UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Spent Fuel Pool Beyond-Design-Basis Earthquake Consequence Study

Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

NAS Briefing, June 24, 2013

Spent Fuel Safety

- Spent Fuel Pools (SFP) originally designed for limited storage of spent fuel until removed off-site
- SFPs are robust structures, with reinforced concrete walls and floors, 3 to 6 feet thick
  - Leak-tight stainless steel liner plates, typically ¼ inch thick, line the walls and floors of SFPs
- Safety of spent fuel in pools achieved primarily by maintaining water inventory, geometry, and soluble boron (PWRs)

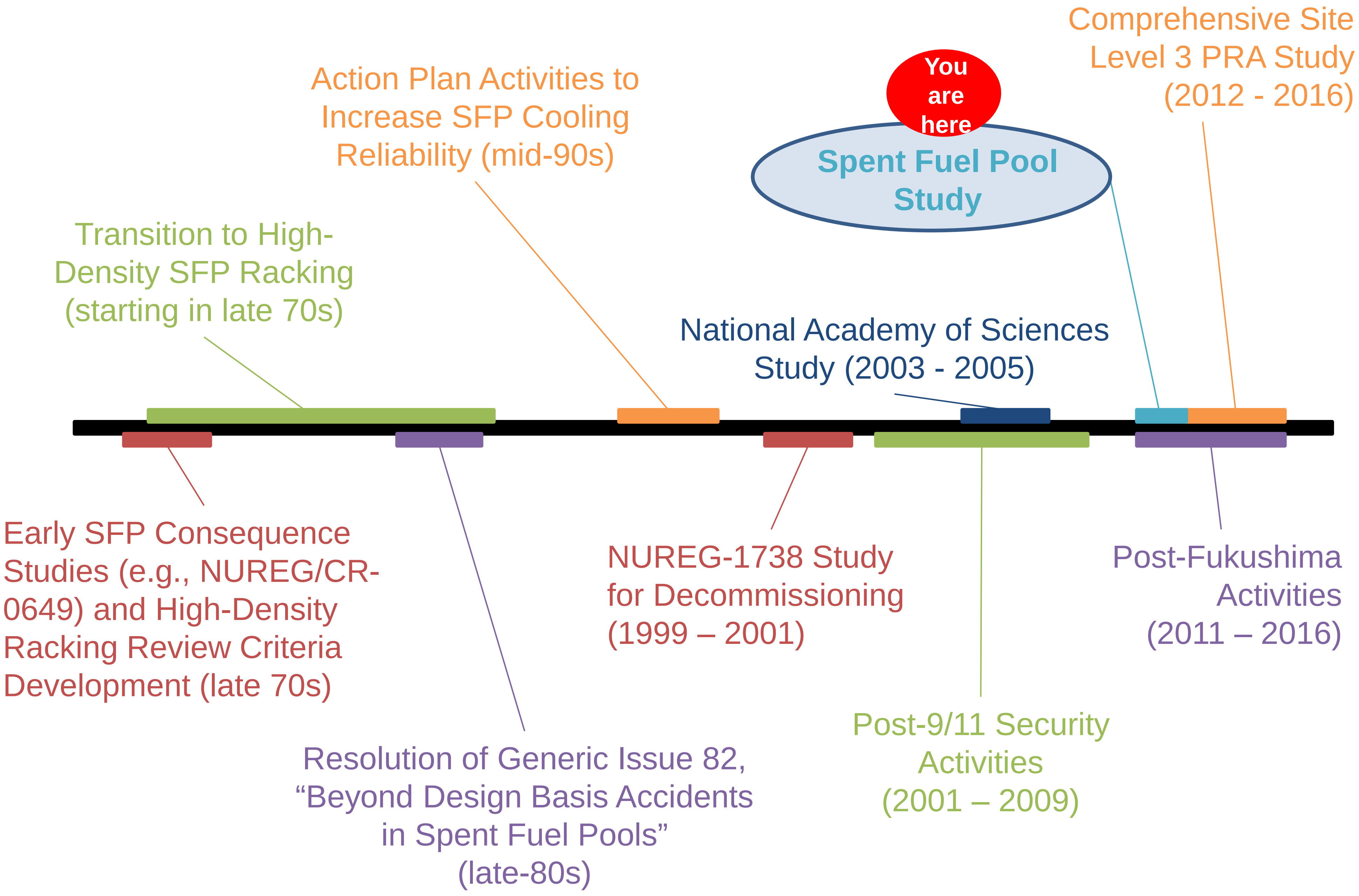
Risk of Large Release

- SFP risk is low, due to the low frequency of events that could damage the thick reinforced pool walls
  - Frequency of fuel uncovery; 6E-7 to 2E-6/yr – NUREG-1738
- Past studies have shown that consequences have been assessed to be large due to the potential for heat-up of all the fuel in the pool
  - Heat-up of the fuel in the pool can lead to “zirconium fire” initiation and propagation
  - Large inventory of Cs-137
- The above prompts stakeholders to ask if older fuel should be moved to casks

Overview of Spent Fuel Pool Study (SFPS)

- Events at Fukushima led to questions about safety of spent fuel storage in pools during earthquakes
- Past SFP risk studies have shown that storage of spent fuel in pools or casks is safe and risk is low
- Should NRC require expedited movement of spent fuel from pools to casks?
- SFPS uses state-of-the-art tools to compare accident progression and consequences of a beyond design basis earthquake on a high density and low density loaded SFP
- BWR4 Mark I was used as reference plant
- SFPS results are consistent with past studies

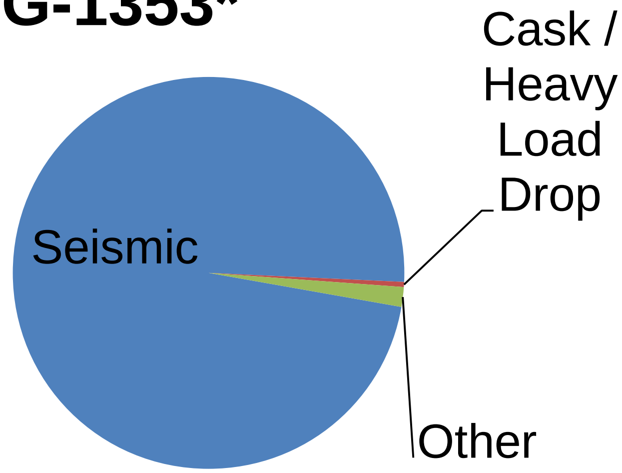
Timeline of Major SFP-related Activities



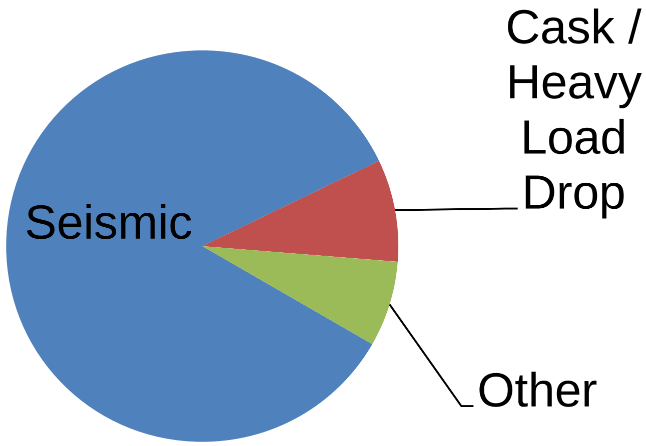
Past SFP Studies

Annual frequency of SFP fuel uncovery as reported in previous SFP risk studies

NUREG-1353*



NUREG-1738**



*BWR, best estimate results

**Based on Livermore hazard curves which generally more closely match the updated USGS curves for the studied plant

Past SFP risk studies indicate that seismic hazard is the most prominent contributor to SFP fuel uncovery. While these studies have known limitations, this is sufficient motivation to focus on this class of hazards in the SFPS.

Technical Approach

- Two conditions to be considered:
  - Representative of the current situation for the reference plant (i.e., high-density loading and a relatively full SFP)
  - Representative of expedited movement of older fuel to a dry cask storage facility (i.e., low-density loading)
- Elements of the study include
  - Seismic and structural assessments based on available information to define initial and boundary conditions
  - SCALE analysis of reactor building dose rates
  - MELCOR accident progression analysis (effectiveness of mitigation, fission product release, etc.)
  - Emergency planning assessment
  - MACCS2 offsite consequence analysis (land contamination and health effects)
  - Probabilistic considerations
  - Human reliability analysis of mitigation measures (Note: Performed after interim report was completed)

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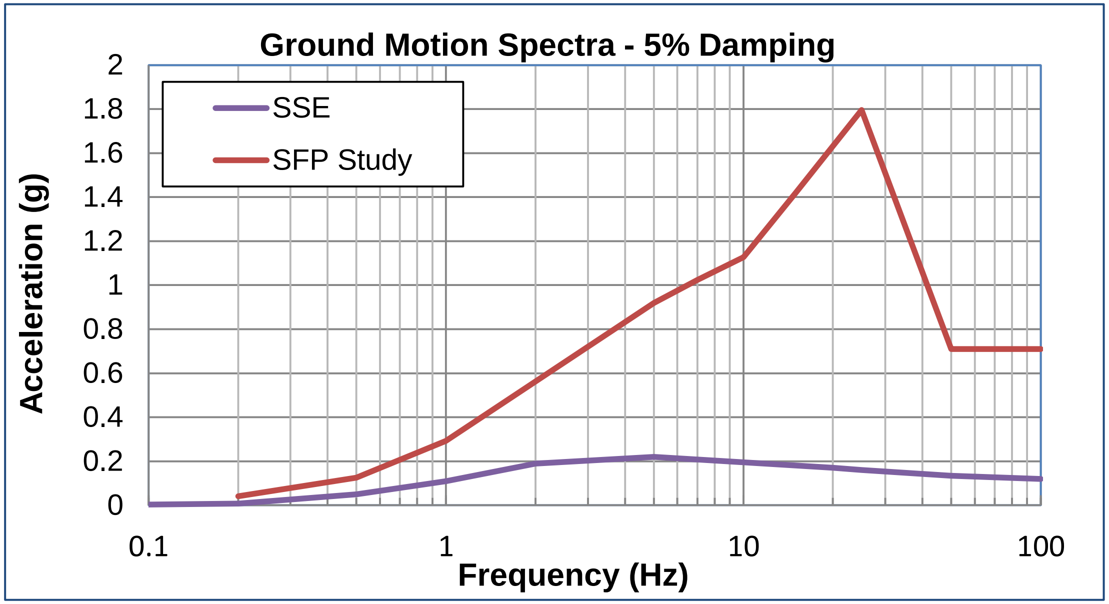
Likelihood of Chosen Seismic Event

Seismic Bin #	PGA Range (g)	Geometric Mean Accel. (g)	Likelihood based on PGA (yr)	Potential for damage to SFP liner?
1	0.1 to 0.3	0.2	1 in 2,000	Damage not expected
2	0.3 to 0.5	0.4	1 in 40,000	Damage not expected
3	0.5 to 1.0	0.7	1 in 60,000	Damage possible
4	> 1.0	> 1.0	1 in 200,000	Damage possible

- A severe seismic event was chosen to challenge SFP integrity
  - Chosen to allow assessment location and size of failure, and its likelihood
- Similar severity to the SOARCA Short-Term Station Blackout
- No more severe than events considered in past SFP PRAs
- More severe than representative plant’s SSE (and most US plants’ SSEs)
- Likelihoods based on USGS 2008 hazard model

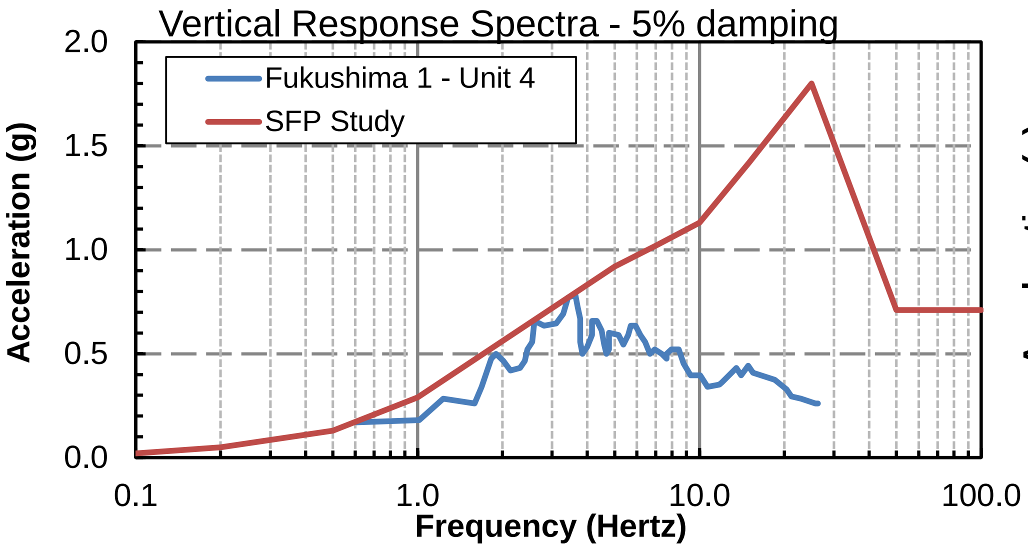
Seismic/Structural Analysis

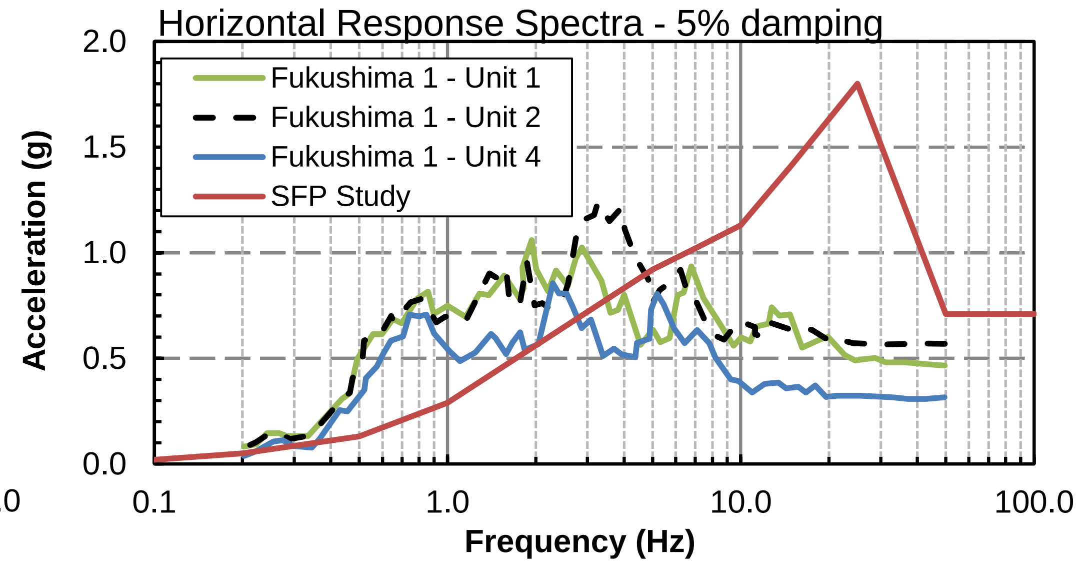
- Ground motion characteristics for the chosen seismic event
  - Site ground motion response spectra
  - Assumed equal horizontal and vertical PGA and spectra



Comparison to the design basis ground motion (SSE)

Comparison to the motions recorded at the foundation slabs of Fukushima Daiichi Units 1 and 4

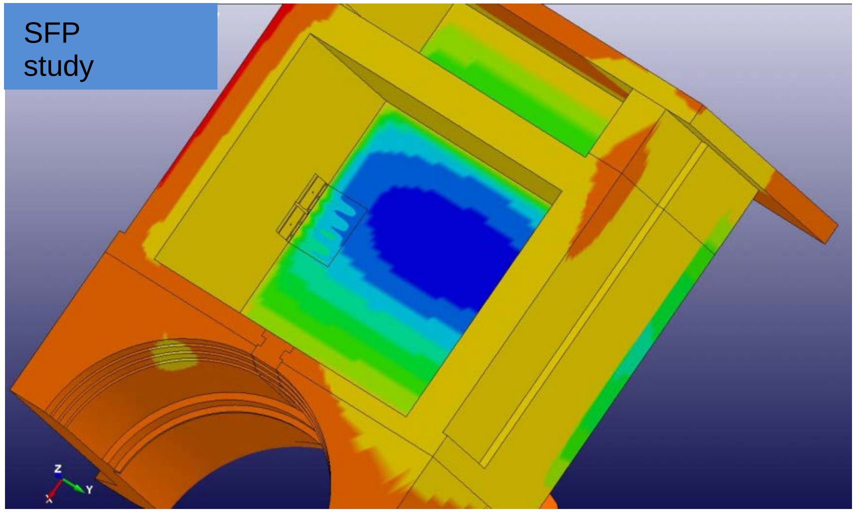




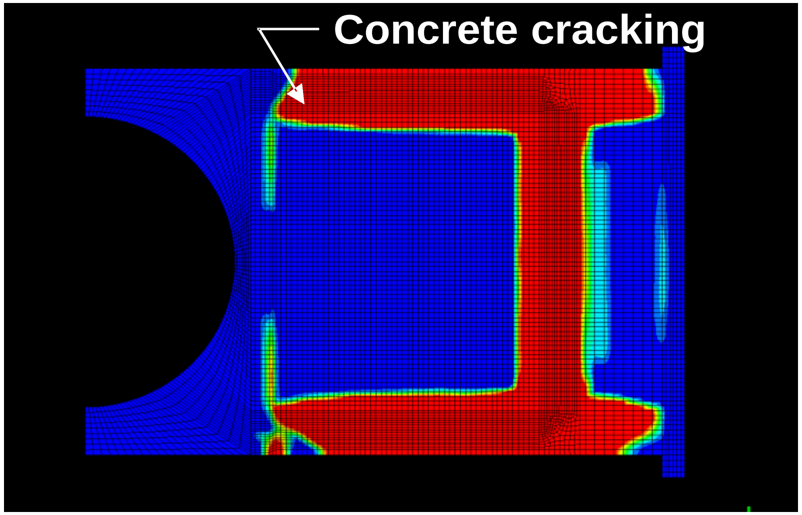
Seismic/Structural Analysis

- Objective:
  - Estimate the likelihood of a pool failure, location and size

- Approach:
  - Estimated loads on the SFP structure
    - Static weight of concrete, steel, water, fuel assemblies and racks
    - Dynamic forces from the ground motion calculated using response spectrum analysis
      - Includes vertical and horizontal hydrodynamic impulsive forces
  - Used 3D finite element analysis (pseudo-dynamic) to calculate SFP deformations, concrete cracking and liner strains



Vertical displacement contours (maximum at the center of the floor ~ 15 mm)



Concrete vertical strains contours to highlight footprint of cracking at the bottom of the walls

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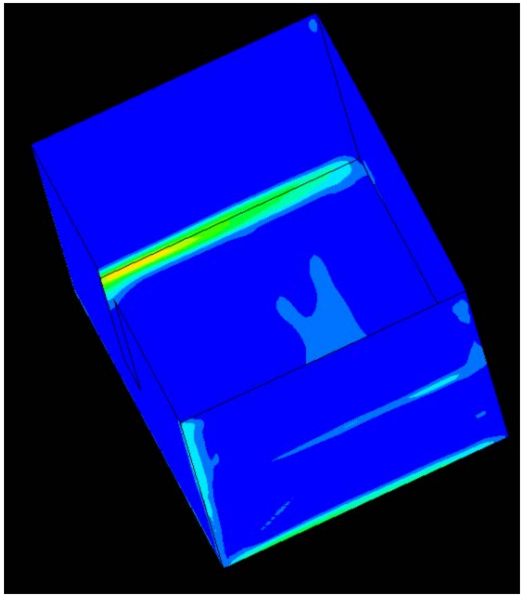
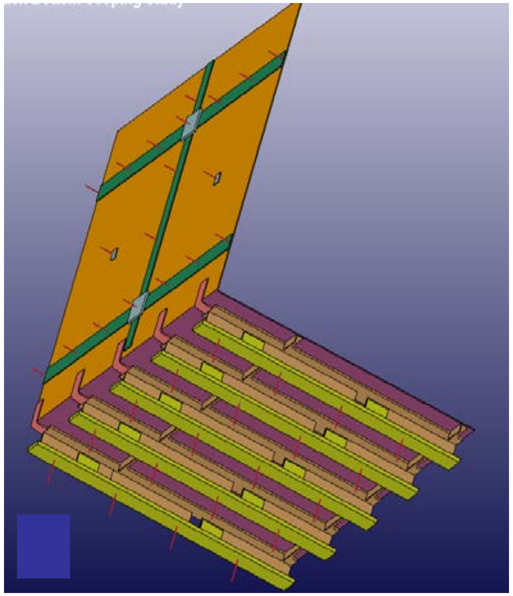
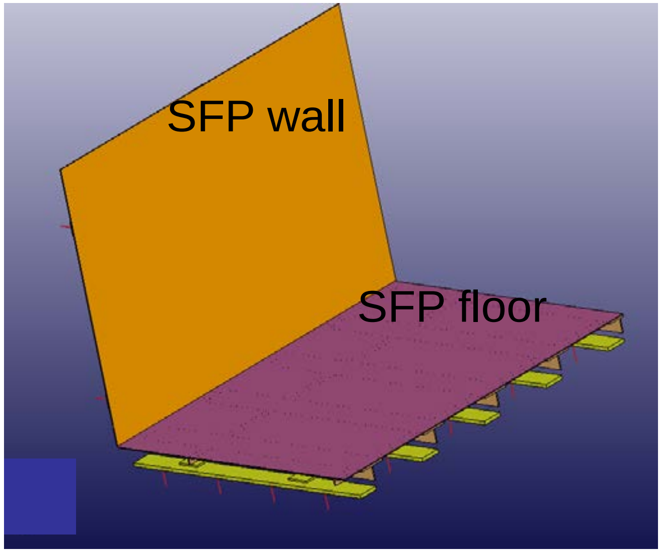
Seismic/Structural Results



Maximum liner strains to show locations of strain concentrations





Liner attachments

For 1 in 60,000 per year event:

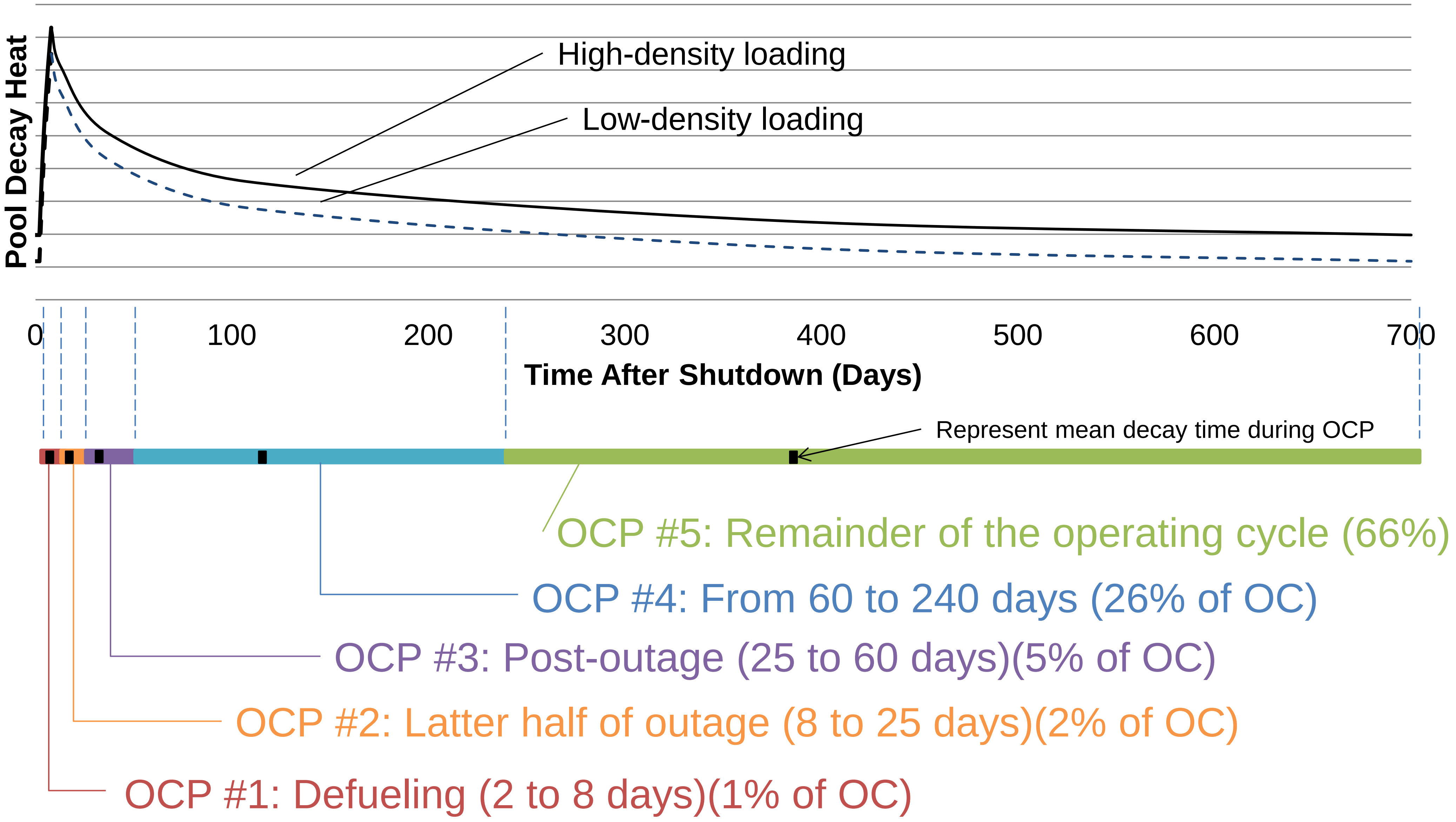
- No liner tearing and no leaking (90% likelihood)
- Liner tearing spreading along the base of the wall (5% likelihood)
  - Moderate damage state (moderate leak)
- Liner tearing localized near the liner backup plates (5% likelihood)
  - Low damage state (small leak)

No leakage of water near the bottom of the walls was reported for 20 SFPs affected by two major recent earthquakes in Japan

- Consistent with low likelihood of leakage estimated for this study

MELCOR Analysis

Pool Decay Heat and Operating Cycle Phases (OCPs)



MELCOR SFP Modeling

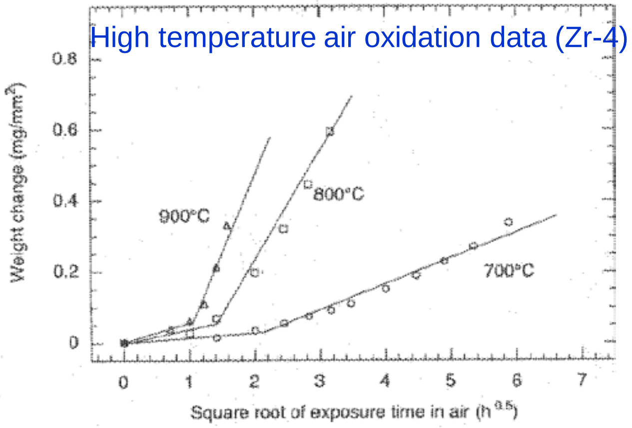
- Rack component
- Thermal radiation modeling
- Air oxidation modeling (ANL data)
  - NUREG/CR-6846, “Air Oxidation Kinetics for Zr-Based Alloys”
- Hydraulic resistance model
  - NUREG/CR-7144, “Laminar Hydraulic Analysis of a Commercial Pressurized Water Reactor Fuel Assembly,” (Jan. 2013)
- Integral spray model
- Decay heat and Radionuclide modeling
  - MELCOR models fission product release and transport (all relevant phenomena including aerosol dynamics and deposition by various mechanisms are included)
  - SCALE/ORIGEN analysis to characterize decay power and radionuclide masses for all assemblies (involves fuel assemblies with multiple shutdown times)
  - Control system developed to track the releases from fuel in each ring. The non-dimensional release fractions together with actual inventories can be used as input for consequence analysis (not the focus of the study)

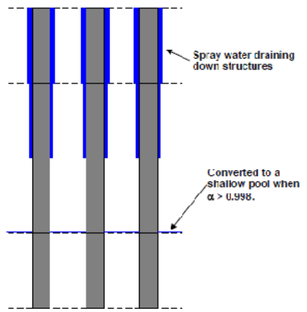
Convective Heat Transfer Surfaces:

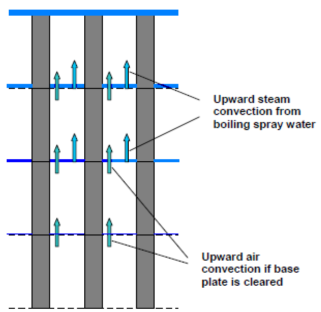
Ring 1 — Clad, Canister / Water Rods, Rack | Ring 2 — Clad, Canister / Water Rods, Racks

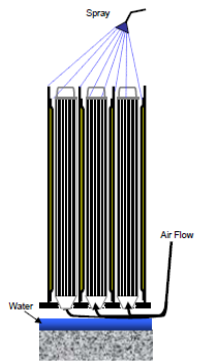
Radiative Heat Transfer Flow Path:

Ring 1: Fuel → Clad → Canister / Water Rods → Rack → Ring 2: Canister / Water Rods → Clad → Fuel; Canister / Water Rods ↓ Racks

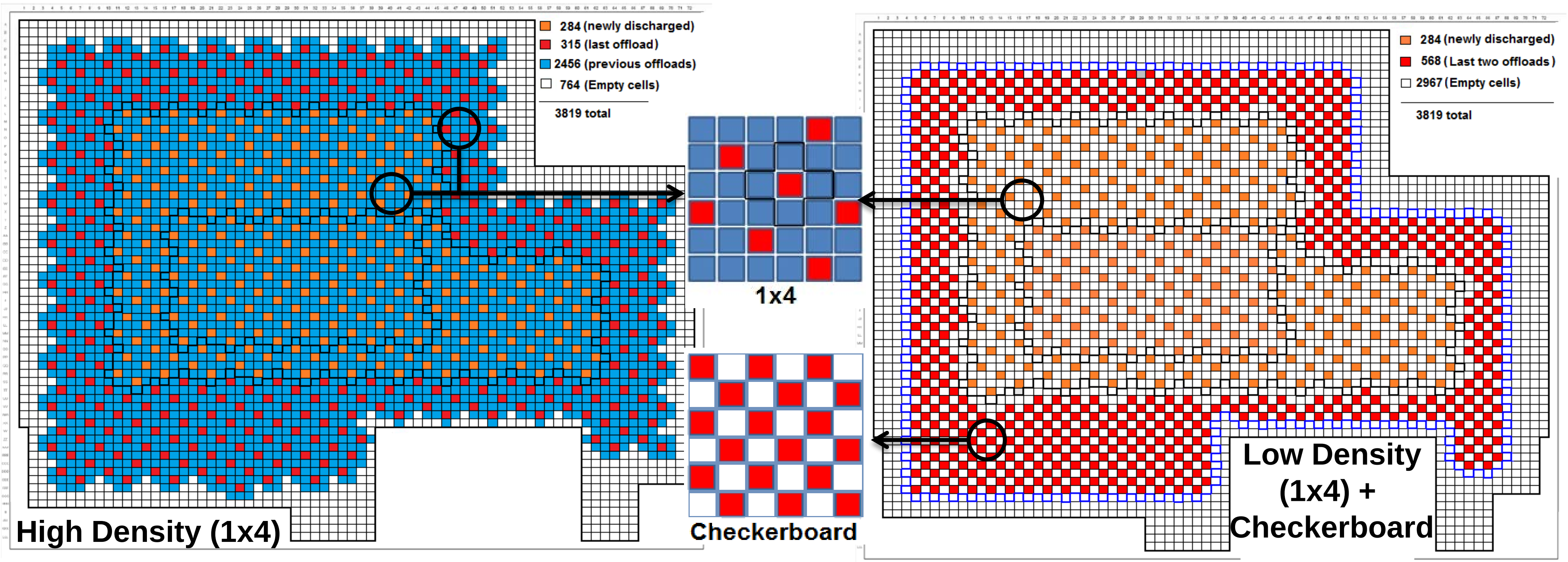


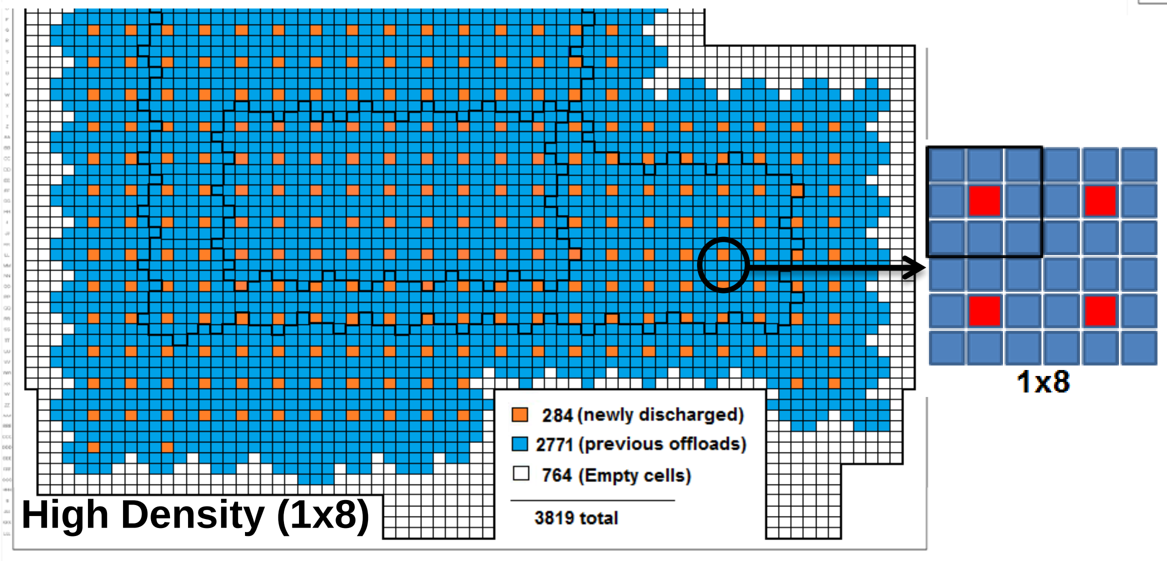






SFP Loading (OCP2/3/4/5)





- Newly discharged 1x4 (or 1x8)
- Previous 2 offloads (fuel < 5 years) checkerboard for low density (due to limitation of available cells)
- Blue cells represent older fuel
- White cells represent empty locations for full core offload capability (and after removal of older fuel in low density case)

MELCOR Analysis

<table>
<tr><th></th><th>No Leak
(90%)</th><th>Small Leak
(5%)</th><th>Moderate Leak
(5%)</th></tr>
<tr><td>OCP1 (1%)</td><td rowspan="3"></td><td></td><td>~0.05%</td></tr>
<tr><td>OCP2 (2%)</td><td colspan="2" rowspan="2">~0.8%</td></tr>
<tr><td>OCP3 (5%)</td></tr>
<tr><td>OCP4 (26%)</td><td colspan="3" rowspan="2">~99.2%</td></tr>
<tr><td>OCP5 (66%)</td></tr>
</table>

- Percentages are percent of the time for corresponding condition
- Assumed accident terminated at 72 hours

Release does not occur even without mitigation or long available response time for boiloff (i.e., > 7 days)

Release is prevented when the 10CFR50.54(hh)(2) endorsed SFP makeup is deployed in time

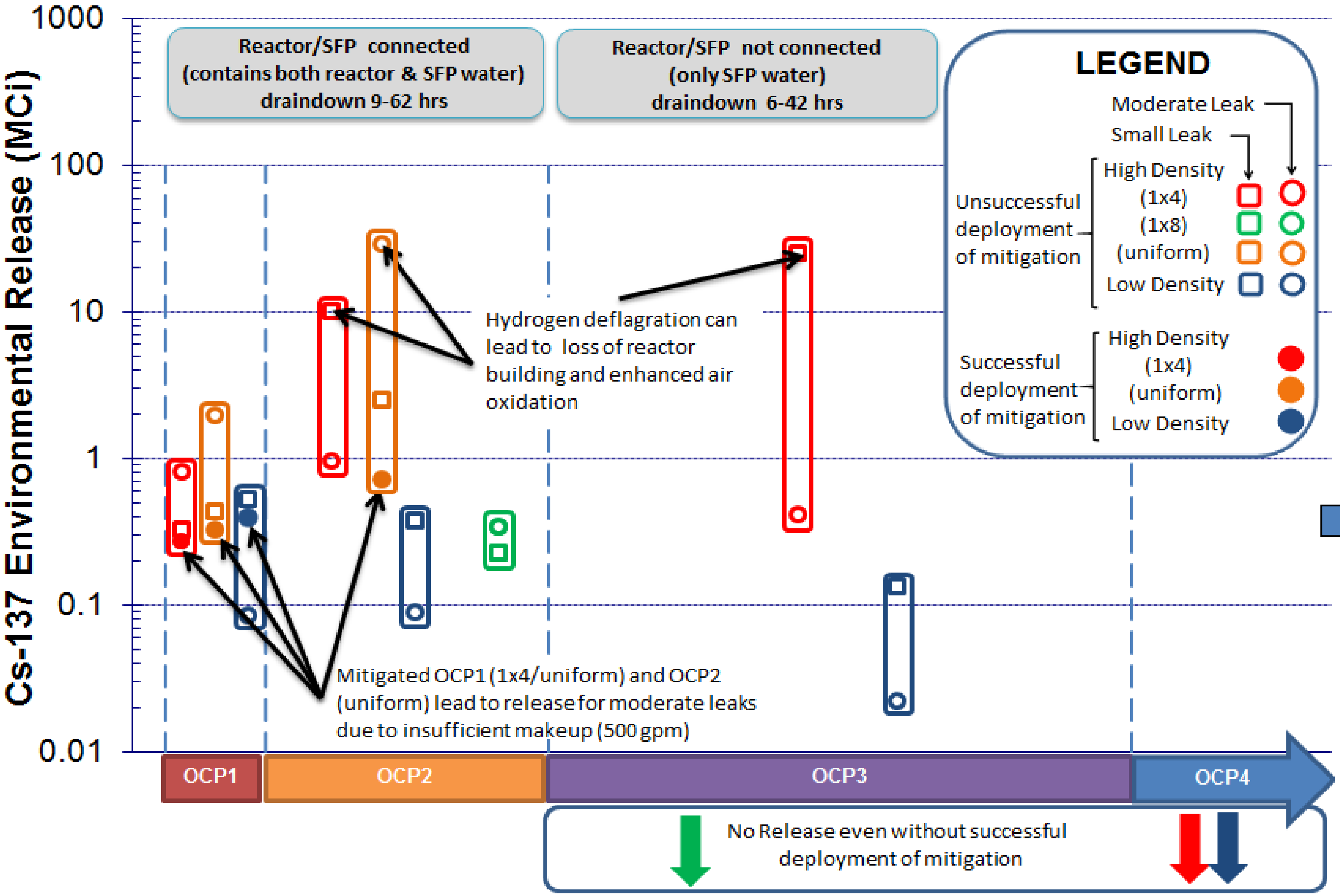
Release occurs even though the 10CFR50.54(hh)(2) endorsed makeup flow is deployed

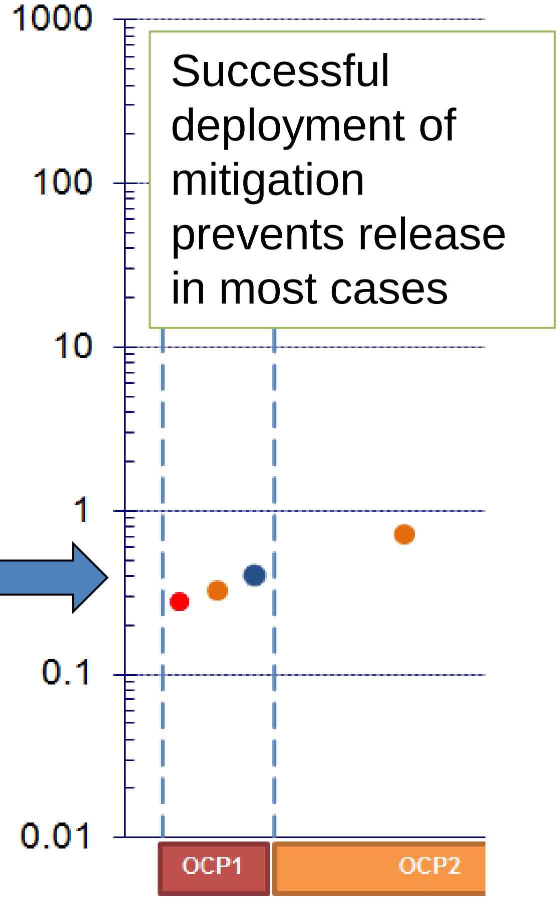
10CFR50.54(hh)(2) endorsed SFP makeup flow rate (per unit):

- 500 gpm of injection or
- 200 gpm of spray

MELCOR Analysis

Cases that lead to release (OCP1/2/3)





Cs-137 Inventory (MCi)

High density: 54-59
Low density: 17-22

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MELCOR Results

- Pool loading (high- vs. low-density) does not have a significant effect on whether a release occurs but can affect the size of release
    - Decay power not significantly different (dominated by last offload), but inventory of long-lived radionuclides is considerably reduced (e.g., > 60% of Cs-137 removed)
- Boil-off scenarios resulted in no radioactive release within our selected truncation time of 3 days
- Most drain-down scenarios did not lead to radioactive release in 3 days. (Releases limited to first 8% of the operating cycle)
- Successful deployment of 50.54(hh)(2) mitigation is capable of having a significant effect on preventing a release of radioactive material
- For high-density loading without successful deployment of mitigation, the size of release could be up to two orders of magnitude larger (these cases are associated with hydrogen deflagration and loss of the reactor building)
- Sensitivity calculations revealed that a more favorable fuel loading pattern (i.e., 1x8) can significantly reduce the release of radioactive material

Likelihood of SFP Release

Seismic event

- Initiating event frequency of 1 in 60,000 years (**1.7E-5**/yr)

Loss of normal SFP cooling (as modeled)

- Assumed to be **84%** (based on station blackout probability given a 0.7g seismic event)

1.7E-5 x 0.84 = 1.4E-5/yr

SFP damage

- Leak probability of **10%** given a 0.7g seismic event

1.7E-5 x 0.84 x 0.1 = 1.4E-6/yr

Radionuclide release

- Fraction of operating cycle when fuel is susceptible to ignition in the event of pool leak
  - **8%** **without** credit for 10 CFR 50.54(hh)(2) mitigation

1.7E-5 x 0.84 x 0.1 x 0.08 = **1.1E-7/yr or lower** (by about a factor of twenty with credit for 10 CFR 50.54(hh)(2) mitigation)

MACCS2 Consequence Results – Frequency Weighted

Average Consequences (per year) – Weighted by the Likelihood of Release				
SFP Fuel Loading	High Density (1x4)		Low Density	
10 CFR 50.54(hh)(2) mitigation credited	Yes	No	Yes	No
Release Frequency (/yr)	6E-09	1E-07	6E-09	1E-07
Cumulative Cs-137 Release at 72 hours (MCi)	0.3	9	0.2	0.1
Measures Related to Individual Health and Safety				
Individual Early Fatality Risk (/yr)	0	0	0	0
Individual Latent Cancer Fatality Risk (LNT) within 10 Miles (/yr)	2E-12	5E-11	2E-12	2E-11
Measures Related to Cost Benefit Analysis				
Societal Dose (Person-Sv/yr)	3E-04	4E-02	3E-04	3E-03
Land Interdiction (mi^2/yr)	1E-06	1E-03	1E-06	2E-05
Displaced Individuals(/yr)	7E-04	4E-01	7E-04	9E-03

- In the unlikely event a release occurs, no early fatalities predicted in any scenarios
- Protective actions limit individual latent cancer fatality risks
- These individual risks are dominated by long-term exposures to very lightly contaminated areas for which doses are small enough to be considered habitable.
- Implementation of protective actions may require significant amounts of land interdiction and displacement of individuals for some scenarios

Offsite Consequence Analysis

- In the unlikely event a release occurs, no offsite early fatality risk in either high- or low-density scenarios
- Individual latent cancer fatality risk within ten miles is similar in both high- or low-density scenarios due to low event frequency and implementation of protective actions
- Societal dose and latent cancer fatalities are reduced by an order of magnitude with either successful deployment of mitigation or low-density loading
- Land interdiction and displaced individuals are reduced by up to two orders of magnitude with either successful deployment of mitigation or low-density loading
- SFPS results consistent with or lower than past studies

Mitigation Failure Probability and Improving Mitigation Success

<table>
<tr><th>Failure Probability</th><th>No Leak</th><th>Small Leak</th><th>Moderate Leak</th></tr>
<tr><td>OCP 1</td><td rowspan="3">Negligible</td><td rowspan="3">- 0.1 if SBO
- 0.25 if SBO w/o DC</td><td>1.0</td></tr>
<tr><td>OCP 2</td><td>- 0.3 if SBO
- 0.75 if SBO w/o DC</td></tr>
<tr><td>OCP 3</td><td>1.0</td></tr>
<tr><td>OCP 4 and 5</td><td colspan="3">Inconsequential</td></tr>
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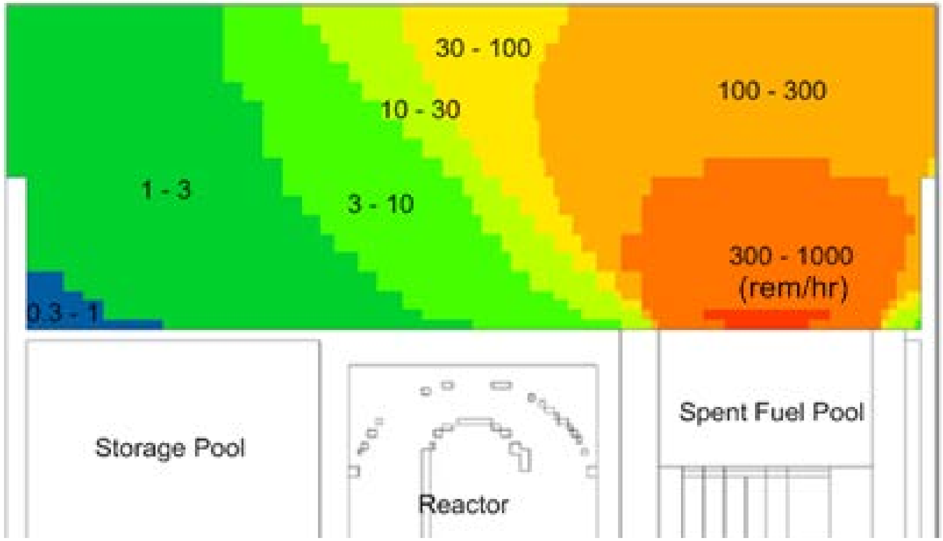

Refueling floor radiation profile when SFP water level drains to the top of fuel racks

With some plant modifications, release can be prevented in all event classes

- OCP1 moderate leak
  - Due to insufficient 50.54(hh)2 flow rate requirement
  - Increase flow rate
- OCP3 moderate leak
  - Due to short available time (~2.5 hr)
  - Move mitigation equipment to low radiation area.

Summary & Conclusions

- Past SFP risk studies have shown that storage of spent fuel in a high density configuration is safe and risk is appropriately low
- SFPS consistent with past studies' conclusions that SFPs are robust and not expected to leak as a result of a seismic event
- SFPS estimated that the likelihood of release is 1 in 10,000,000 years or lower
- Spent fuel is only susceptible to a release within a few months after defueling; after that it is coolable by air.
- SFPS demonstrated that successful mitigation generally prevented potential releases
- In the very unlikely event a release occurs, no early fatalities were predicted for any of the scenarios studied
- A more favorable loading pattern or improvements to mitigation strategies significantly reduced potential releases