Impact of Fuel Failure on Criticality Safety of Used Nuclear Fuel

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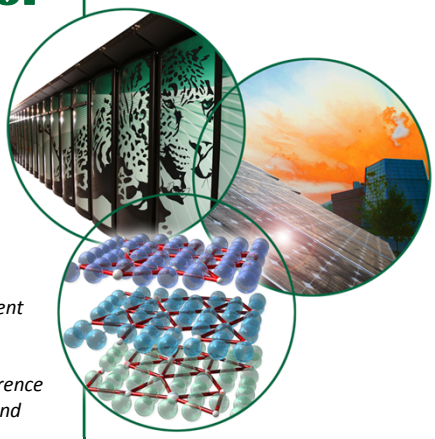

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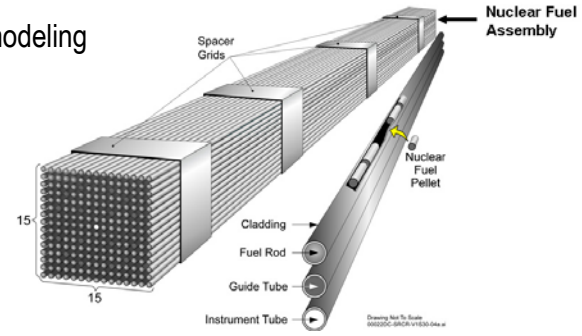
Overview

- Background and motivation for work
- Analysis
  - Failed fuel configurations
  - Casks and fuel types
  - Computer codes & modeling
- Results
- Conclusions
- Future work



Background

- In the United States, used nuclear fuel (UNF) is currently stored in multi-assembly canisters, and will continue to be for the foreseeable future
- There is no assurance currently that UNF (cladding and fuel) and canister internals will be intact (not degraded) after extended storage (ES) periods
- This lack of assurance exists regardless of aging study R&D conducted on UNF in the near future (next ~10-20 years) due to uncertainties in extrapolating test results (e.g., over ES durations or to include consideration of non-experiment conditions).

Source: Connecticut Yankee, http://www.connyankee.com/html/fuel_storage.html

Motivation for work

- The potential for fuel/clad degradation and reconfiguration is a key issue for ES that cross-cuts virtually all safety-significant regulatory requirements
  - Will UNF remain in the configuration considered in the original safety analysis?
  - If the as-analyzed configuration cannot be assured, what are the safety and operational implications?
- UNF could be “canned” in single assembly fuel canisters that are inserted into larger multi-assembly canisters.
  - This approach would ensure future retrievability of the assemblies, but would impact cost and operations

Motivation for work (cont.)

- To address the issue of, or potential for, fuel reconfiguration it is necessary to understand the…

1 *Likelihood of fuel reconfiguration and associated dependencies*
- *Thermal history*
- *Burnup – low, med, high?*
- *Storage time, conditions*
- *Stress history and future stresses during normal transport*
- *Cladding specifics*
- *etc…*

2 *Potential extent of fuel reconfiguration and associated dependencies*
- *Thermal history*
- *Burnup – low, med, high*
- *Storage time, conditions*
- *Stress history and future stresses during normal transport*
- *Cladding specifics*

3 *Impact of fuel reconfiguration on safety*
- ***Criticality safety***
- *Containment*
- *Shielding*
- *Thermal*
- *Structural performance*
- *Fuel handling and ability to retrieve*

Experimental efforts are planned to address the likelihood and extent of fuel reconfiguration during ES; MANY inter-dependencies to consider

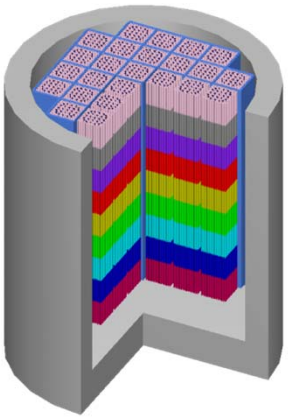
Effort described here to assess impact of fuel reconfiguration on safety, with initial focus on criticality safety

Analysis – failed fuel configurations

- Six configuration categories identified and considered
  - **Gross rod failures** - Removal of single and multiple rods from assembly lattice
  - **Cladding thinning/loss** – Reduced cladding thickness up to removal of cladding material (non-physical condition)
  - **Loss of rod pitch control** – Uniform rod pitch expansion within fuel storage cell, both with and without cladding; "birdcaging"; non-uniform pitch expansion
  - **Neutron absorber degradation** – Gaps of varying location and size; uniform thinning of absorber panels
  - **Loss of assembly position control** – Axial displacement of fuel assemblies
  - **Gross assembly failure** – Dodecahedral arrays of pellets with varying pitch and homogenous rubble with varying H/X ratios

Analysis – casks and fuel types

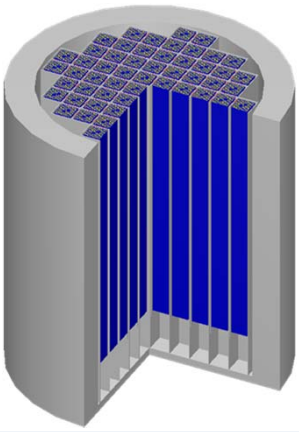
- 32-assembly (high-capacity) PWR cask
  - Loaded with W 17x17 OFA assemblies
  - Representative loading curve end points considered
    - Fresh 1.92 w/o ^{235}U fuel
    - 5 w/o ^{235}U with 44.25 GWd/MTU burnup
  - Also considered:
    - High burnup (70 GWd/MTU)
    - Variations in cooling time (5 – 300 y)



Bottom half cutaway of 32-assembly PWR canister

Analysis – casks and fuel types

- 68-assembly (high-capacity) BWR cask
  - Loaded with GE 10x10 assemblies
  - Fresh 5 w/o ^{235}U fuel
  - Also considered:
    - Variations in burnup (35 and 70 GWd/MTU)
    - Variations in cooling time (5 – 300 y)



Bottom half cutaway of 68-assembly BWR canister

Analysis – codes and modeling

- SCALE 6.1 code system used for all analyses
  - Depleted fuel compositions calculated with ORIGEN-ARP
  - Criticality calculations performed with KENO using 238-group ENDF/B-VII library
- Modeling assumptions
  - Canister inner volumes flooded with 1.0 g/cm^3 water
  - All assemblies have identical compositions
  - All fuel assemblies/absorber panels experience the same degradation
  - Canister wall, lid, base plate, and storage basket do not degrade
    - Fuel assembly spacers assumed to fail in axial displacement configurations

Results – interpretation

- Our assessment of credibility and relevance for ES
  - **Gross rod failures**
    - Single rod removal credible
    - Multiple rod removal credible
  - **Cladding thinning/loss**
    - Cladding thinning credible
    - Cladding loss not credible
  - **Loss of rod pitch control**
    - Expansion with cladding credible
    - Expansion without cladding not credible
  - **Neutron absorber degradation**
    - Gaps via degradation credible
    - Uniform thinning via degradation credible
  - **Loss of assembly position control**
    - Small ($\leq$20 cm) axial misalignments credible
    - Large (>20 cm) axial misalignments not credible
  - **Gross assembly failure**
    - Uniform pellet array not credible
    - Homogeneous rubble within absorber region credible
    - Homogeneous rubble outside absorber region not credible

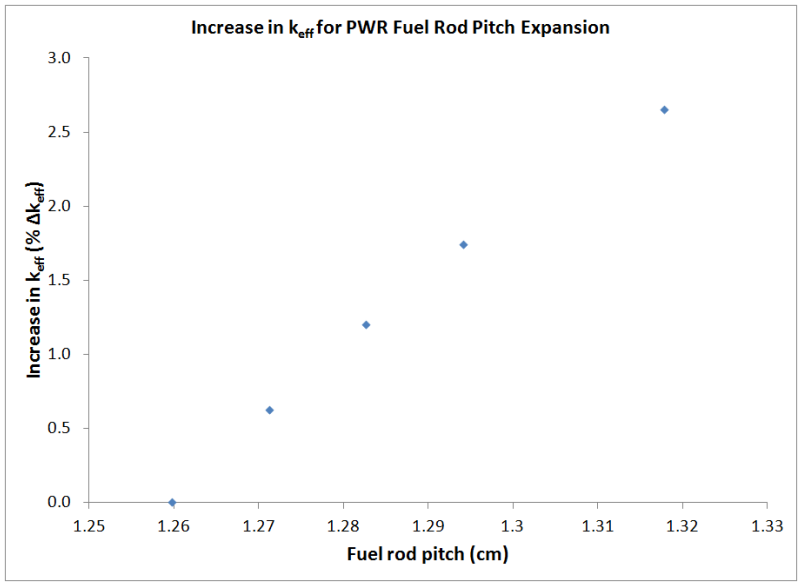
Configurations in green considered relevant and potentially credible

Configurations in red considered not credible

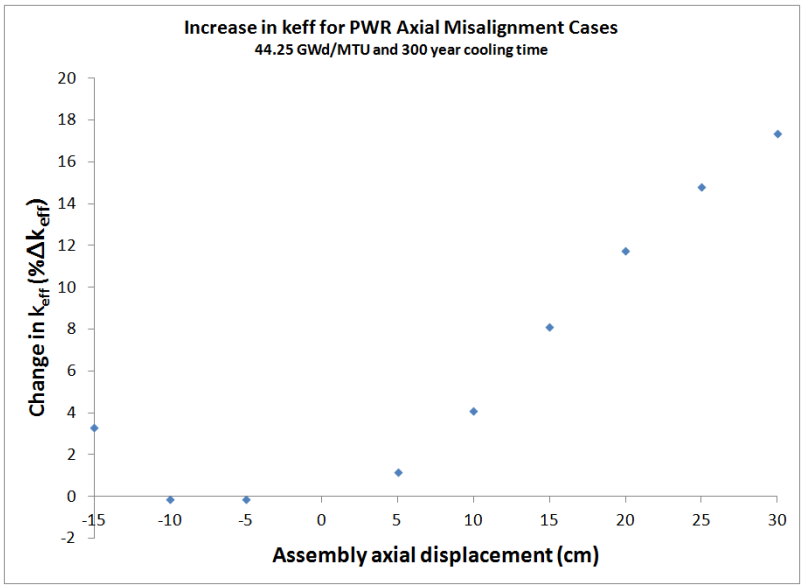
Results – 32-assembly PWR cask

Configuration	Maximum k_{eff} increase (% Δk_{eff})
Single rod removal	0.10
Multiple rod removal	1.87
Cladding thinning/loss	0.035% Δk_{eff}/% cladding loss (3.52 total)
Loss of rod pitch control, with cladding	2.65
Loss of rod pitch control, without cladding	5.34
Neutron absorber degradation – 5 cm gap	1.24
Neutron absorber degradation – 10 cm gap	2.63
Loss of assembly position control, 20 cm/30 cm	12.49/17.38
Uniform pellet array	22.21
Homogeneous rubble, within absorber region	-3.58
Homogeneous rubble, outside absorber region	15.34

Results – 32-assembly PWR cask



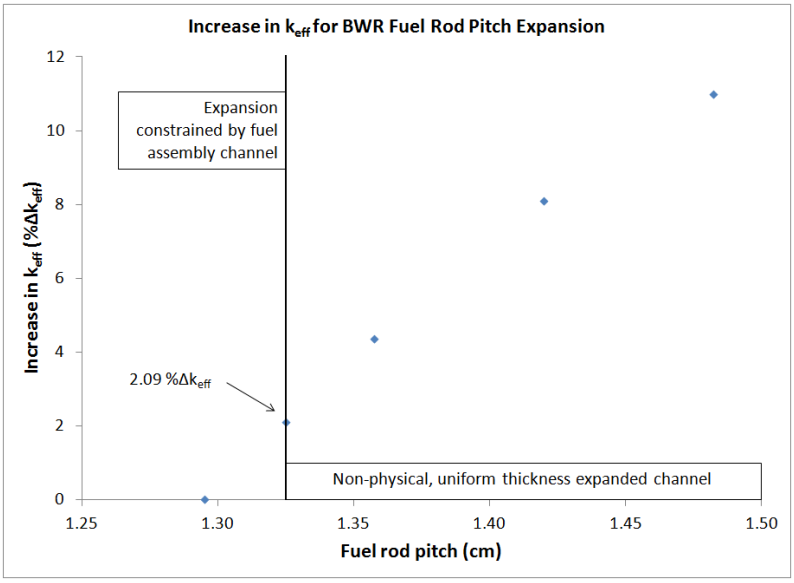
Results – 32-assembly PWR cask



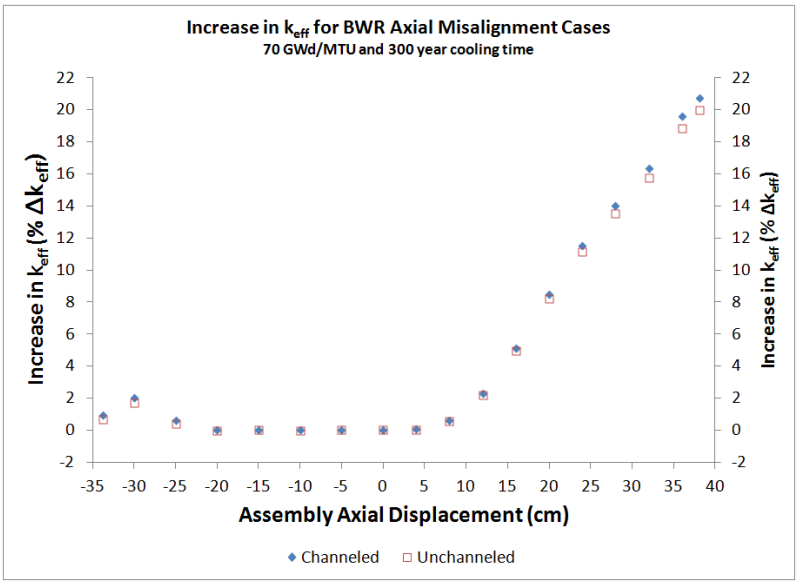
Results – 68-assembly BWR cask

Configuration	Maximum k_{eff} increase (% Δk_{eff})
Single rod removal	0.29
Multiple rod removal	2.42
Cladding thinning/loss	0.050% Δk_{eff}/% cladding loss (4.98 total)
Loss of rod pitch control, with cladding	2.09 (channel)
Loss of rod pitch control, without cladding	15.33
Neutron absorber degradation – 5 cm gap	2.90
Neutron absorber degradation – 10 cm gap	6.36
Loss of assembly position control, 20 cm/38 cm	8.52/20.76
Uniform pellet array	35.63
Homogeneous rubble, within absorber region	9.51
Homogeneous rubble, outside absorber region	30.40

Results – 68-assembly BWR cask



Results – 68-assembly BWR cask



Observations – 32-assembly PWR cask

- Maximum increase in k_{eff} for all potentially credible configurations considered is: 2.65% Δk_{eff}
- Key assumptions associated with this max increase (that must be confirmed/justified):
  - Configurations judged to be not credible can be justified
  - Axial assembly displacement (beyond absorber panel elevations) cannot exceed 7.5 cm
  - Cell walls constrain rod pitch expansion
  - Absorber degradation conditions do not result in a case that is worse than a uniform 10-cm gap in the most reactive axial region

Observations – 68-assembly BWR cask

- Maximum increase in k_{eff} for all potentially credible configurations considered is: 6.36%Δk_{eff}
- Key assumptions associated with this max increase (that must be confirmed/justified):
  - Configurations judged to be not credible can be justified
  - Axial assembly displacement (beyond absorber panel elevations) cannot exceed 17.5 cm
  - Fuel channel constrains rod pitch expansion
  - Poison degradation conditions do not result in a case that is worse than a uniform 10-cm gap in the most reactive axial region

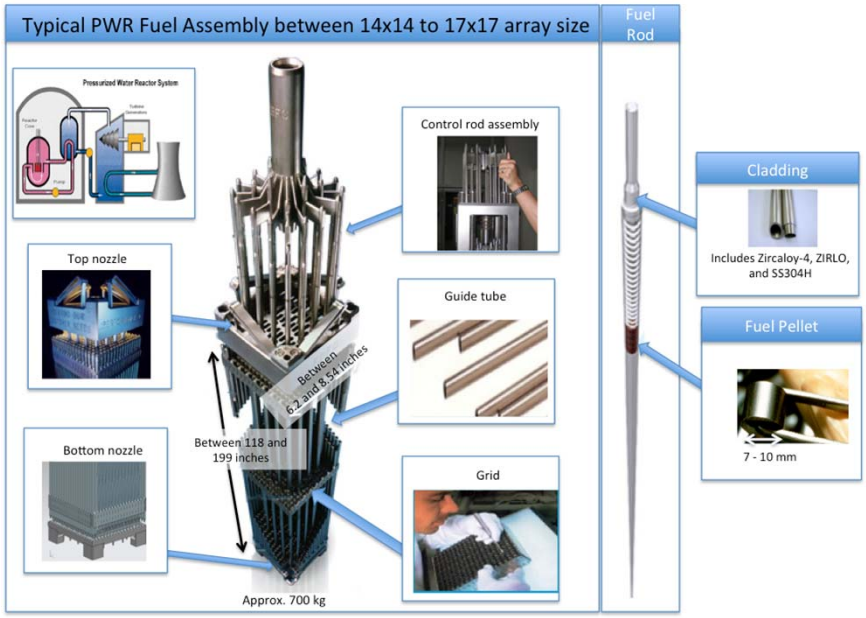
Conclusions

- A set of potential failed fuel configurations was developed and analyzed relative to criticality safety
  - Study was motivated by ES, but configurations have broader relevance
  - Analysis considered representative casks, fuel types, and parameter ranges
- The configurations were then assessed for credibility and relevance to ES
- Pending confirmation of key assumptions related to credibility of configurations, the increase in k_{eff} is < 6.5% Δk (for the casks and fuel types considered)
- Increases not significantly dependent on burnup or cooling time

Future work

- Focus effort on reconfiguration of fuel at points on canister loading curve
  - Consider more enrichment/burnup/cooling time combinations
- Investigate impacts of non-uniform pitch expansion
- Consider range of number of failed assemblies within canister

Backup Slides



Results: 32-Assembly PWR Canister

Configuration	Maximum k_{eff} increase (% Δk_{eff})	Limiting Condition	
		Burnup (GWd/MTU)	Cooling Time (years)
Single rod removal	0.10	44.25	300
Multiple rod removal	1.87	44.25	80
Cladding thinning/removal	0.035% Δk_{eff}/% cladding loss (3.52 total)	44.25	80
Expanded rod pitch, clad	2.65	44.25	5
Expanded rod pitch, unclad	5.34	44.25	5
Poison degradation – 5 cm gap	1.24	70	300
Poison degradation – 10 cm gap	2.63	70	300
Axial misalignment, 20 cm/30 cm	12.49/17.38	70/44.25	300/300
Uniform pellet array	22.21	44.25	80
Homogeneous rubble, poison elevations	-3.58	0	0
Homogeneous rubble	15.34	44.25	300

Results: 68-Assembly BWR Canister

Configuration	Maximum k_{eff} increase (% Δk_{eff})	Limiting Condition		
		Burnup (GWd/MTU)	Cooling Time (years)	Channel present?
Single rod removal	0.29	0	0	Yes
Multiple rod removal	2.42	35	300	Yes
Cladding thinning/removal	0.050% Δk_{eff}/% cladding loss (4.98 total)	0	0	Yes
Expanded rod pitch, clad	2.09 (channel)	0	0	No
Expanded rod pitch, unclad	15.33	0	0	No
Poison gap – 5 cm	2.90	70	80	Yes
Poison gap – 10 cm	6.36	70	300	Yes
Axial displacement, 20 cm/38 cm	8.52/20.76	70/70	80/300	Yes/Yes
Uniform pellet array	35.63	70	300	No
Homogeneous rubble, poison elevations	9.51	0	0	No
Homogeneous rubble	30.40	70	300	No