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Title: Modeling of Source Term Uncertainties in the Pedestal Region for Neutron Multiplication Monitoring in Fukushima Daiichi Fuel Debris Retrieval Operations

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Modeling of Source Term Uncertainties in the Pedestal Region for Neutron Multiplication Monitoring in Fukushima Daiichi Fuel Debris Retrieval Operations

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Jesson Hutchinson

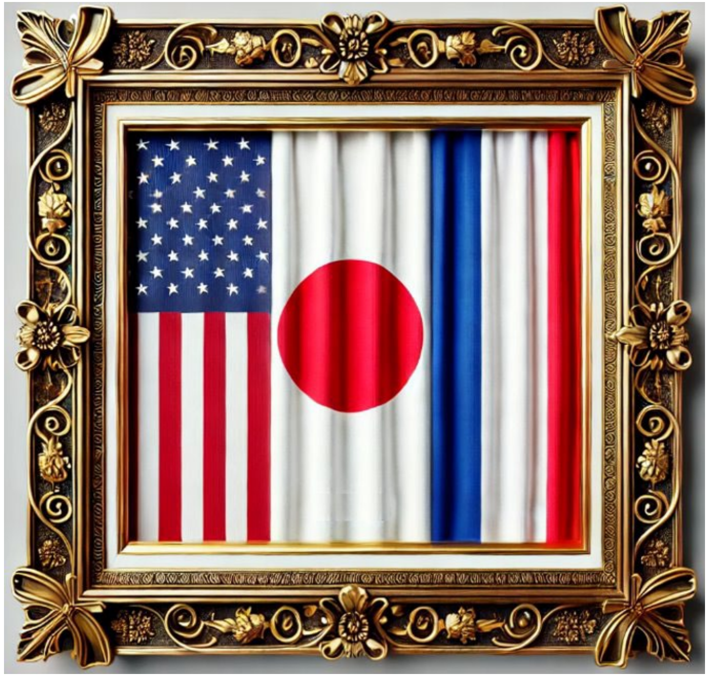
2025 MCNP® User Symposium
July 7-10, 2025

Fukushima Daiichi Nuclear Accident

- Great East Japan Earthquake on March 11, 2011
- Fukushima Daiichi Nuclear Power Station (1F) shut down their operating Units 1-3 (Units 4-6 were already shutdown)
- Subsequent tsunami caused loss of power in their emergency power systems
- With insufficient cooling, Units 1-3 experienced various states of reactor core melt
- Ongoing efforts to decommission Units 1-4

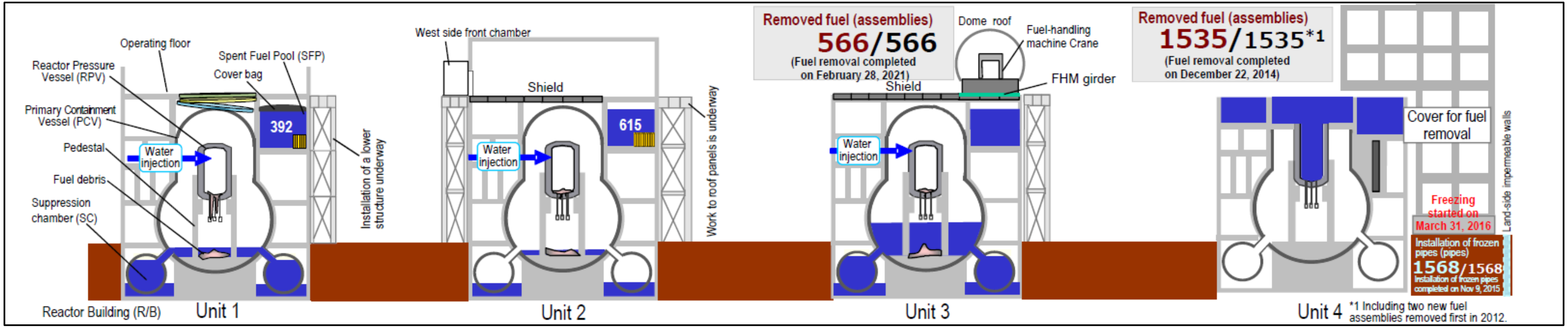
1FRAME

- Focus on collaborative research in the area of criticality monitoring for fuel debris removal at Fukushima Daiichi nuclear power station (1F)
- 1FRAME: 1F Fuel Retrieval and Monitoring Experiments
- Work will include blind tests (analysis of unknown data) using existing measured data, simulated data, and new experimental data
- DOE NCSP IE task (IE 35)
- Work started in Oct 2024



Modeling and Simulation Challenges for 1FRAME

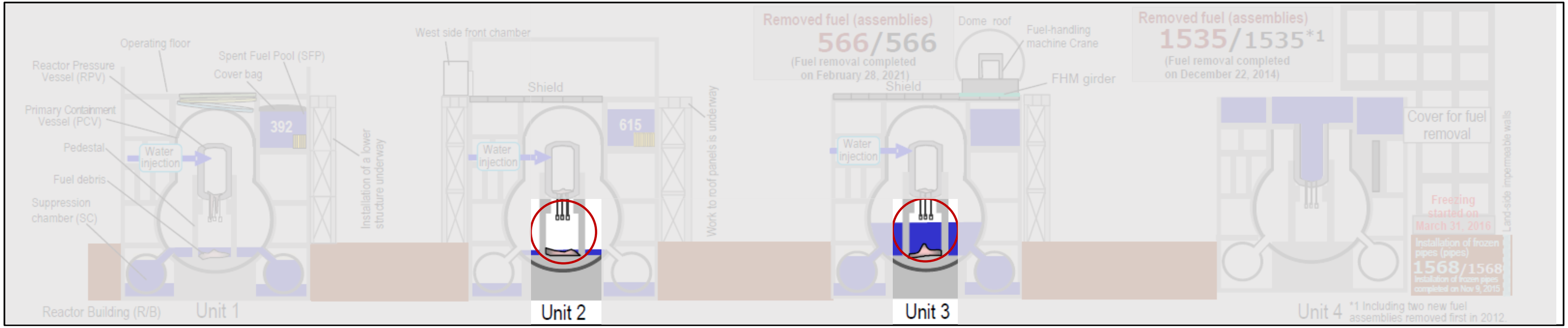
- Very large, complicated geometries, further complicated by structural damage
- Much is still unknown about material compositions, particularly for debris regions
- Units 1-3 are in different states of damage, requiring a unique model for each one



Secretariat of the Team for Countermeasures for Decommissioning, Contaminated Water and Treated Water. “Outline of Decommissioning, Contaminated Water and Treated Water Management.” Technical Report, Council for the Decommissioning of TEPCO’s Fukushima Daiichi Nuclear Power Plant (2024). URL https://www.tepco.co.jp/en/hd/decommission/information/committee/pdf/2024/roadmap_20241128_01-e.pdf

Modeling Efforts Begin with Pedestal Region and Simplified Geometries

- More investigations and data are available for debris found in pedestal region
- Literature review of primary containment vessel investigations by TEPCO
- Unit 2 and 3 are focus of the initial study



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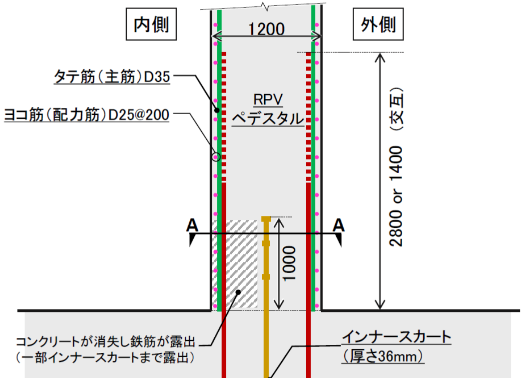
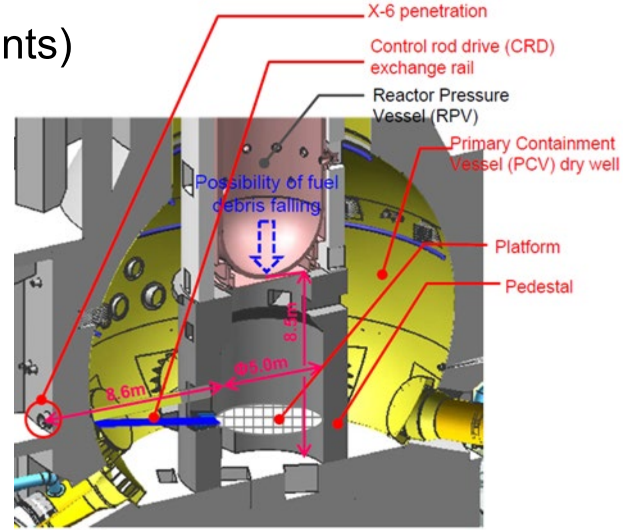
Gross Dimensions of Pedestal Region

- Pedestal floor to bottom of reactor pressure vessel (RPV) is 8.5 meters
- Inner diameter of pedestal is 5 meters
- Walls of pedestal are 1.2 meters thick (ignored reinforcements)
- Arbitrarily set the bottom of pedestal to be 3 meters thick
- Did not model bottom of RPV (top of pedestal)



Tokyo Electric Power Company Holdings, Inc. “Reinforcement of Unit 1 RPV pedestal.” (2023). URL https://www2.nra.go.jp/data/000464455.pdf.

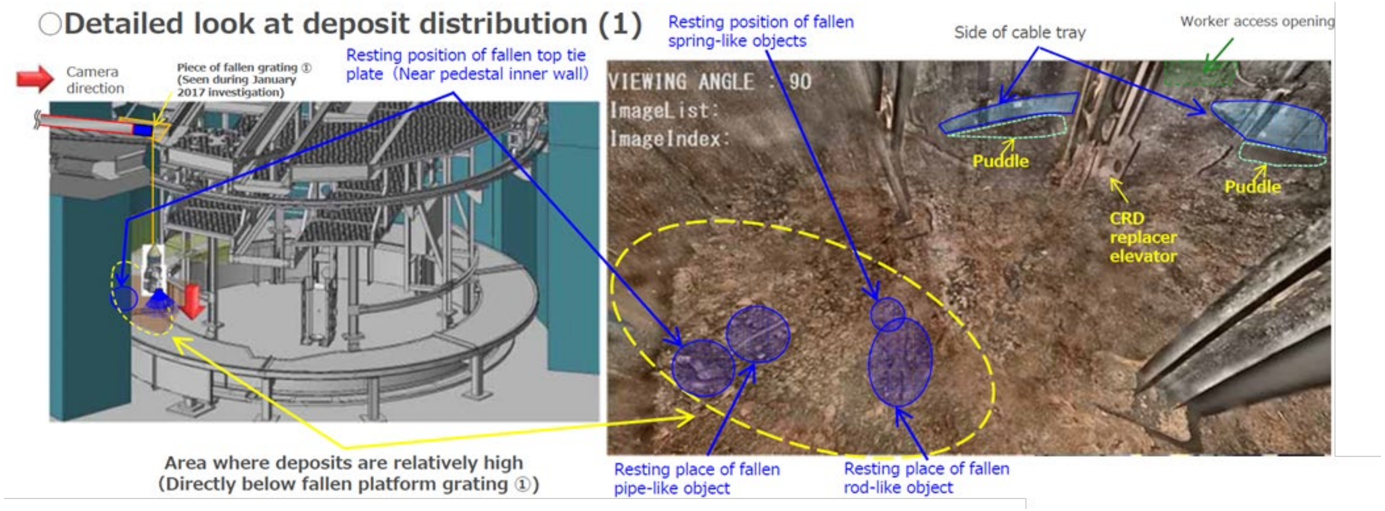


Cross section of the bottom of Primary Containment Vessel

Tokyo Electric Power Company Holdings, Inc. “Pre-investigation results of the area inside the pedestal for the Unit 2 Primary Containment Vessel Investigation at Fukushima Daiichi Nuclear Power Station (examination results of digital images).” (2017). URL https://www.tepco.co.jp/en/nu/fukushima-np/handouts/2017/images/handouts 170202 01-e.pdf.

Unit 2 Geometry Specifics

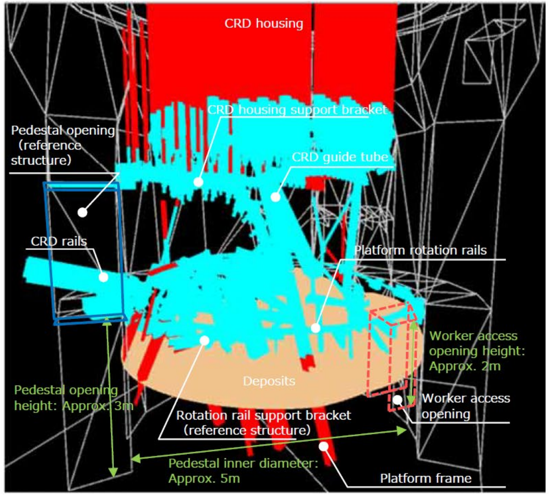
- TEPCO investigations, comparing to known structures, suggest debris heights varying from 40-70cm
  - Initial model assumes flat 70 cm thick debris region above pedestal floor
- Only puddles of water were found
  - Ignored water inside pedestal and assumed sea level atmosphere
- Intact structures were ignored: platform, control rod drive (CRD) housings, CRD replacer elevator, etc

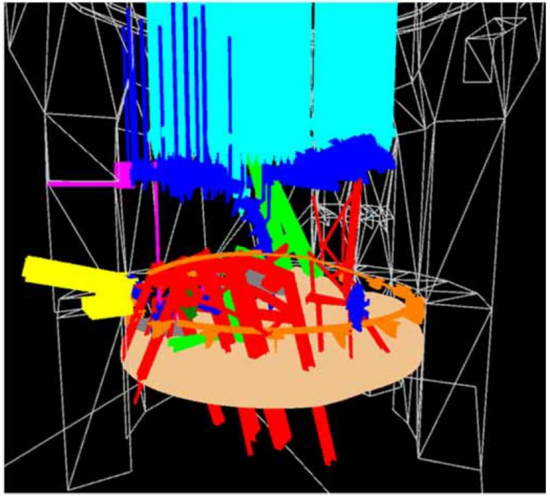


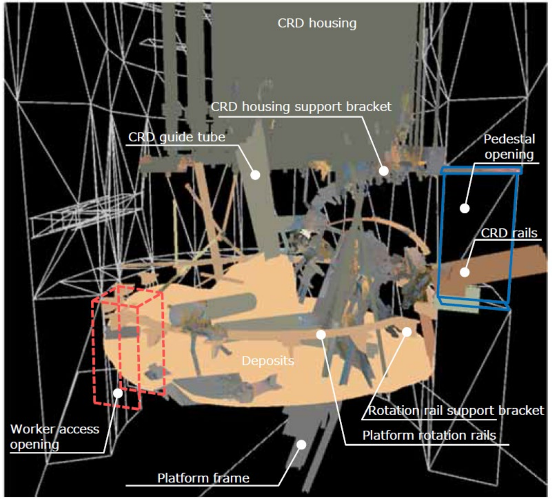
Tokyo Electric Power Company Holdings, Inc. "Fukushima Daiichi Nuclear Power Station Unit 2 Primary Containment Vessel Internal Investigation." (2018). URL https://www.tepco.co.jp/en/nu/fukushima-np/handouts/2018/images/handouts 180426 02-e.pdf.

Unit 3 Geometry Specifics

- TEPCO created 3D renderings of images during investigations
- Based on references of worker access opening, debris region was estimated/modeled to be 2 meters
- Structures were ignored: platforms, control rod drive (CRD) housings, etc







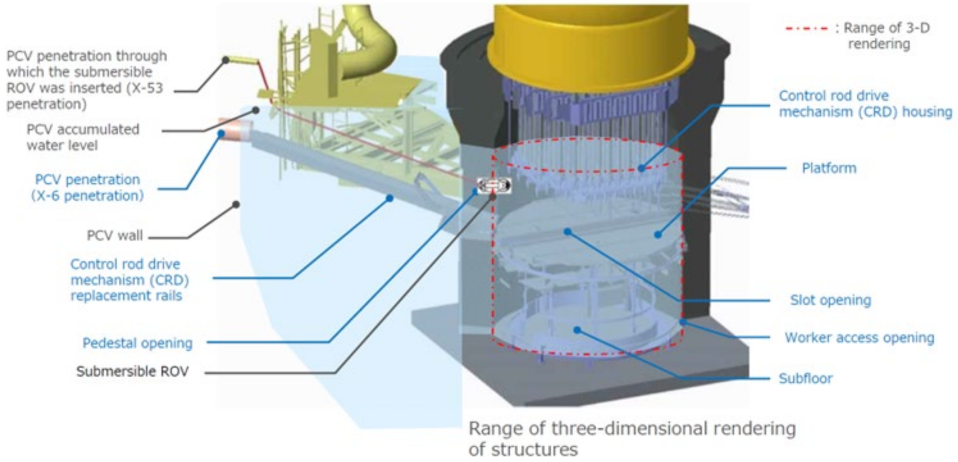
: Structures identified in the videos
: Structures that could not be identified in the videos (the estimated from design data)

: Platform, frame, etc., structures
: Platform rotation motor
: CRD housing support bracket
: CRD housing
: CRD guide tube
: CRD replacement rails
: Platform rotation rails, support brackets
: Terminal boxes, electric wire conduits, pipes
: Grating

Tokyo Electric Power Company Holdings, Inc. "3-D Rendering of images obtained during the Fukushima Daiichi Nuclear Power Station Unit 3 Primary Containment Vessel (PCV) Internal Investigation." (2018). URL https://www.tepco.co.jp/en/nu/fukushima-np/handouts/2018/images/handouts/18042603-e.pdf.

Unit 3 Geometry Specifics

- Investigations required a submersible robot and entered through CRD replacement rail opening
- Reports indicate water level to be approximately 6.3 meters above pedestal floor
- Modeled water to be 4 meters thick, sitting above the 2 meter thick debris region



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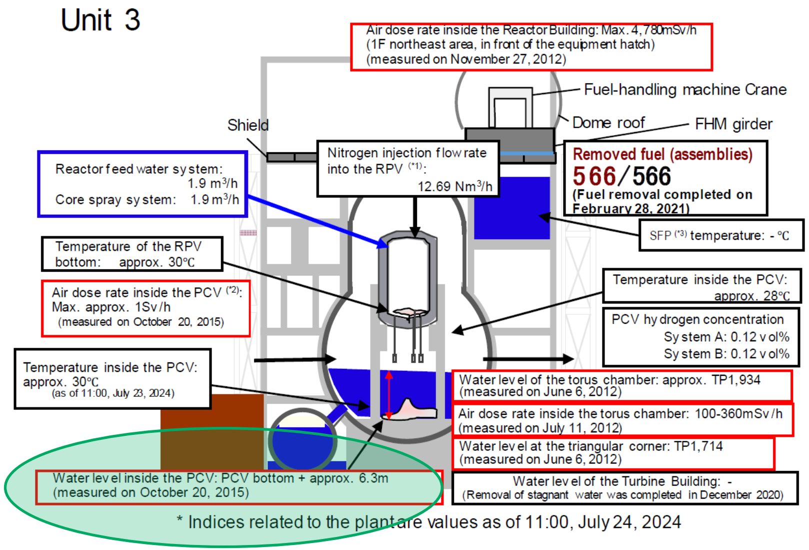

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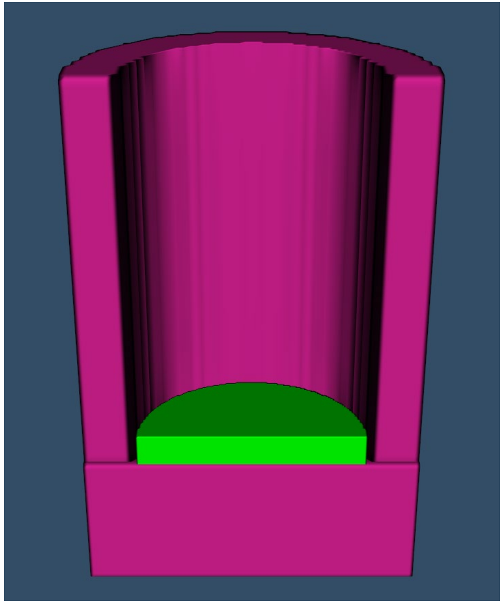
URL https://www.tepco.co.jp/en/hd/decommission/information/committee/pdf/2024/roadmap_20241128_01-e.pdf

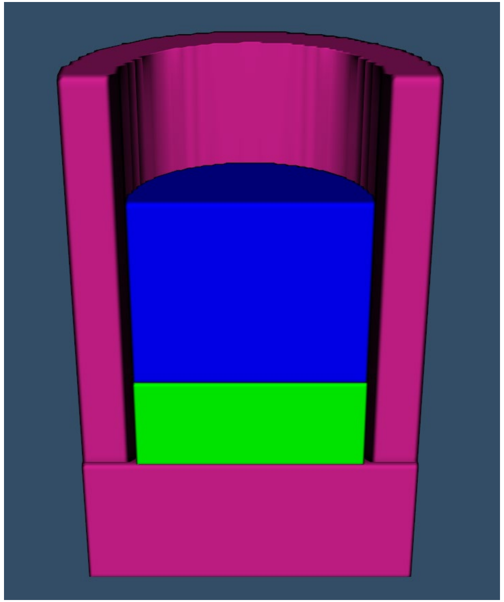
MCNP® models of Units 2 and 3

- Visualizations created using Gxsview
- Magenta: concrete
- Green: debris region
- Blue: water
- Not shown: atmosphere that fills inside of pedestal

Unit 2



Unit 3



S. Ohnishi. "Gxsview: Geometry and cross section viewer for calculating radiation transport." SoftwareX, volume 14, p. 100681 (2021). URL https://www.sciencedirect.com/science/article/pii/S2352711021000261.

Material Modeling

- Water assumed to be nominal 1.0 g/cm^3 with no impurities
- Concrete composition and density (2.3 g/cm^3) taken from [1]
  - Still an area of uncertainty
- Assumed sea level atmosphere composition and density [2]
- Debris region leveraged a JAEA dataset produced in 2012 [3]
  - Created using ORIGEN2
  - "results given for irradiated Uranium pellet and the activated cladding tube of Zirconium alloy…"
  - Used isotopes weights for the 10.0 Year data point of Unit 2 and 3 cores (next nearest data was at 20 Year; time of study is ~14 years from 2011)

1. K. Izawa, Y. Uchida, K. Ohkubo, M. Totsuka, H. Sono, and K. Tonoike. "Infinite multiplication factor of low-enriched UO2–concrete system." Journal of Nuclear Science and Technology, volume 49(11), pp. 1043–1047 (2012)
2. R. S. Detwiler, R. J. McConn, T. F. Grimes, S. A. Upton, and E. J. Engel. "Compendium of Material Composition Data for Radiation Transport Modeling." Technical Report 200-DMAMC-128170; PNNL-15870, Rev. 2, Pacific Northwest National Lab. (PNNL), United States (2021).
3. K. Nishihara, H. Iwamoto, and K. Suyama. "Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant." Technical Report JAEA-Data/Code 2012-018, Japan Atomic Energy Agency (2012).

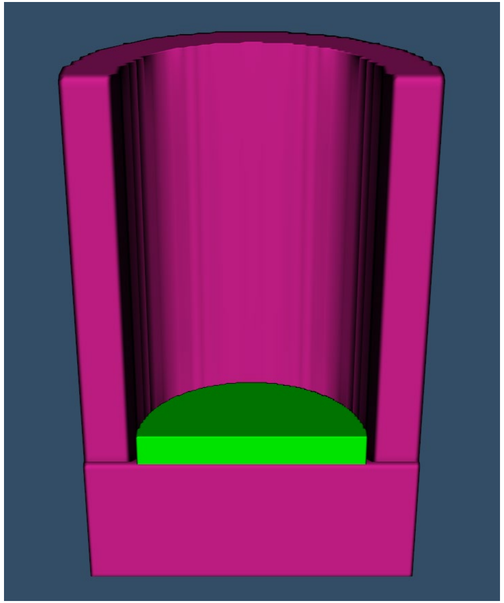
Debris Region Material Modeling with JAEA Dataset

- ORIGEN2 lists isotopics into 3 categories: “Activation”, “Actinides”, and “Fission Products”
- Structural material (Zirconium alloy cladding) is in “Activation” isotopics
- Fuel material (Uranium pellet) is in “Actinides” and “Fission Products”
- Due to uncertainty in debris composition, 3 modeling approaches were taken for Units 2 and 3 (6 total models)
    1. Homogeneous model
    2. Layered model
    3. Lattice model

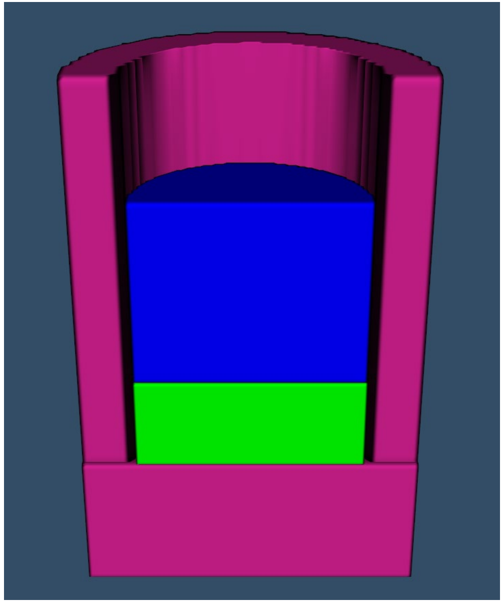
Debris Region Material Modeling: Homogeneous Debris

- Green: debris region uses a material card with normalized isotopics from Activation, Actinide, and Fission Product materials

Unit 2



Unit 3



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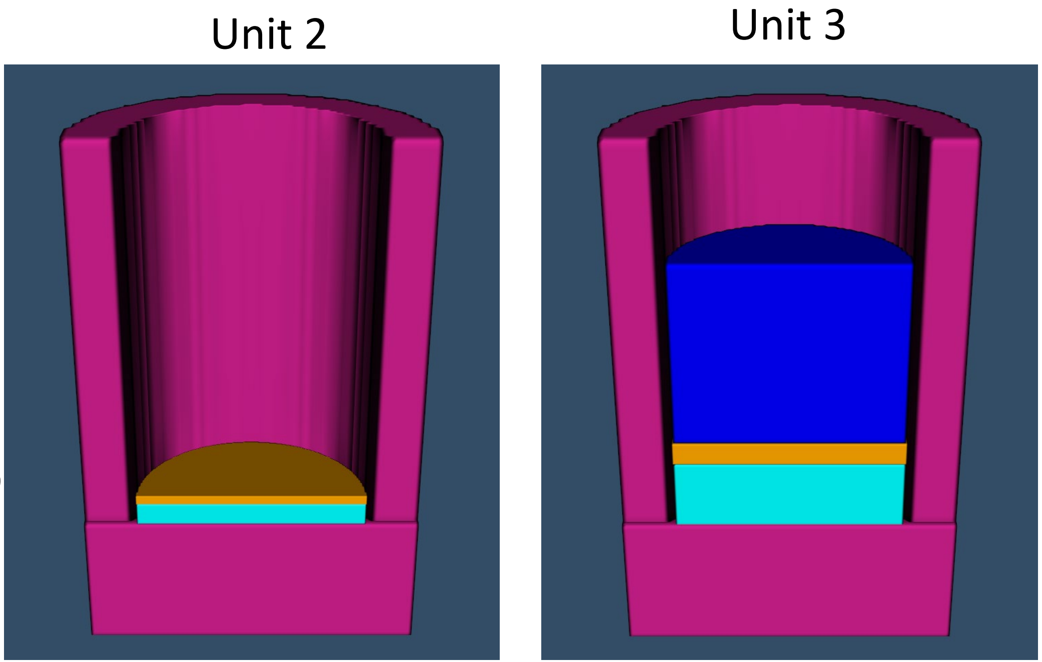
Debris Region Material Modeling: Layered Debris

- Orange: structural debris uses a material card with normalized isotopics from Activation
- Cyan: fuel debris uses a material card with normalized isotopics Actinide and Fission Product materials
- Arbitrarily chosen layer thickness
- Unit 2 debris thicknesses (70 cm total)
  - 50 cm fuel debris
  - 20 cm structural debris
- Unit 3 debris thicknesses (200 cm total)
  - 150 cm fuel debris
  - 50 cm structural debris



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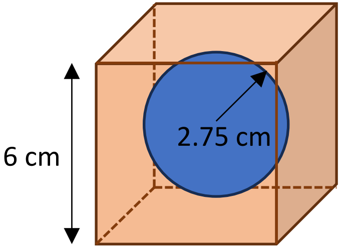
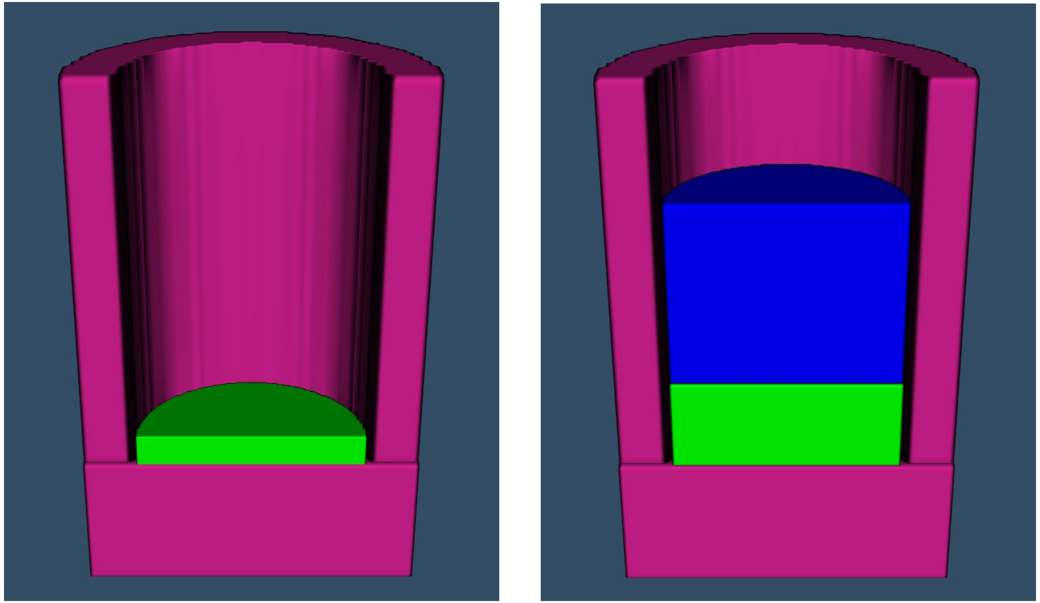
Debris Region Material Modeling: Lattice Debris

- Green: rectangular lattice structure
- Lattice element:
  - 2.75 cm radius sphere filled with normalized isotopics from Actinide and Fission Product materials
  - 6 cm cube filled with normalized isotopics from Activation



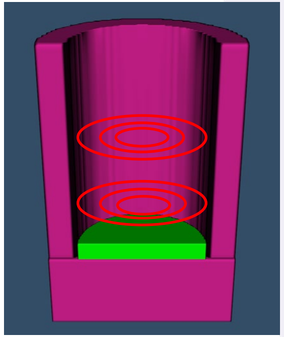
Unit 2 Unit 3



S. Ohnishi. "Gxsview: Geometry and cross section viewer for calculating radiation transport." SoftwareX, volume 14, p. 100681 (2021). URL https://www.sciencedirect.com/science/article/pii/S2352711021000261.

Source and Tally Specifications

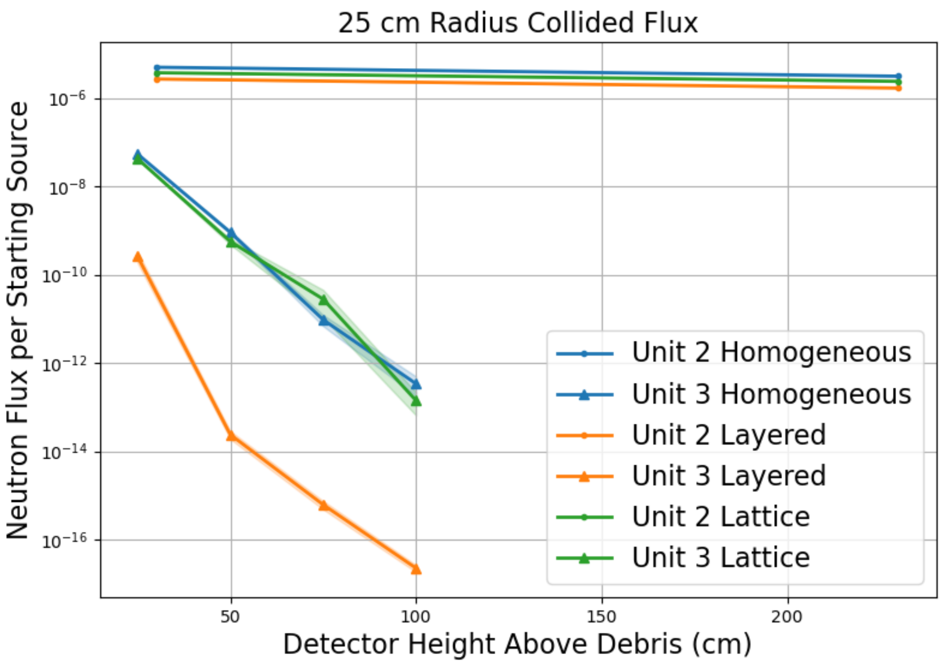
- Distributed source term within the fuel debris region of model, using a neutron energy spectra from Cm-244 spontaneous fission [1]
- Tallies were ring detectors (F5z) at various heights and radii above debris region
- Unit 2: 30 and 200 cm above debris (3 radii, 25/100/200 cm)
- Unit 3: 25/50/75/100 cm above debris (9 radii, 25 – 225 cm in 25 cm increments)



1. T. Matsumura, K. Okumura, M. Sakamoto, K. Terashima, E. S. Riyana, and K. Kondo. "Characterization of neutrons emitted by an expected small amount of fuel debris in a trial retrieval from Fukushima Daiichi Nuclear Power Station." Nuclear Engineering and Design, volume 432, p. 113791 (2025).

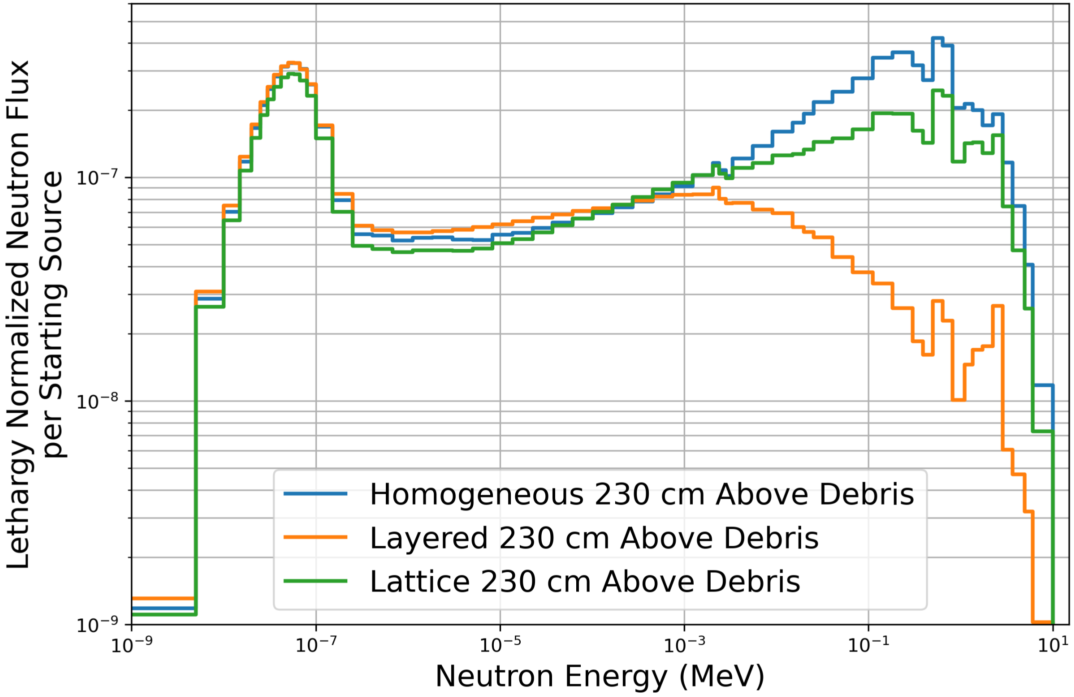
Water Significantly Reduces Neutron Flux in Unit 3

- Unit 2 integral neutron flux relatively unchanged as a function of height (60% max change)
- Unit 3 integral neutron flux reduced by ~5 orders of magnitude over 1 meter
- Approximate Mean Free Paths
  - Unit 2 air: 4.7×10^3 cm
  - Unit 3 water: 0.71 cm



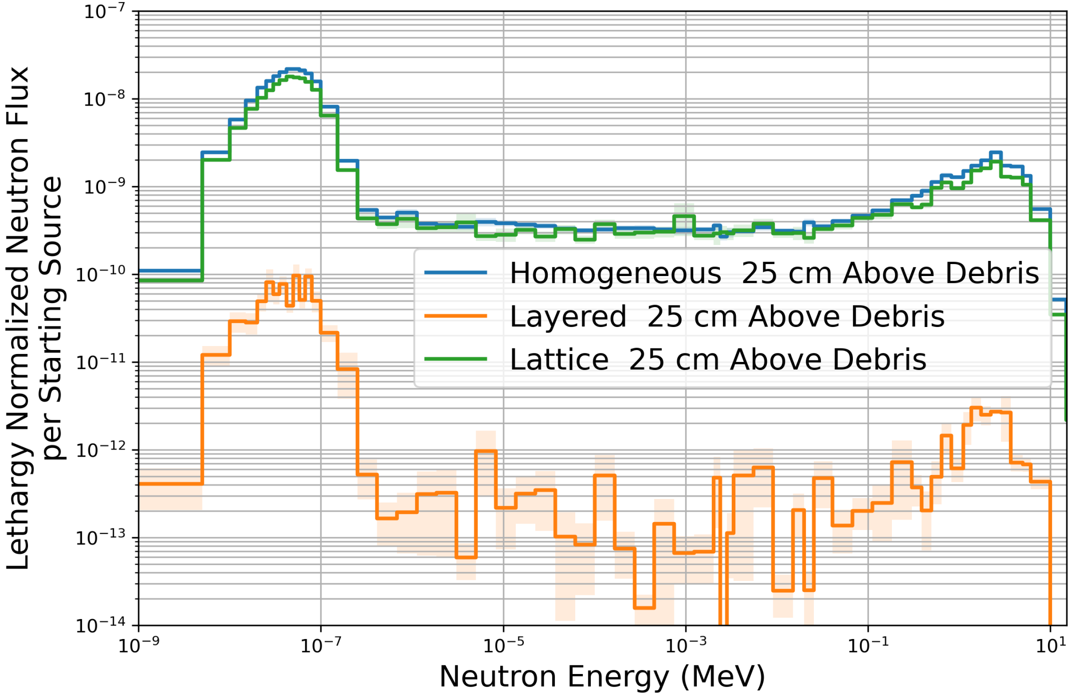
Unit 2 at 30 cm radius, 230 cm above debris

- Noticeable fission energy spectrum in neutron flux for Homogeneous and Lattice models
- Structural debris sitting atop fuel debris in Layered model significantly alters spectra
- Neutron flux changed by ~8% as a function of radial location for a given detector height



Unit 3 at 200 cm radius, 25 cm above debris

- Same spectral shape regardless of model type
  - Significant scattering and thermal buildup due to water
- Structural debris sitting atop fuel debris in Layered model significantly reduces spectra
- Neutron flux changed by ~20% as a function of radial location for a given detector height



Neutron Multiplicity Estimates and Masses

- Layered model concentrates fissioning material into a single region, while placing structural material as a reflector on top
  - Example: Unit 2 fuel mass is smaller in Layered model but higher k_{eff}
- Addition of water also acts as a reflector
- Lattice model may be unrealistic and would need further study

Calculated masses (metric tons) for various primary atoms of structural and fuel debris and Cm-244 neutron yield (n/s)

Unit 2					
Debris Model Choice	Zr Mass	U Mass	Pu Mass	Cm-244 Mass	Cm-244 Neutron Yield
Homogeneous	13.36	63.90	0.413	5.134×10^{-4}	5.613×10^{9}
Layered	15.07	61.09	0.395	4.909×10^{-4}	5.366×10^{9}
Lattice*	31.22	34.49	0.223	2.771×10^{-4}	3.030×10^{9}
Unit 3					
Debris Model Choice	Zr Mass	U Mass	Pu Mass	Cm-244 Mass	Cm-244 Neutron Yield
Homogeneous	38.16	182.6	1.414	1.236×10^{-3}	1.352×10^{10}
Layered	37.73	183.3	1.420	1.241×10^{-3}	1.357×10^{10}
Lattice*	89.19	98.55	0.763	6.674×10^{-4}	7.295×10^{9}

*Estimated Values based on volumes of total debris region and lattice elements

k_{eff}

Debris Model Choice	Unit 2	Unit 3
Homogeneous	0.517601 +/- 0.000012	0.548653 +/- 0.000011
Layered	0.620163 +/- 0.000013	0.670515 +/- 0.000012
Lattice	0.463880 +/- 0.000035	0.491120 +/- 0.000011

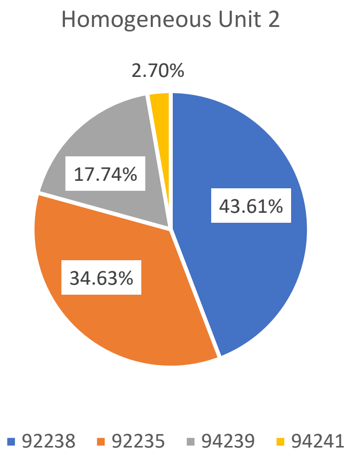
Neutron Energies Causing Fission

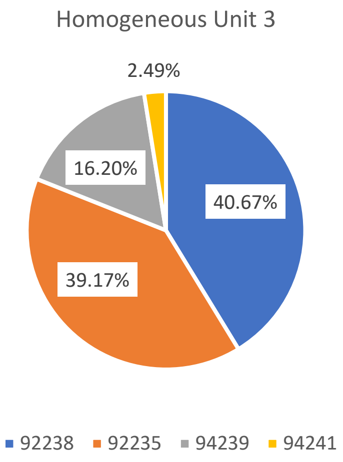
- Layered and Homogeneous models seem to be fast systems, while Lattice model is more in the intermediate energy range

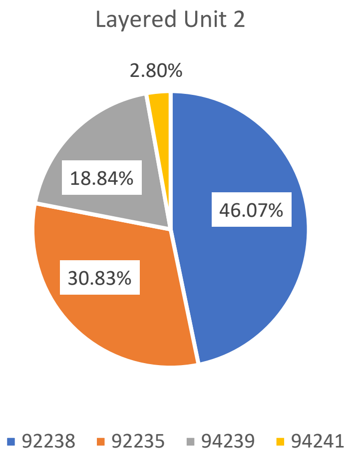
Percentages of fissions caused by neutrons in the thermal, intermediate, and fast neutron energy ranges			
Unit 2			
Debris Model Choice	Thermal (<0.625 eV)	Intermediate (0.625 eV - 100 keV)	Fast (>100 keV)
Homogeneous	29.87%	26.97%	43.16%
Layered	24.25%	22.08%	53.67%
Lattice	34.71%	39.67%	25.62%
Unit 3			
Debris Model Choice	Thermal (<0.625 eV)	Intermediate (0.625 eV - 100 keV)	Fast (>100 keV)
Homogeneous	24.94%	30.46%	44.60%
Layered	15.84%	21.04%	63.12%
Lattice	28.74%	45.16%	26.11%

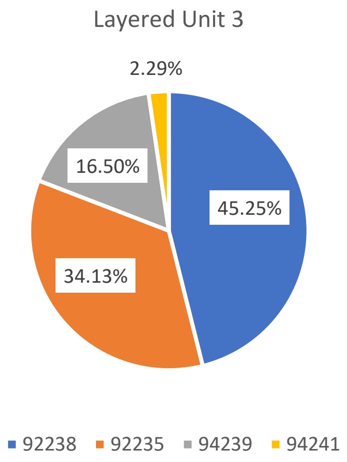
Isotopes Causing Fission

- Special Tally Treatment "First Fission Tally" (FFT) on a F4 flux tally in fuel debris region
- U-238 is dominant fissioning isotope
- Going from Homogeneous to Layered model increases U-238 contribution
  - Coincides with faster neutron spectra causing fissions









Conclusions and Future Work

- Modeling approach has significant impact on expected neutron spectral flux
- Presence of water in Unit 3 greatly reduces neutron signal
- Neutron flux from Homogeneous and Lattice models behaved more similarly as opposed to Layered model
- Lattice is very computationally intensive, making parameter studies difficult
  - Unless evidence suggests otherwise, Homogenous and Layered model will be focused on moving forward
- Significant uncertainty in material compositions and spatial makeup still remain
- Future work will continue to add fidelity to models
  - Ideal goal is to incorporate point-cloud/CAD geometry from investigations