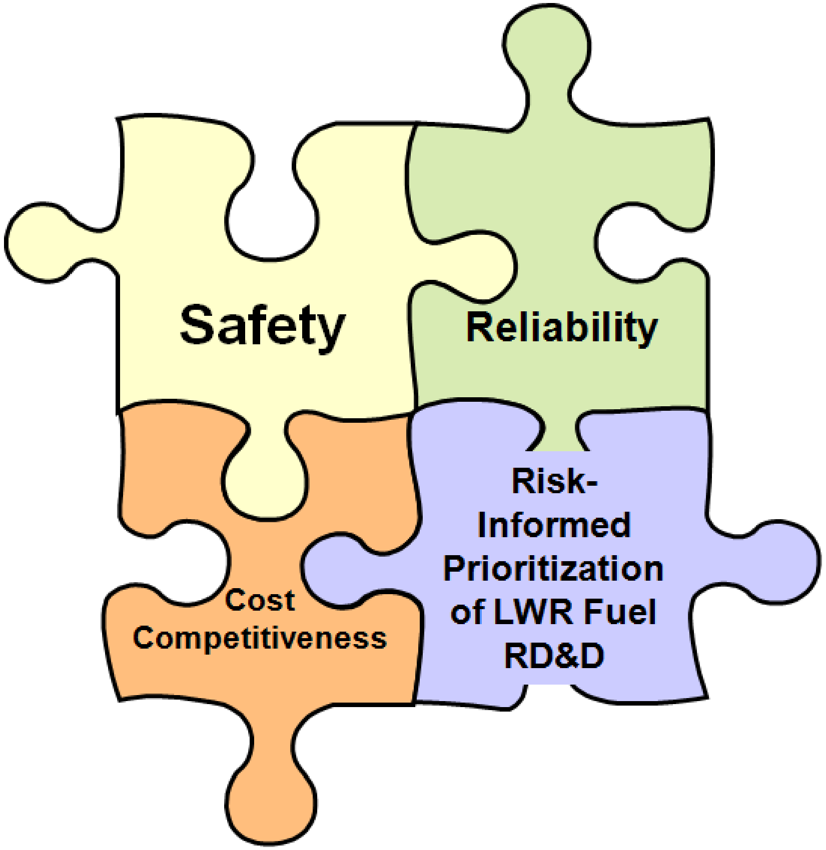
Perspective

RD&D investment for commercial nuclear power is focused on safety, reliability, and affordability of electricity generation.

- Useful lessons from history of U.S. fuel cycle and fuel RD&D
- Remarkable fuel performance in current U.S. LWR fleet
- Observations from Fukushima
- Best opportunities for gains in back-end performance likely to derive from risk-informed RD&D for in-reactor performance



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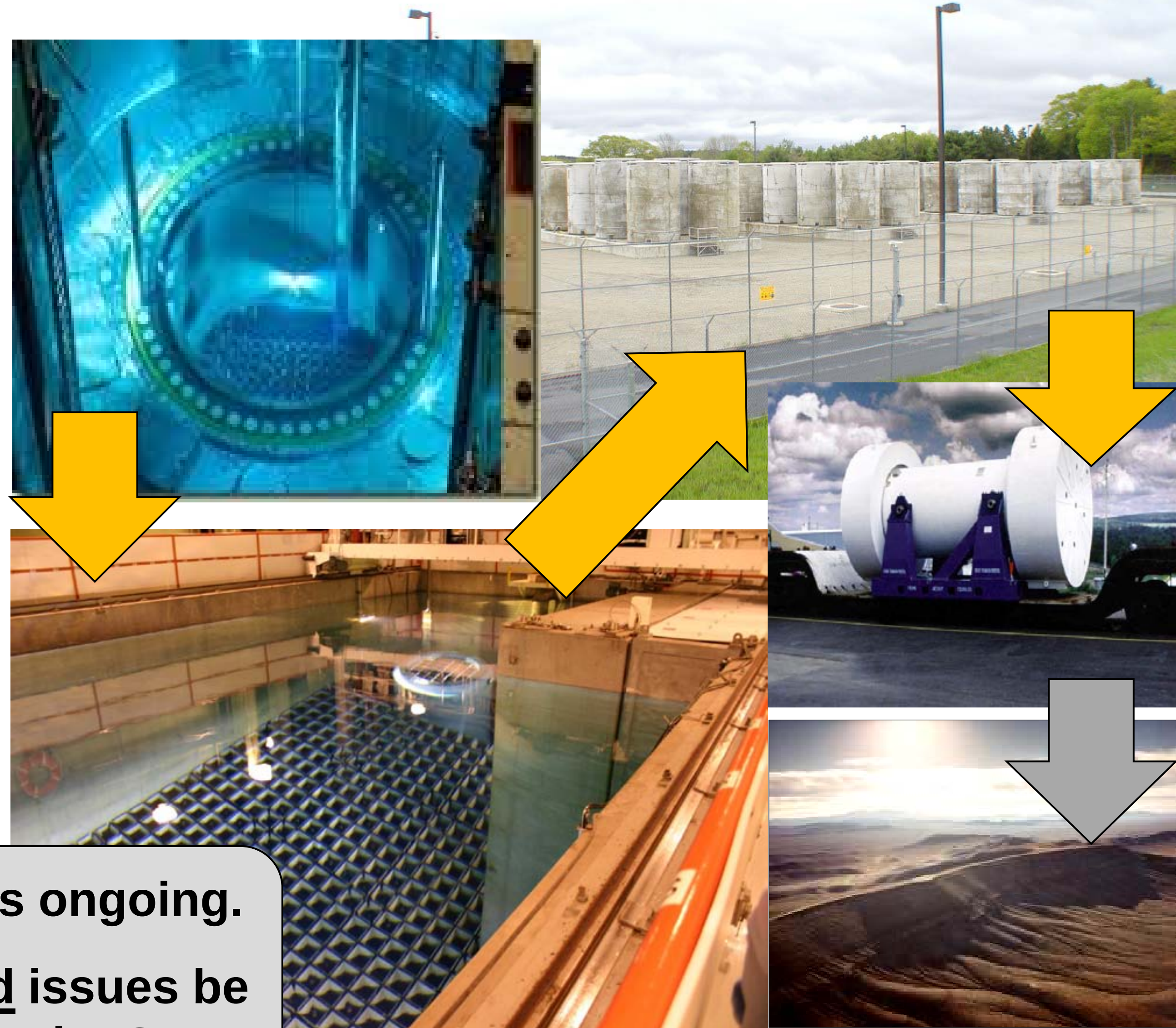
Back-End Fuel Performance Concerns

- Creep and creep rupture
- Hydride reorientation
- Delayed hydride cracking
- Severe accident performance
- Mitigating factors
  - internal rod pressurization
  - fuel-cladding interactions



- **Evaluation of issues is ongoing.**
- **Can/should <u>confirmed</u> issues be addressed with fuel design?**

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Historical Context: Evolution of U.S. Back-End

1950's
Light water reactor technology and zirconium-based fuels emerge from mission-oriented U.S. submarine propulsion program

1960's
U.S. commercial fuel cycle back-end developed with recycling in mind; fleet of 100's envisoned

1970's
Proliferation concern drives U.S. policy to once-through fuel cycle

1980's
Finite pool storage drives utilities to onsite dry storage solutions

1990's
Delay in disposal program drives industry-wide implementation of dry storage

2000's
Post-9/11 assessment of used fuel storage and B5b enhancements

Continuing disposal program delay drives dry storage license extensions in dry storage and initiation of extended storage R&D

2010's
Post-Fukushima assessments and actions

Historical Context: Fuel Development

- Current LWR fuel system reflects over five decades of optimization for <u>in-reactor</u> performance for:
  - increased burnups
  - decreased fuel failures
  - substantial increases in nuclear plant availability
- Successful evolution of zirconium fuel system has balanced tangible benefits against costs
  - safety benefits accrue from widespread application
  - benefits in back-end cannot be decoupled from in-reactor performance
- Even minor tweaks in zirconium fuel designs have required substantial timeframes and resources for deployment

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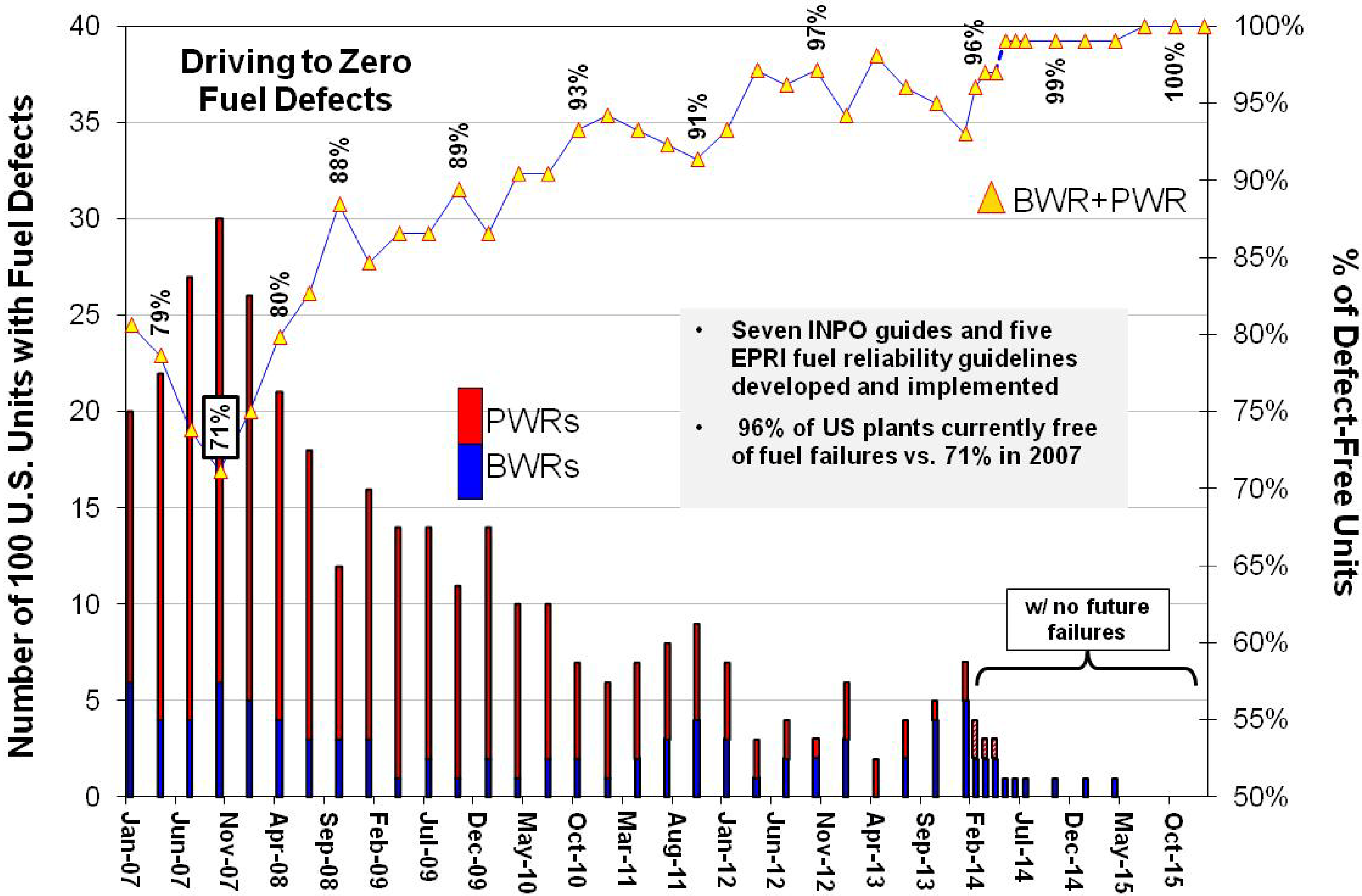
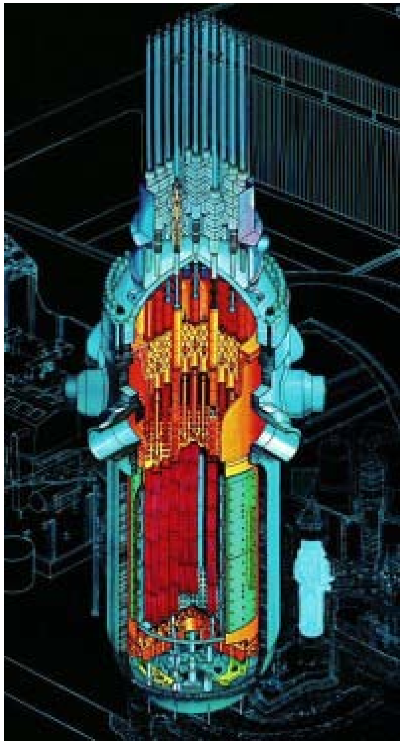
Current Context: LWR Fuel Performance in U.S. Fleet

10^{-6} annual failure rate (~5 rods/yr out of 5 million in service)



Fukushima Reinforced Prior Understanding: Low Risks for At-Reactor Used Fuel Storage

- Negligible calculated risk for fuel in storage relative to operating reactors*
- Events at Fukushima support this paradigm**
  - drivers (energy and hydrogen) for onsite damage and offsite releases originated in reactor cores
  - neither used fuel nor pool performance issues contributed to infrastructure damage or offsite releases
  - pool structures survived seismic and tsunami events and reactor building explosion, maintaining water inventory for cooling and shielding of used fuel
  - used fuel integrity maintained despite violent reactor building explosions, subsequent debris impacts, and extended periods without active cooling

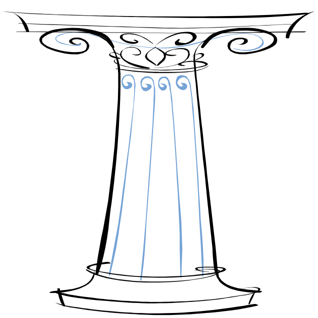


*WASH-1400 (1975); EPRI NP-3365(1984); NUREG-1150 (1990)
** EPRI 1025058 (2012)

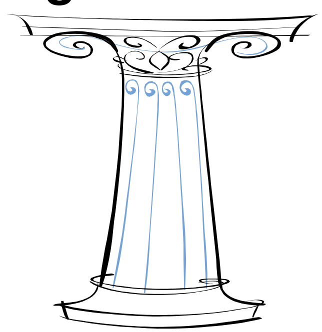
Drivers for New Fuel Development: Enhanced Accident Tolerant Fuel (ATF) Example

- Fukushima focused international attention on benefits of increased safety margins through improvement of fuel and core components

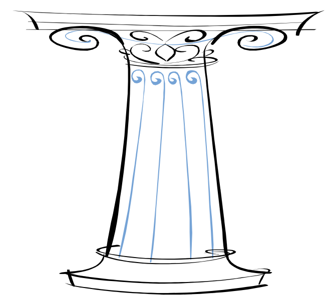
Maintain coolable core geometry following recovery



Eliminate or reduce hydrogen generation



Maintain or improve performance

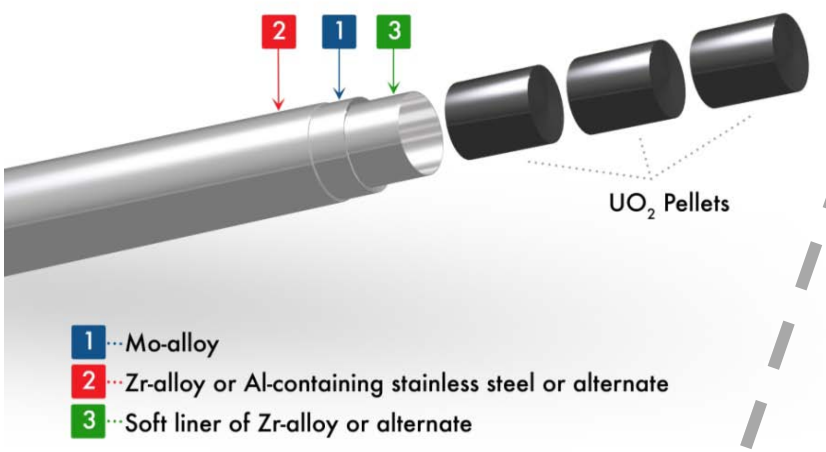


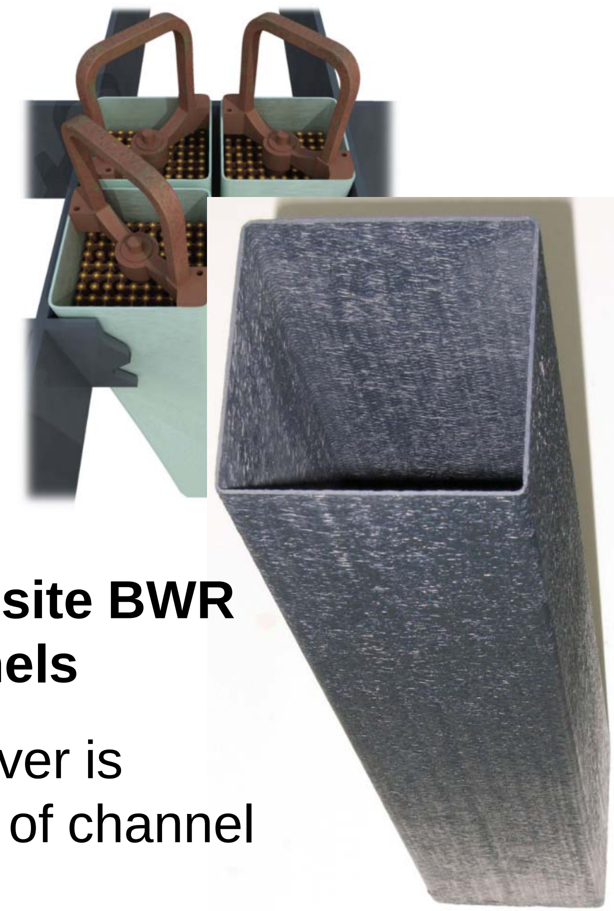
Reduction or elimination of exothermic zirconium oxidation would reduce driving force for core and infrastructure damage.

EPRI R&D for Enhanced Accident Tolerance: Mo-Alloy Cladding and SiC Fuel Channels

Mo-Alloy Fuel Cladding

- Corrosion resistant under normal ops
- High strength to ~1500ºC
- Potential for steam oxidation resistance at > 1000ºC
- Compatible with current fuel/core designs & normal ops





SiC Composite BWR Fuel Channels

- Primary driver is elimination of channel distortion
- Eliminates >35% of Zr from BWR core

Opportunities and Challenges with New Fuel

- New materials may eliminate key fuel failure modes (e.g., hydride formation) but could (re-)introduce others
- DOE-NE performance metrics for ATF explicitly capture performance for storage, transportation and disposal
- Focus on back-end vs. in-reactor performance mirrors tension in ATF R&D between accident tolerance and normal operational performance
  - emphasis on performance for severe accident conditions cannot be at expense of performance for normal/off-normal operation and design-basis accidents and commercial viability
  - emphasis on performance for back-end cannot be at expense of in-reactor performance and commercial viability

Closing Thoughts

- Consideration of storage, transportation, disposal, and reprocessing issues is now informing enhanced accident tolerant fuel design and assessment
- Opportunities may emerge for LWR fuel design enhancements that could result in benefits for the back-end
- **No <u>confirmed</u> back-end performance issues warrant major changes to fuel or cladding design**
- **In-reactor performance continues to drive fuel design**

RD&D for commercial nuclear power should remain focused on safety, reliability, and affordability of electricity generation.

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References: General Storage Risk

- Spent-fuel pool risks vs. reactor risks from probabilistic safety assessments
  - WASH-1400 (1975) and NUREG-1150 (1990)
- Spent-fuel pool risks for shutdown plants
  - NUREG-1353 (1989) and NUREG-1738 (2001)
- Spent-fuel pool risks in light of Fukushima events
  - SECY-13-0112 *"Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling-Water Reactor"* (Oct. 9, 2013)
  - EPRI 3002000498 *"Spent Fuel Pool Risk Assessment Integration Framework (Mark I and II BWRs) and Pilot Plant Application"* (May 1, 2013)
  - EPRI 1025206 *"Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage Pools to Dry Storage After Five Years of Cooling, Revision 1"* (August 2012).
  - EPRI 1025058 "*Summary of EPRI's Early Event Analysis of the Fukushima Dai-ichi Spent Fuel Pools Following the March 11, 2011 Earthquake and Tsunami*." (May 31, 2012)

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References: Dry Storage Risk

- Bolted Dry Storage Cask Systems
  - EPRI 1009691 *“Probabilistic Risk Assessment (PRA) of Bolted Storage Casks – Update Quantification and Analysis Report”* (November 2004)
- Welded Dry Storage Canister Systems
  - NUREG-1864 *“A Pilot Probabilistic Risk Assessment Of a Dry Cask Storage System At a Nuclear Power Plant”* (March 2007)
- Comparative Risk Study for Pool, Dry Cask, Caisson, and Vault
  - EPRI NP-3365 *“Review of Proposed Dry-Storage Concepts Using Probabilistic Risk Assessment”* (1984)

References: Transportation Risk

- NUREG-0170 *"Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes"* (December 1977)
- NUREG/CR-4829 *"Shipping Container Response to Severe Highway and Railway Accident Conditions"* (February 1987)
  - Also referred to as the *"Modal Study"*
- NUREG/CR-6672 *"Reexamination of Spent Fuel Shipment Risk Estimates"* (March 2000)
- NUREG-2125 *"Spent Fuel Transportation Risk Assessment"* (Draft for Comment Dated May 2012)
- EPRI 1016635 *"Criticality Risks During Transportation of Spent Nuclear Fuel – Revision 1"* (December 2008)