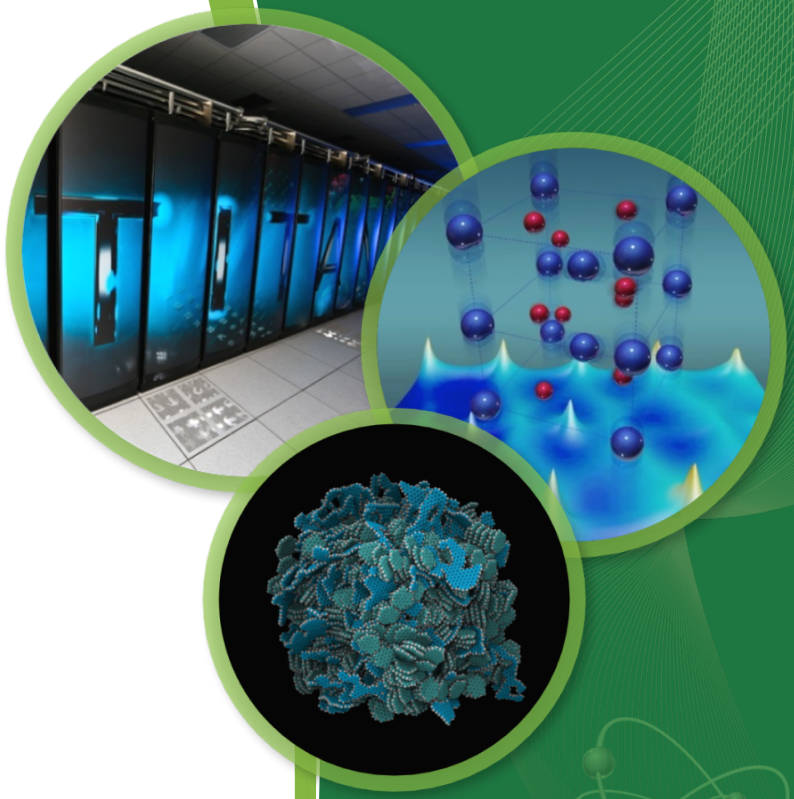
MAVRIC Shielding Analyses of SNF Transportation and Dry Storage Casks



SCALE Users' Group Workshop
ORNL, September 26-28, 2017

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Outline

- Shielding analyses of as-loaded transportation packages
- Shielding analysis of a proposed consolidated interim spent nuclear fuel (SNF) storage facility
- Regulatory dose rate limits for SNF transportation packages and shielding requirements for dry storage facilities
- SCALE shielding and source term analysis capabilities
- Dose rate calculation results

Regulatory Shielding Requirements for SNF Transportation Packages

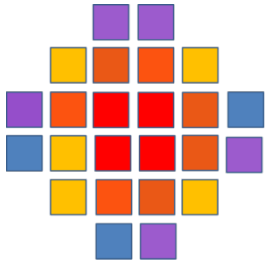
- 10 CFR 71, *Packaging and Transportation of Radioactive Material*
- SNF transportation packages comply with regulatory dose rate limits for exclusive shipment provided in:
  - 10 CFR 71.47 for transportation packages under normal conditions of transport (NCT)
    - The dose rate on the external surface of the package must be < 200 mrem/h (< 1,000 mrem/h shipment in closed transport vehicle)
    - The dose rate at any point on the outer surface of the vehicle, including the top and underside of the vehicle, must be < 200 mrem/h
    - The dose rate at any point 2 m from the outer lateral surfaces of the vehicle (excluding the top and underside of the vehicle) must be < 10 mrem/h
  - 10 CFR 71.51 for transportation packages under hypothetical accident conditions (HAC)
    - The dose rate at at 1 m from the cask must be < 1,000 mrem/h

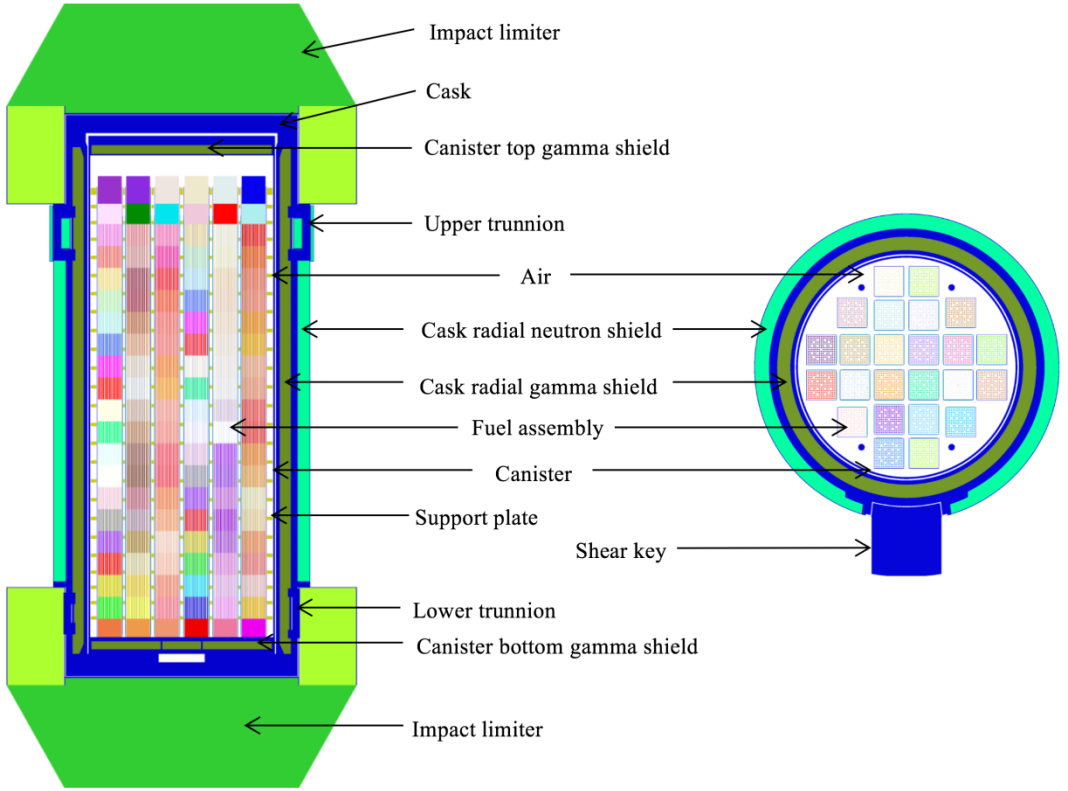
Transportation Package Models*

- Detailed packaging, canister, and fuel basket geometry
  - Packaging models for both normal conditions of transport (NCT) and hypothetical accident conditions (HAC)
- Fuel assembly
  - Pin-by-pin assembly representation
  - Axial burnup profile (18 zones for PWR SNF; 10 zones for BWR SNF)
  - Fuel assembly hardware materials and activation sources homogenized within corresponding volumes
  - Damaged assemblies represented with fuel sources in assembly top and bottom hardware regions
- Activation radiation sources for non-fuel components placed within PWR fuel assemblies

Assembly Burnup

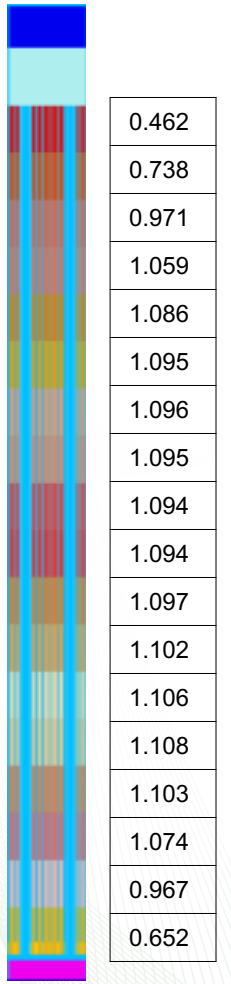
Color	Burnup range (GWd/MTU)
	45–50
	40–45
	35–40
	30–35
	20–25
	15–20
	< 15





SNF Source Terms Calculated with ORIGAMI

- Depletion/decay calculations for SNF assemblies with burnup-dependent axial burnup profiles
- Fast calculations using pre-generated ORIGEN cross-section libraries for representative fuel assembly types
- Fuel gamma and neutron source terms
- Activation source terms for fuel assembly hardware materials
  - Cobalt impurity concentrations in stainless steel and Inconel alloys
- Output includes nuclide inventories, decay heat, and radiation source terms (ORIGEN ft71 binary files)



Example of PWR axial burnup profile

Dose Rate Calculations Performed with the MAVRIC Shielding Calculation Sequence*

- Monte Carlo radiation transport with automated variance reduction
- Continuous-energy cross-section data for the Monte Carlo transport
- Large number of different photon and neutron sources (e.g., 432 neutron sources and 504 photon sources for a canister with 24 PWR assemblies)
- Source spectrum and strength values directly from ORIGEN ft71 binary files generated by ORIGAMI
- Dose rate map using a cylindrical tally mesh
- Code utilities to identify maximum dose rate values within tally mesh

*D. E. PEPLOW, "Monte Carlo Shielding Analysis Capabilities with MAVRIC," *Nucl. Technol.* **174**(2), 289–313 (2011).

Variance Reduction Method

- *Forward-weighted consistent adjoint driven importance sampling* (FW-CADIS)* method
  - Acceptable statistical accuracy of dose rate estimates within every geometry region outside a SNF transport package/storage cask
  - Requires both forward and adjoint discrete ordinates calculations with Denovo † to determine energy- and space-dependent neutron and photon importance maps
  - Particles that make important contributions to dose rate are sampled more often to increase calculation efficiency
  - Particles reaching tally regions have similar weight values, thereby reducing the statistical variance of the Monte Carlo estimate
  - Adjoint source region for Denovo adjoint calculations is defined within the air region surrounding the transportation package in radial and axial directions

*J. C. WAGNER, D. E. PEPLOW, and S. W. MOSHER, "FW-CADIS Method for Global and Regional Variance Reduction of Monte Carlo Radiation Transport Calculations," *Nucl. Sci. Eng.* **176**(1), 37–57 (2014).
† T. M. EVANS et al., "Denovo: A New Three Dimensional Parallel Discrete Ordinates Code in SCALE," *Nucl. Technol.* **171**(2), 171–200 (2010).

Easy Source Energy Spectrum Specifications

read definitions

' neutron source distributions for the active fuel region; ft71 binary file for canister_inventory.position ID = 1

distribution 1001 special="origensBinaryConcentrationFile" filename="assem01_assembly_dump.f71" parameters 1 1 end end distribution

---

distribution 1018 special="origensBinaryConcentrationFile" filename="assem01_assembly_dump.f71" parameters 18 1 end end distribution

distribution 101 special="origensBinaryConcentrationFile" filename="assem01_assembly_dump.f71" parameters 19 1 end end distribution

' photon source distributions for the active fuel region; ft71 binary file for canister_inventory.position ID = 1

distribution 2001 special="origensBinaryConcentrationFile" filename="assem01_assembly_dump.f71" parameters 1 5 end end distribution

---

distribution 2002 special="origensBinaryConcentrationFile" filename="assem01_assembly_dump.f71" parameters 19 5 end end distribution

' co-60 activation source; 1 g Co/MTU; ft71 binary file for canister_inventory.position ID = 1

distribution 1 special="origensBinaryConcentrationFile" filename="assem01_co60_assembly_dump.f71" parameters 1 5 end end distribution

---

Easy Source Sampling Specifications

read sources

' neutron source strength for the active fuel region; canister_inventory.position ID = 1

src 1001 neutrons useNormConst cuboid -24.40781 -45.85811 69.28009 47.82979 121.12240 100.80240 mixture=1001 eDistributionID=1001 end src

---

' photon source strength for the active fuel region; canister_inventory.position ID = 1

src 2001 photons useNormConst cuboid -24.40781 -45.85811 69.28009 47.82979 121.12240 100.80240 mixture=1001 eDistributionID=2001 end src

---

' Co-60 source strength for canister_inventory.position upper end fitting; canister_inventory.position ID = 1

src 101 photons useNormConst multiplier=1.50300 cuboid -24.40781 -45.85811 69.28009 47.82979 496.60800 484.68780 mixture=601 eDistributionID=1 end src

---

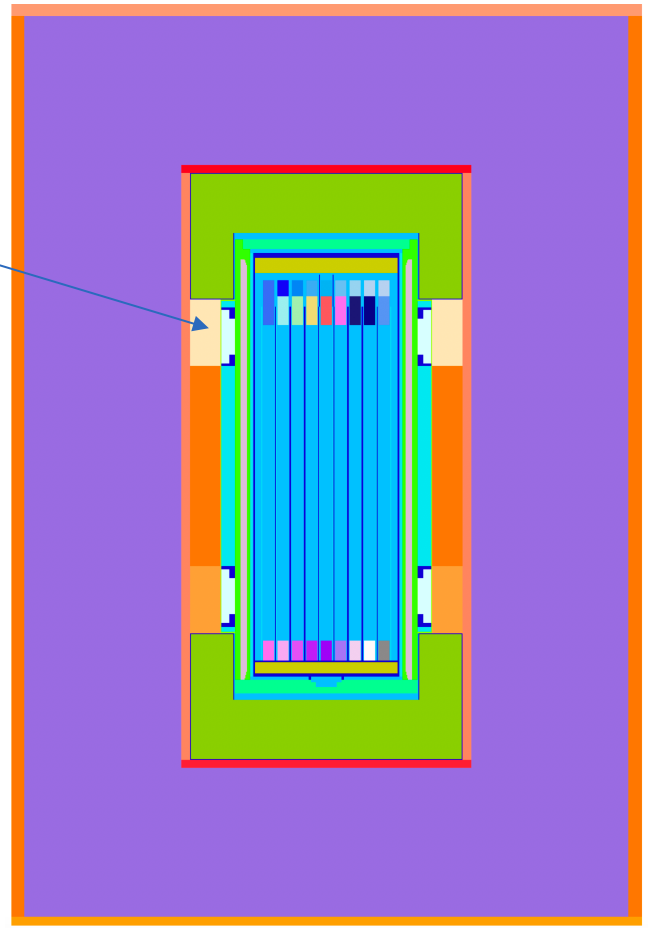
' Fuel sources for damaged fuel canister_inventory.position gas plenum; canister_inventory.position ID = 1

src 3101 neutrons useNormConst multiplier=0.0776 cuboid -24.40781 -45.85811 69.28009 47.82979 484.68780 466.56240 mixture=501 eDistributionID=101 end src

src 4101 photons useNormConst multiplier=0.0776 cuboid -24.40781 -45.85811 69.28009 47.82979 484.68780 466.56240 mixture=501 eDistributionID=201 end src

MAVRIC Utilities for Processing Results

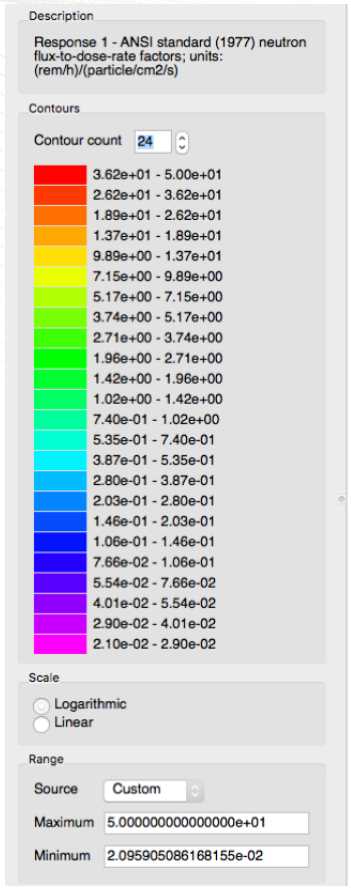
```
=shell
 mv "${OUTBASENAME}.mt1.3dmap" neutron.mt1.3dmap
 mv "${OUTBASENAME}.mt2.3dmap" photon.mt1.3dmap
end
' split off the neutron dose rate
=mtSplit
neutron.mt1.3dmap
2
1
neutron.doseRate.3dmap
end
' split off the photon dose rate
=mtSplit
photon.mt1.3dmap
2
1
photon.doseRate.3dmap
end
' add neutron and photon dose rates
=mtBinOp
neutron.doseRate.3dmap
add
photon.doseRate.3dmap
total.doseRate.3dmap
end
' total dose rate at cask radial surface (mixture=991; upper region)
=mtMask
total.doseRate.3dmap
keepOnly
intersection
-1 -1 991
0.0
total.Cask-UpperRadialSurfaceDoseRate.3dmap
end
```

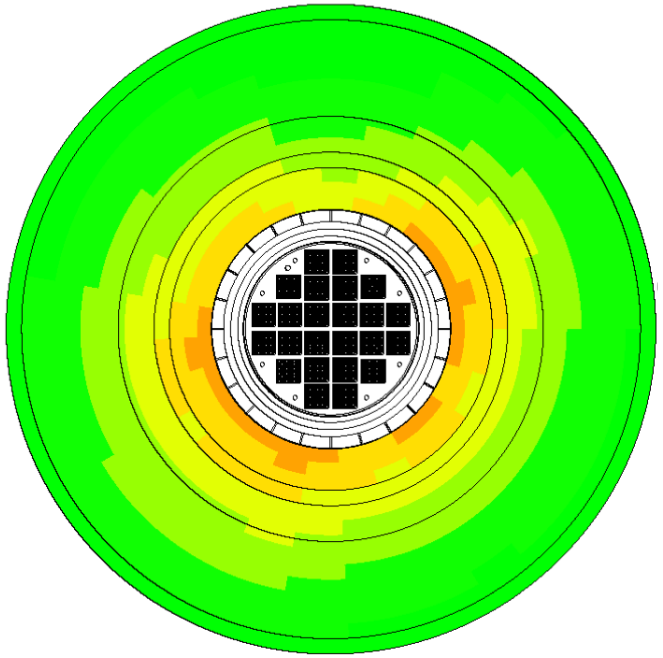


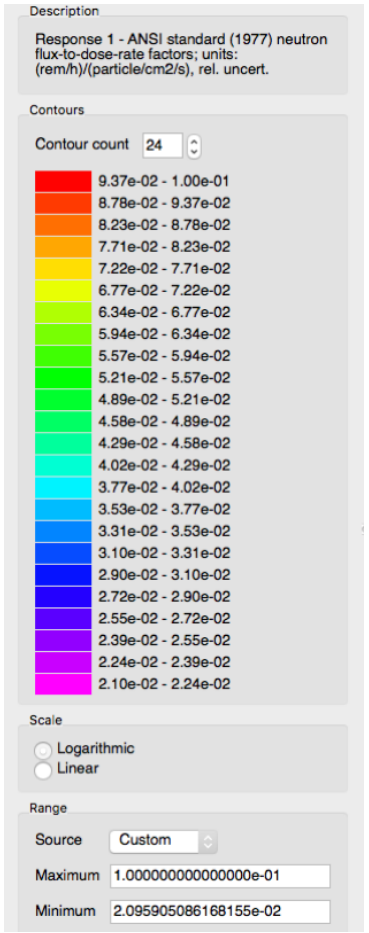
Color-coded 2-D Dose Rate Map Visualization with Fulcrum

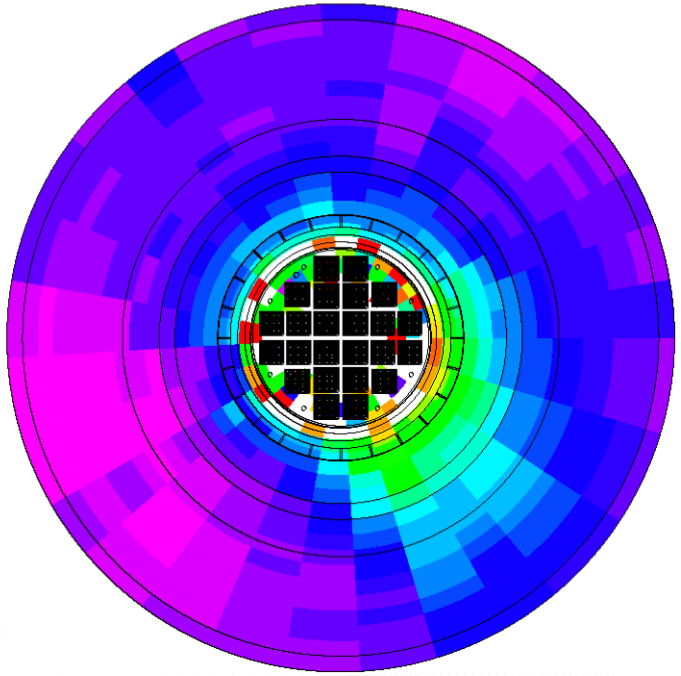
Dose rate (mrem/h)

Relative statistical error



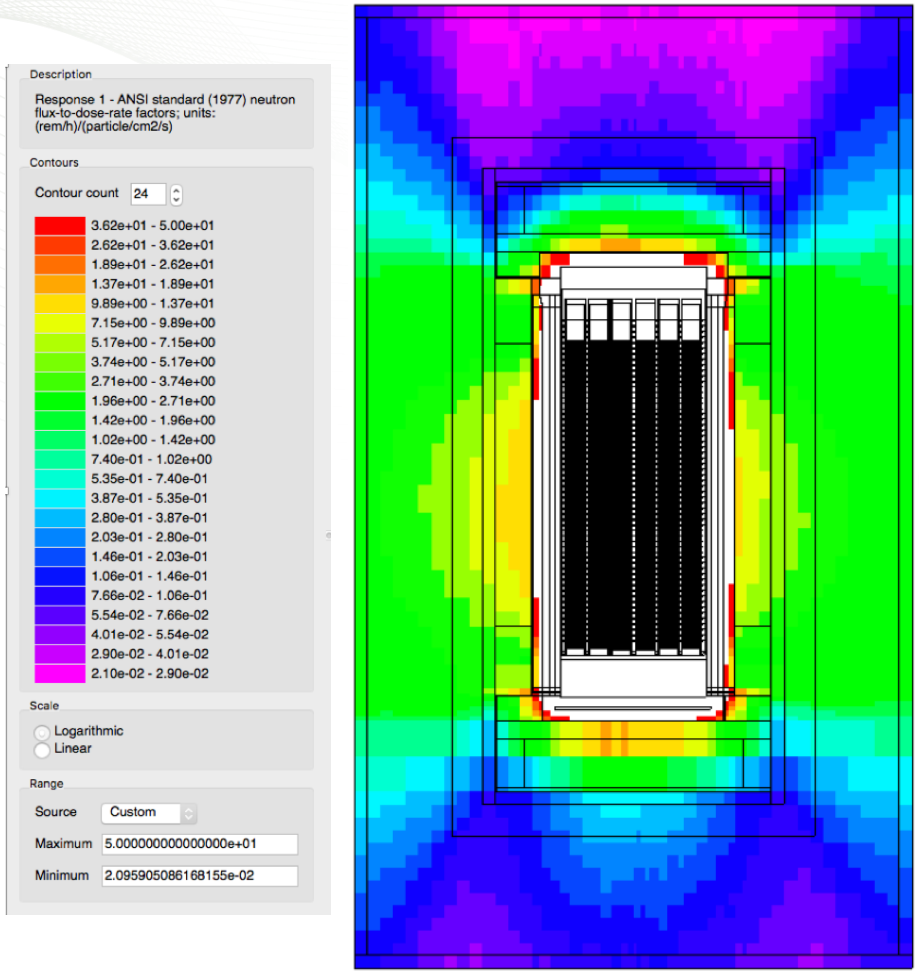




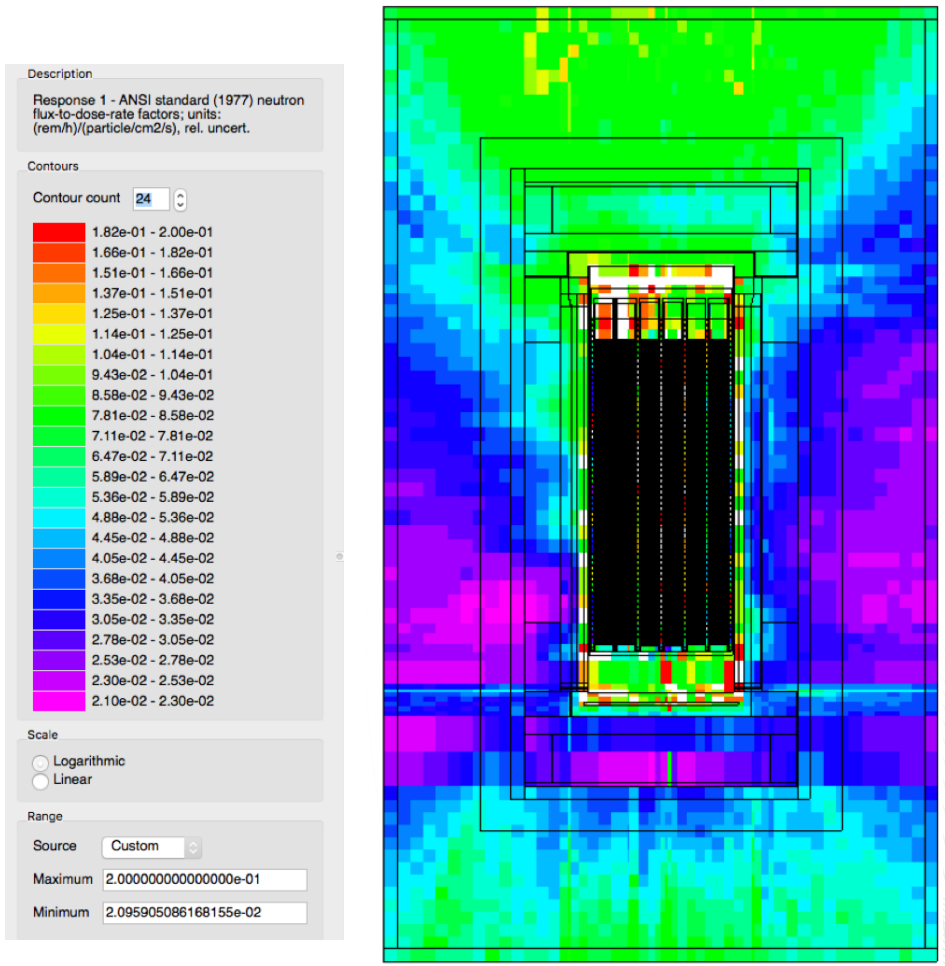


Color-coded 2-D Dose Rate Map Visualization with Fulcrum

Dose rate (mrem/h)



Relative statistical error



Confirmatory Dose Rate Calculations for the WCS Consolidated Interim Storage Facility*


FEDERAL REGISTER
The Daily Journal of the United States Government

Notice

Waste Control Specialists LLC's Consolidated Interim Spent Fuel Storage Facility Project

A Notice by the Nuclear Regulatory Commission on 01/30/2017

- Conceptual design of the Phase 1 concrete pad: 467 NAC vertical storage casks and NUHOMS® horizontal storage modules
- Purpose of the calculations: to determine controlled area boundary

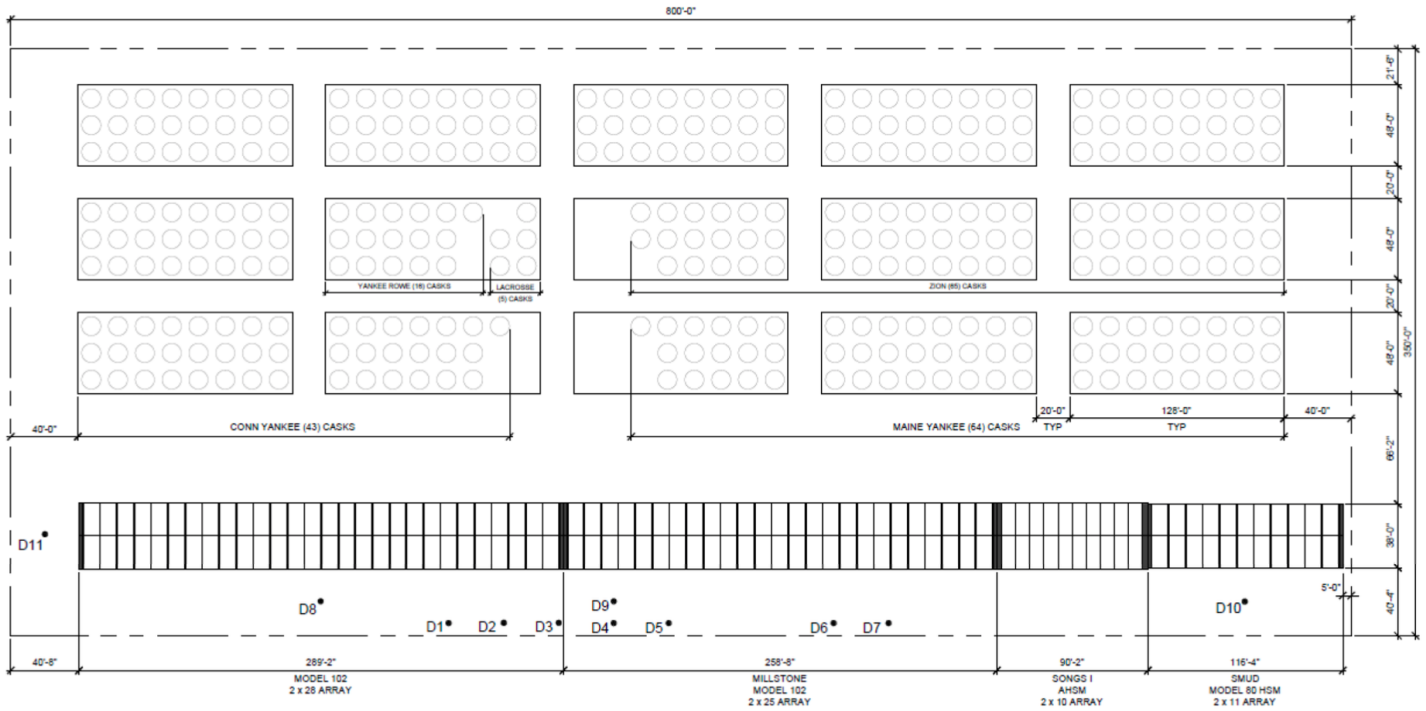


Figure 9-3
WCS CISF Storage Area Layout

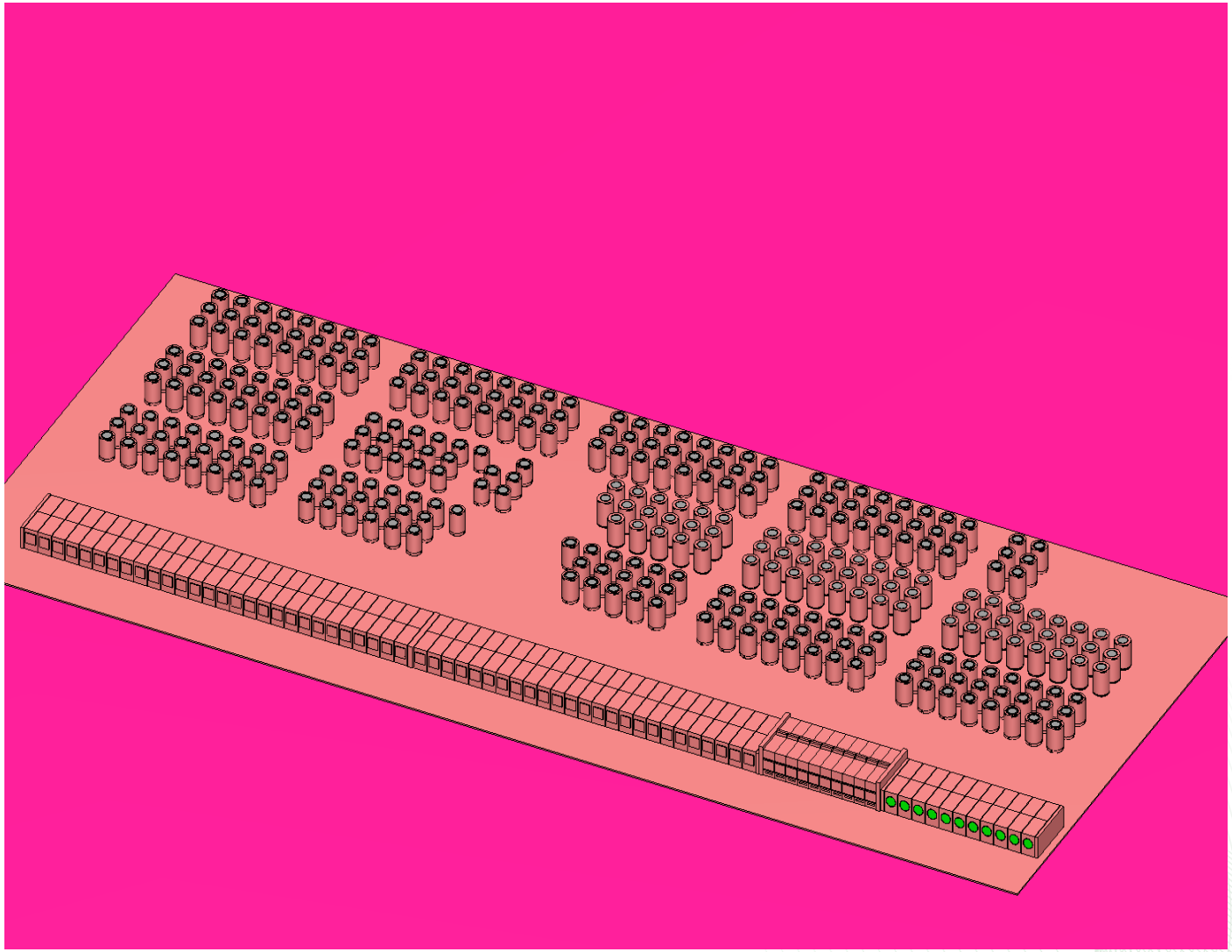
*WCS Consolidated Interim Storage Facility Safety Analysis Report
https://www.nrc.gov/docs/ML1613/ML16133A134.pdf

Regulatory Shielding Requirements for SNF Dry Storage

- 10 CFR 72, *License Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste*
  - Operational aspect (canister loading through drying, sealing, transport, and transfer) is designed to assure that exposure to occupational personnel is as low as reasonably achievable (ALARA)
  - 72.104 (a) : “During normal operations and anticipated occurrences, the annual dose equivalent to any real individual who is located beyond the controlled area must not exceed 0.25 mSv (25 mrem) to the whole body, 0.75 mSv (75 mrem) to the thyroid and 0.25 mSv (25 mrem) to any other critical organ.”
  - 72.106 – Provides dose limits at the controlled area boundary for a design basis accident

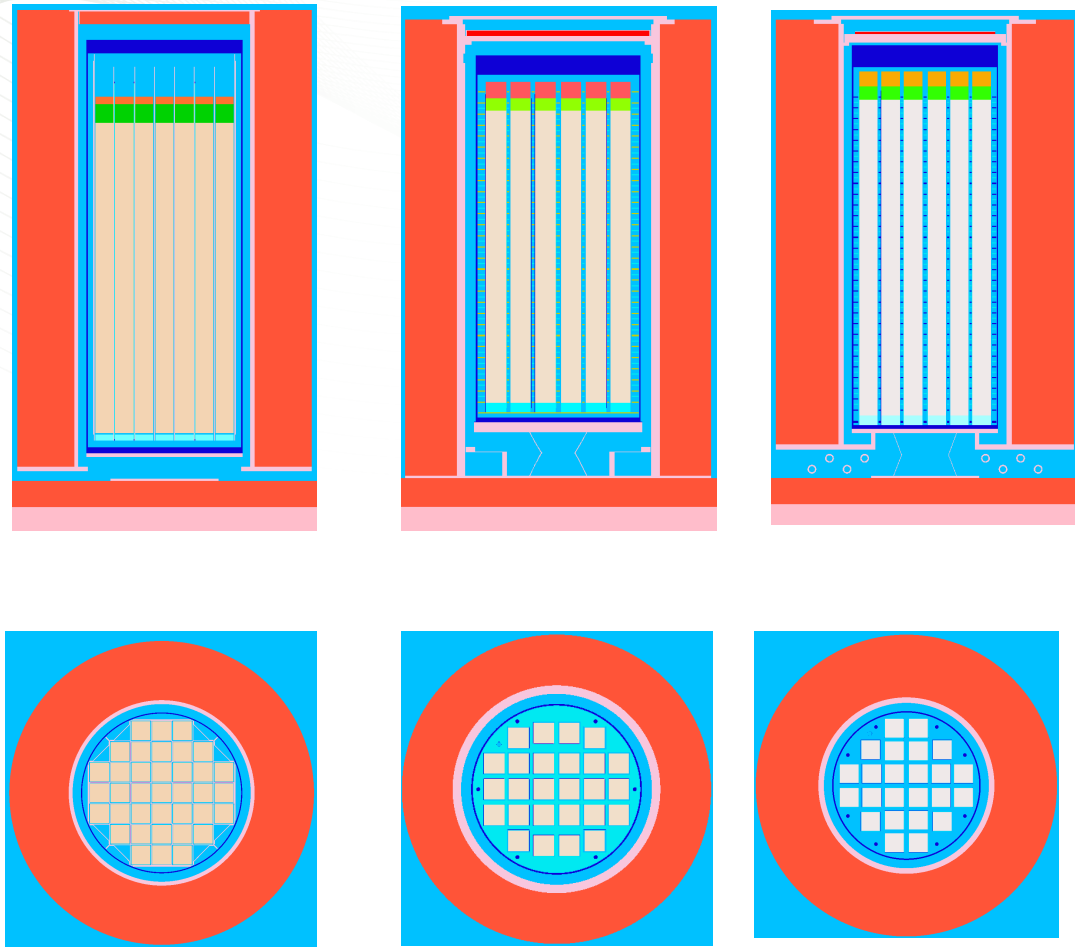
Image from KENO-3D of the Phase 1 Concrete Pad

- Seven different cask models
- Seven different design basis fuel assemblies
- The concrete pad is 243.84m x 106.68m
- The air around the concrete pad is 2713m x 2576m
- The air is 959.1m thick; the concrete pad is 30 cm thick; and the soil is 1m thick

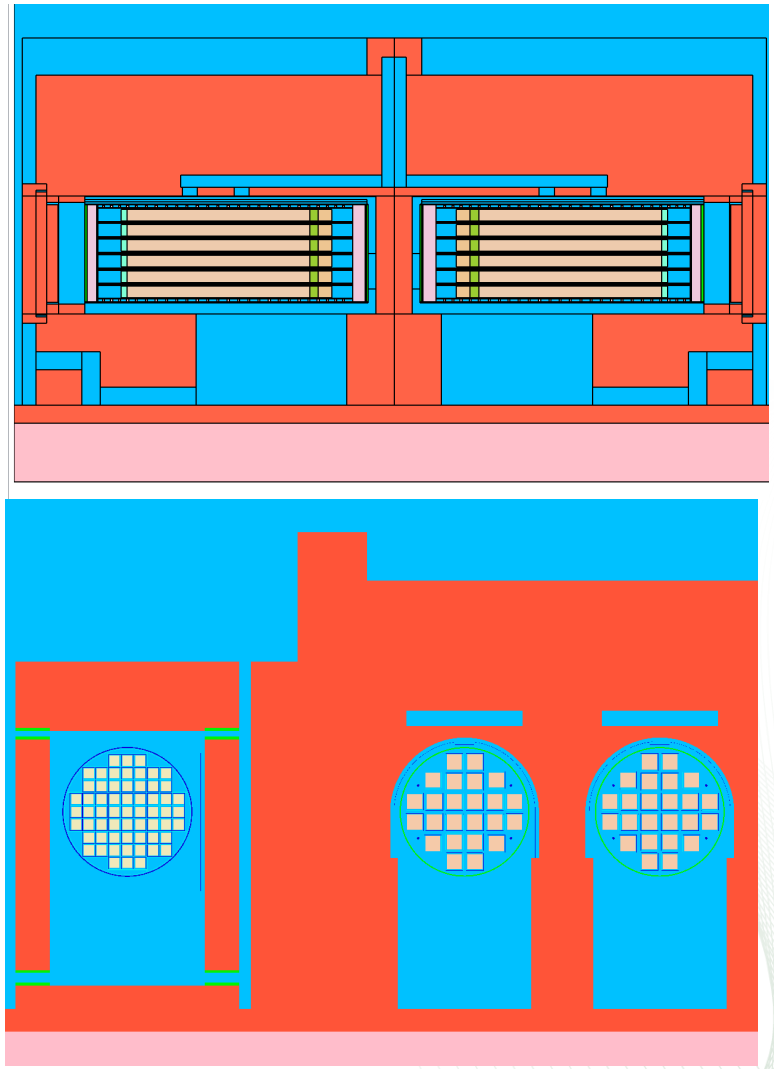


Cross-section Views of the Models for Different Cask Systems

NAC Vertical Concrete Casks

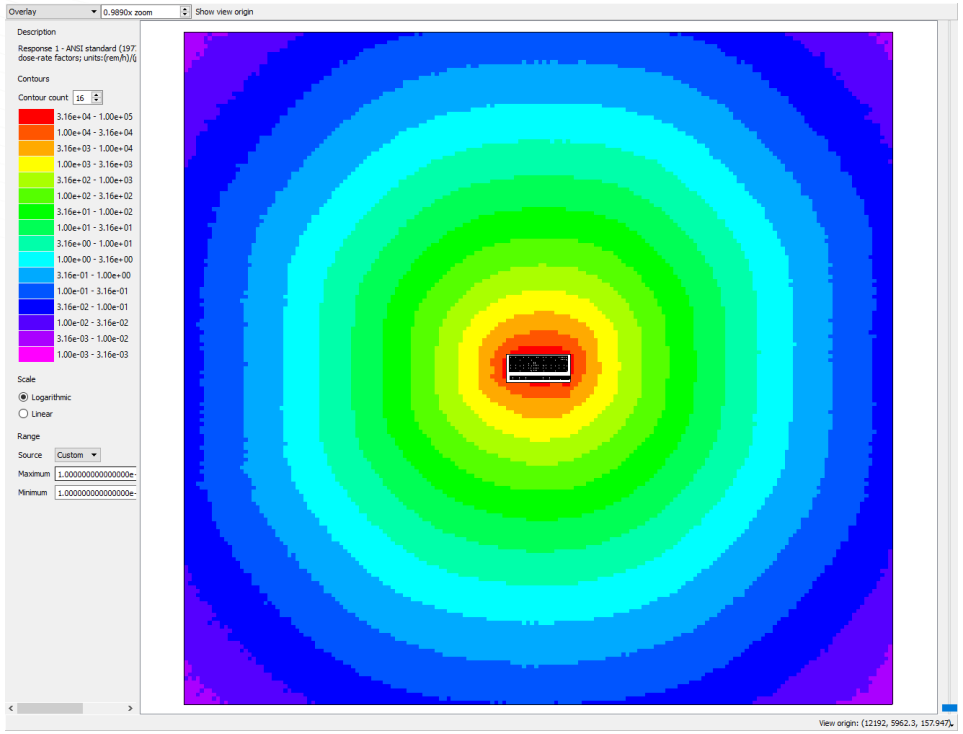


NUHOMS® Horizontal Storage Modules

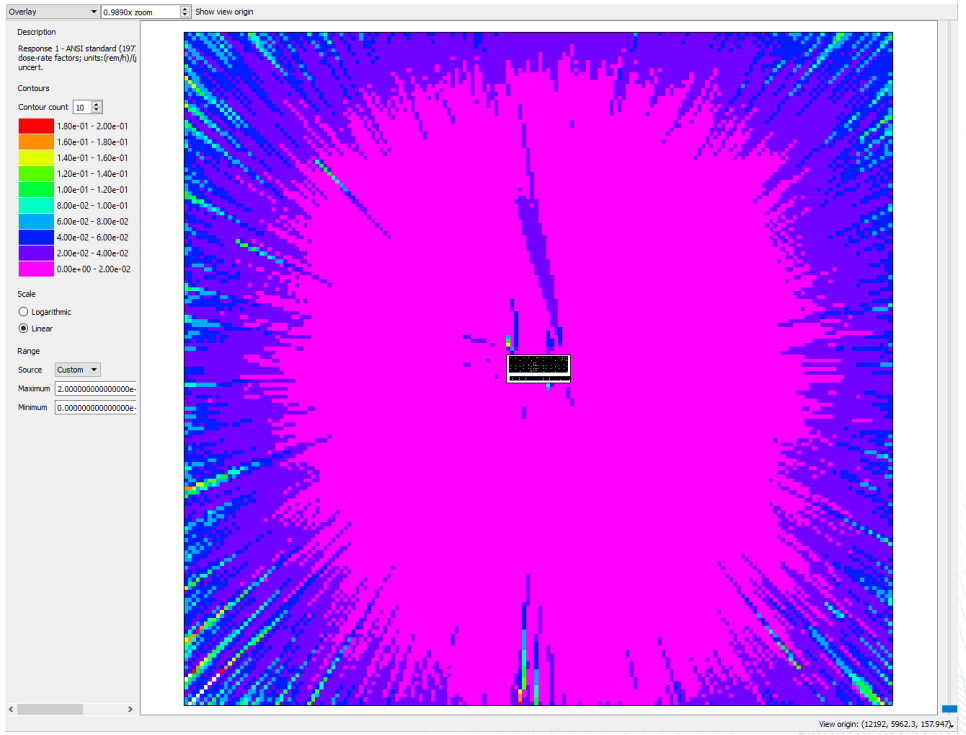


Total Dose Contours Surrounding the Phase 1 Concrete Pad

- One Monaco simulation was run for every cask that tallied dose in a mesh tally around the concrete pad. All 467 of these mesh tallies were added together to create the dose map
- The mesh tally only has one cell in the vertical direction, which extends from the top of the soil to 2m above the soil
- Voxel size: 15.24m x 15.24m x 2m
- The dose response function from ANSI/ANS-1977 *



Dose rate (mrem/yr) map: 2713m x 2576m

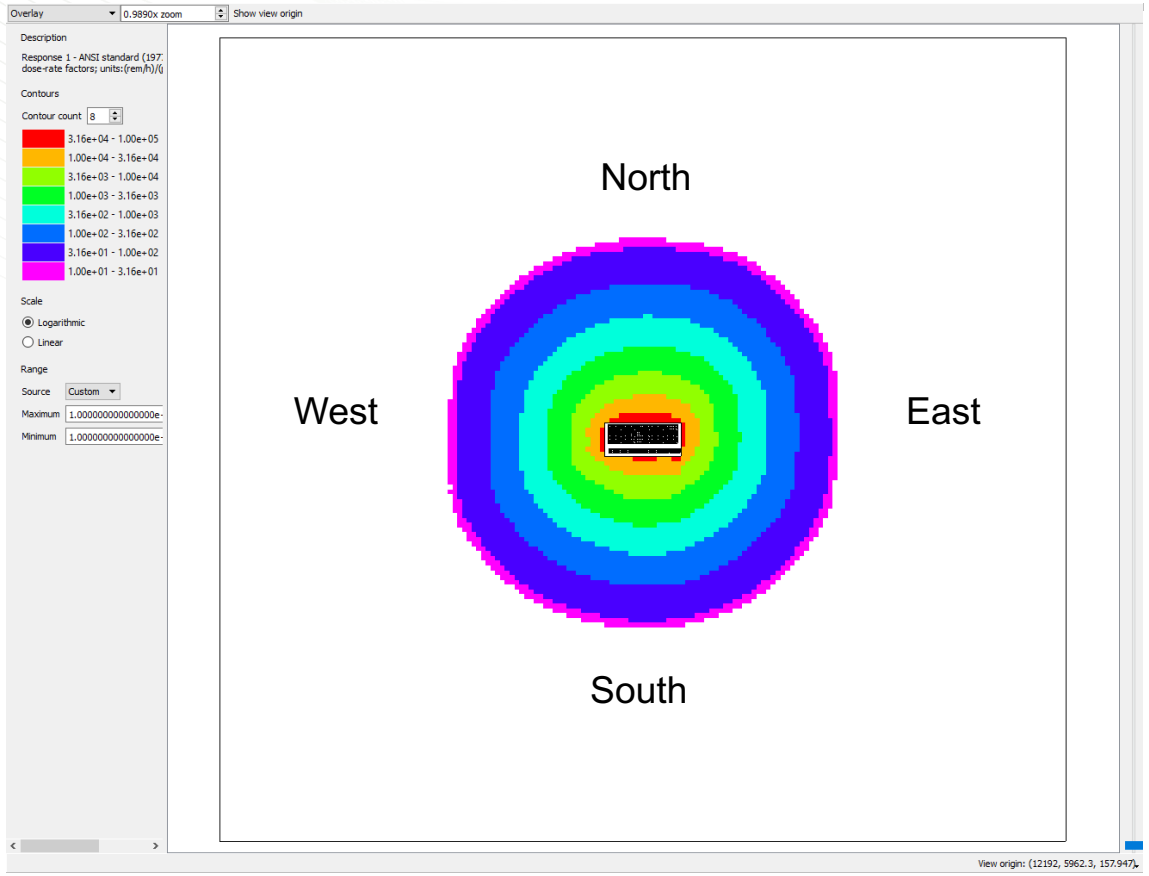


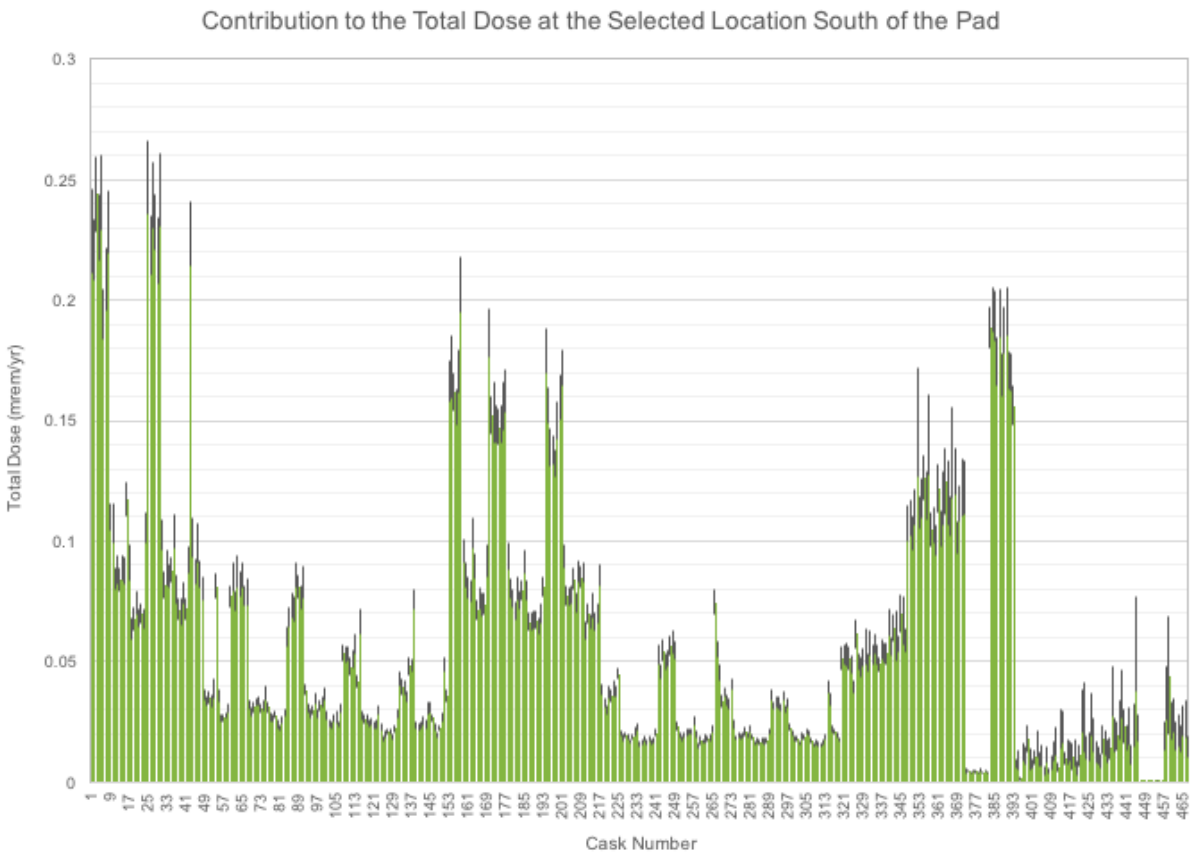
Relative statistical error < 20%

*Recommendation in NUREG-1536 Revision1

25 mrem/yr Dose Rate Contour

These dose contours fit inside a box with these dimensions: 1.25km x 1.25km





Conclusions

- SCALE provides capabilities for detailed shielding analyses of individual SNF casks and large SNF dry storage facilities
- MAVRIC – Monte Carlo shielding analysis sequence
  - Automated variance reduction to efficiently generate detailed dose rate maps
- ORIGAMI for fast radiation source term generation
- Fulcrum to visualize geometry and overlaid dose rate map
- SCALE shielding analyses for simulated as-loaded SNF transportation packages and a proposed consolidated interim storage facility performed at ORNL