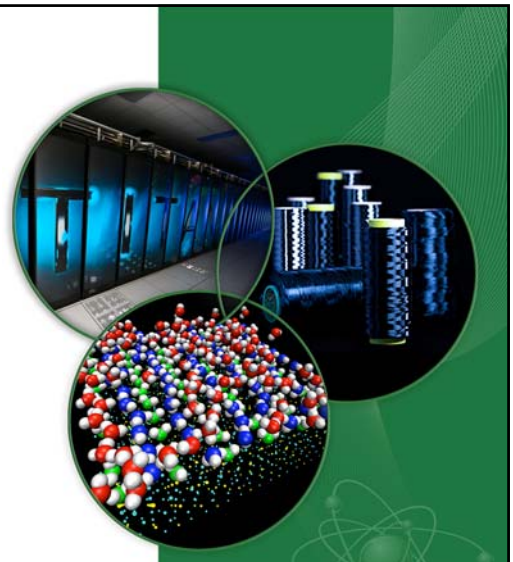
SCALE Enhancements for Detailed Cask Dose Rate Analysis



Douglas E. Peplow, Georgeta Radulescu,
Mark L. Williams, and Robert A. Lefebvre
Reactor and Nuclear Systems Division
Oak Ridge National Laboratory

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18th Topical Meeting of the RPSD of the ANS
Knoxville, TN

ORNL is managed by UT-Battelle
for the US Department of Energy

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Motivation

- US Department of Energy (DOE) Office of Nuclear Energy
  - Nuclear Fuels Storage and Transportation Planning Project
- Need to understand public's health and safety related to the large-scale transportation (1000s of cask shipments) of used nuclear fuel
- Typical analysis used highly conservative, bounding cases
- Realistic analysis should consider as-loaded fuel when examining
  - transportation operational safety (e.g., worker dose)
  - storage facility design
  - handling operations such as repackaging
  - concerns related to fuel failure during and following transportation
  - estimated dose rates

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Motivation

- US Department of Energy (DOE) Office of Nuclear Energy wants the capability to evaluate actual as-loaded systems to quantify actual characteristics and safety margins present in
  - k_{eff}
  - heat generation and temperature distributions
  - external dose rates
- for
  - *any* licensed storage or transportation cask
  - at *any* time after last discharge
- using
  - carrying actual loading of spent nuclear fuel assemblies
  - realistic inventories for the actual power history that was experienced
  - including axial dependence

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Solution: UNF-ST&DARDS

- Used Nuclear Fuel Storage, Transportation & Disposal Analysis Resource and Data System
  - a comprehensive database of used nuclear fuel inventories from utilities
  - detailed models of fuel assemblies
  - detailed models of transportation/storage casks
  - SCALE nuclear analysis code package
- Easy to use graphical user interface
  - visualize and interrogate results from database
- Template Driven

- Provide the final results that stakeholders need/want

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Detailed Cask Dose Rate Analysis

- New code ORGAMI (ORIGEN Assembly Isotopics)
  - Uses ORIGEN depletion and decay
  - Power shape is an input
  - Computes axially varying isotopics for
    - Assemblies
    - Individual pins in an assembly
  - Computes neutron and gamma spectra from
    - Fuel
    - Activated hardware

UMS by NAC International

- MAVRIC – hybrid radiation transport simulation
  - Denovo S_N code to determine variance reduction parameters
  - Monaco Monte Carlo code (now continuous-energy in SCALE 6.2)
- This talk focuses on changes to MAVRIC to better handle detailed cask dose rate analysis

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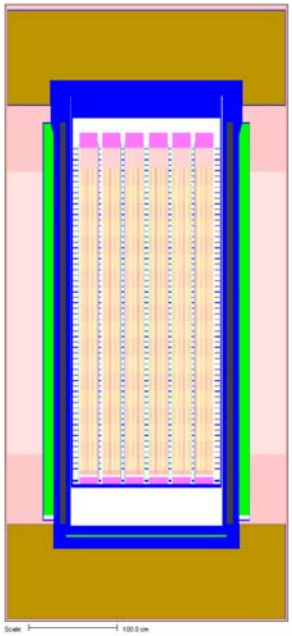
Example: NAC International UMS

- Normal Conditions of Transport (NCT)
- Class 1 transportable storage canister (TSC)
- Bottom forging and a bottom plate with one-inch thick neutron shield sandwiched between them
- Thick top stainless steel lid
- Multiwall cask body consists of concentric layers of stainless steel inner shell, lead radial gamma shielding, outer stainless steel shell, and neutron shielding material
- The neutron shielding material is a borated hydrogeneous material NS-4-FR
- Upper and lower impact limiters included



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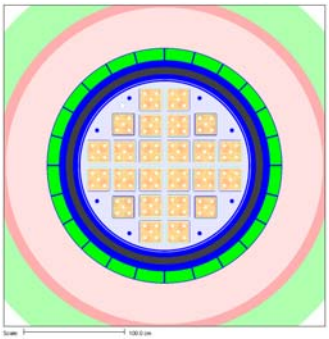
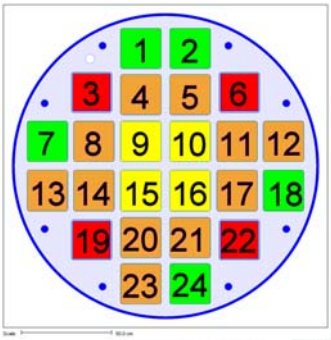
Example: NAC International UMS

- TSC-8 canister includes 24 irradiated fuel assemblies, 4 assemblies of which are placed into fuel cans at locations 3, 6, 19, and 22
- Assemblies are based on 14×14 arrays of pins with five large water holes
- Pin by pin representation of the active fuel region, 18 axial fuel zones
- Homogenized assembly hardware regions





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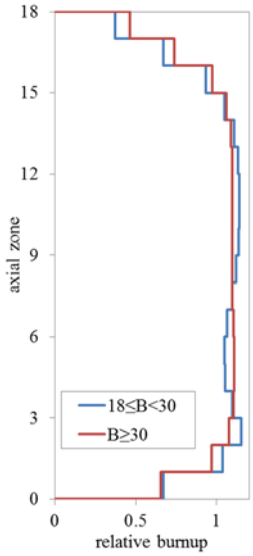
Example: Irradiated Fuel



*Burnup B in GWd/MTU

Position	Contents	Initial Enrichment (% ^{235}U)	Discharge Burnup (MWd/MTU)	Discharge Date	15-year Case: Days to 12/6/11	25-year Case: Days to 12/6/21
1	EF008Z	2.9	22864	7/14/1978	12199	15851
2	EF009R	2.88	22864	7/14/1978	12199	15851
3	N869	3.3	45466	4/7/1990	7914	11566
4	R031	3.68	44018	1/14/1995	6171	9823
5	R036	3.68	44456	1/14/1995	6171	9823
6	N844	3.3	45466	4/7/1990	7914	11566
7	EF009P	2.88	23959	7/14/1978	12199	15851
8	R032	3.68	44018	1/14/1995	6171	9823
9	M002	3.3	36718	12/6/1996	5479	9131
10	M007	3.31	36718	12/6/1996	5479	9131
11	R010	3.69	44018	1/14/1995	6171	9823
12	R442	3.68	44411	1/14/1995	6171	9823
13	R019	3.68	44456	1/14/1995	6171	9823
14	R003	3.7	44018	1/14/1995	6171	9823
15	M004	3.3	36718	12/6/1996	5479	9131
16	M003	3.3	36718	12/6/1996	5479	9131
17	R035	3.68	44456	1/14/1995	6171	9823
18	EF008R	2.89	22864	7/14/1978	12199	15851
19	N846	3.3	45466	4/7/1990	7914	11566
20	R005	3.69	44018	1/14/1995	6171	9823
21	R029	3.69	44018	1/14/1995	6171	9823
22	N850	3.3	45466	4/7/1990	7914	11566
23	R440	3.68	44411	1/14/1995	6171	9823
24	EF0090	2.89	22864	7/14/1978	12199	15851

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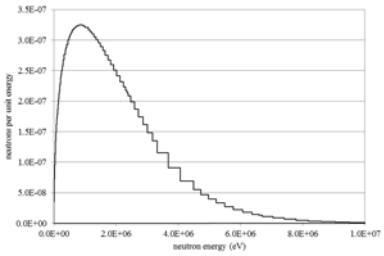
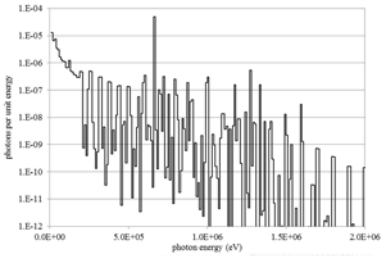
Source terms from ORIGAMI

- 24 assemblies, 18 axial zones
- 432 neutron sources
- 432 photon sources

- First challenge for MAVRIC
  - Could handle 864 sources
  - Time to make Denovo input was *way too long*
  - Time to make biased sources was *way too long*
  - More efficient methods used





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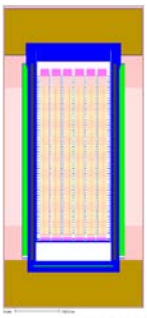
Dose Rates

- Dose Rate Limits -10 CFR 71.47(b) requirements
  1. the surface of the package < 1000 mrem/h
  2. the outer surface of the transport vehicle < 200 mrem/h
  3. the top surface of the transport vehicle < 200 mrem/h
  4. the underside surface of the vehicle < 200 mrem/h
  5. two meters from the outer lateral surfaces of the vehicle < 10 mrem/h
  6. any normally occupied position of the vehicle < 2 mrem/h
- Second challenge to MAVRIC
  - Can compute dose rate on a fine mesh
  - Added utilities to
    - segment mesh tallies by material/region
    - Find min/max values of mesh tally



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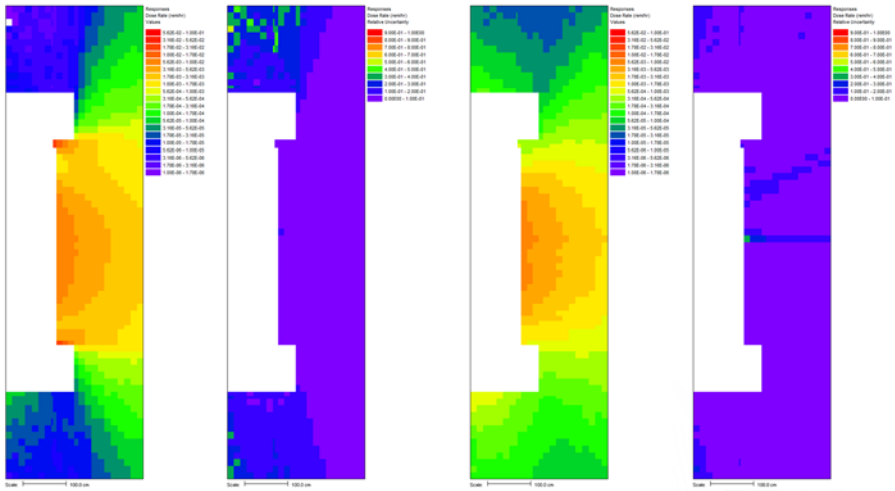
MAVRIC Dose Rate Results



Neutron dose rate (rem/hr) and (left) its uncertainty (right) for the 15 year case.

Photon dose rate (rem/hr) and (left) its uncertainty (right) for the 15 year case.

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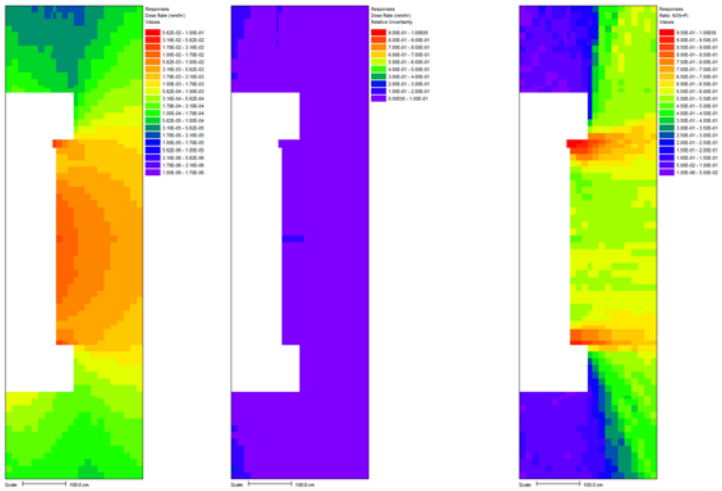
MAVRIC Dose Rate Results



Total dose rate (rem/hr) and (left) its uncertainty (right) for the 15 year case.

Ratio of the neutron and total dose rates.

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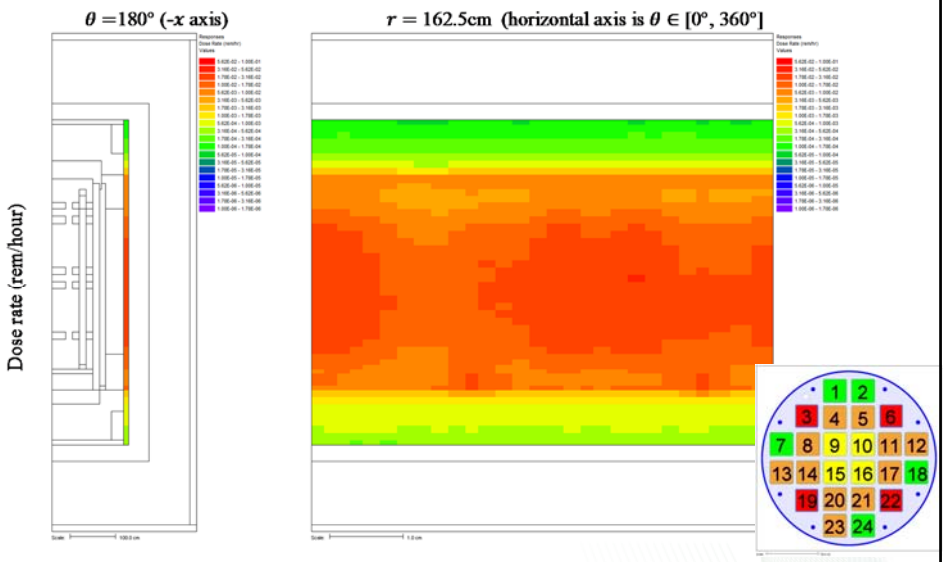
MeshFileViewer – Added new view



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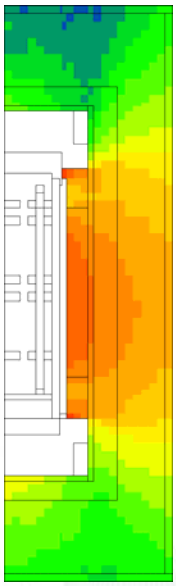
Dose Rate Mesh Tallies - Segmented

Location		15 years after last discharge mrem/hr rel. unc.	25 years after last discharge mrem/hr rel. unc.
Cask	Top		
	Upper Radial		
	Middle Radial		
	Lower Radial		
	Bottom		
PB	Radial		
2 m	Top		
	Radial		
	Bottom		



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Location		15 years after last discharge mrem/hr	rel. unc.	25 years after last discharge mrem/hr	rel. unc.
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	Bottom				
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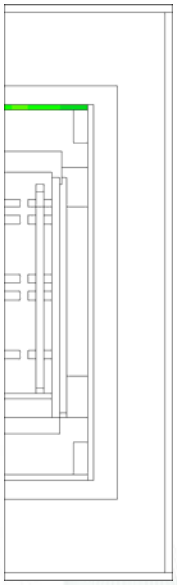
	Bottom				



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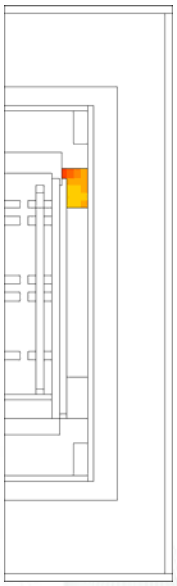

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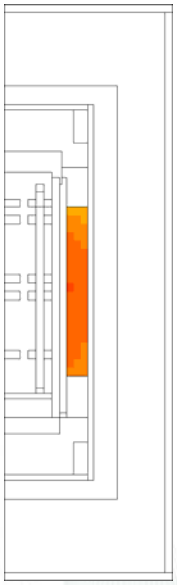

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	Bottom				
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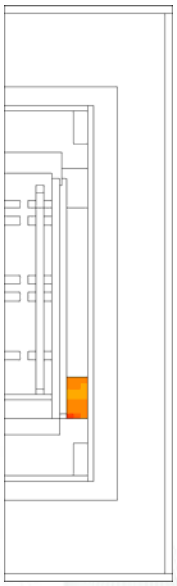

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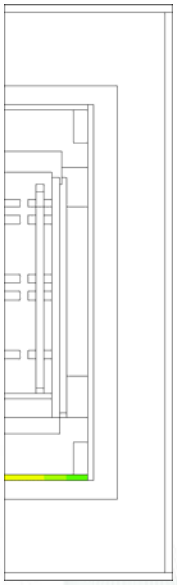

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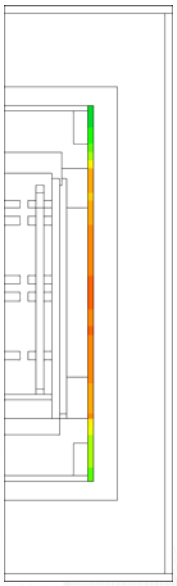
	Bottom				



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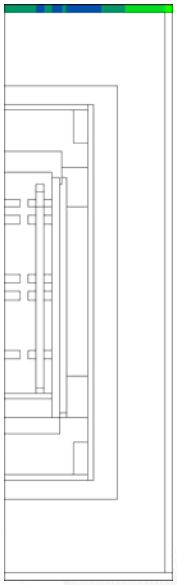

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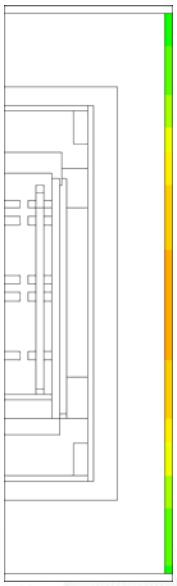
	Bottom				



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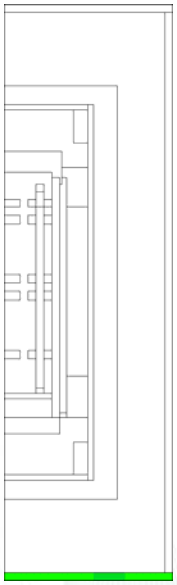

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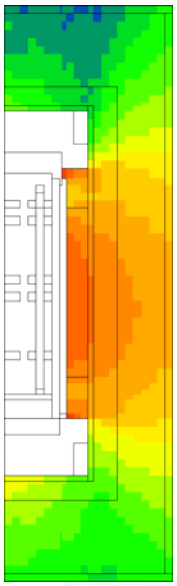

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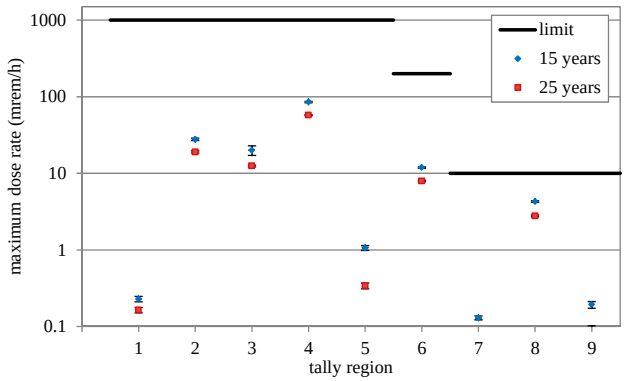
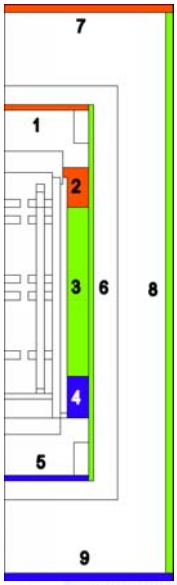
Dose Rates and Limits





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Optimizing Dose Rate Calculations

- MAVRIC - hybrid radiation transport simulation
  - Denovo S_N code to determine variance reduction parameters
    - Accuracy improves with finer meshing (space, angle, energy)
    - Time and memory requirements increase with finer meshing
  - Monaco Monte Carlo code
    - FOM increases with more representative importance map & biased sources
- Need to maximize overall (Denovo+Monaco) figure-of-merit
  - Limit Denovo memory usage to typical PC
- Evaluate the overall FOM
  - Denovo/importance map mesh
  - Macromaterial parameters
  - Quadrature and Legendre scattering expansion
  - Biased source parameters

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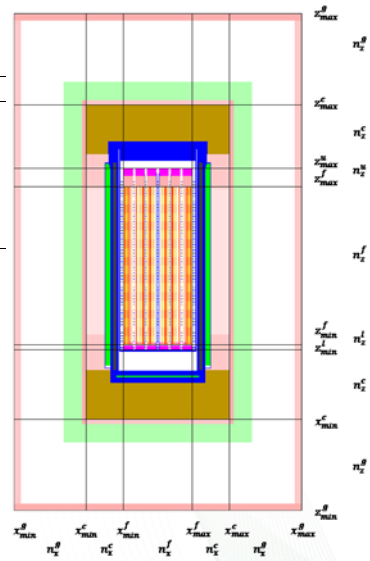
Optimizing Dose Rate Calculations – Mesh Grid

Easy Grid – requires 20 values from the geometry model

	Bounding boxes					
Fuel	x^f_{max}	x^f_{min}	y^f_{max}	y^f_{min}	z^f_{max}	z^f_{min}
Upper hardware	x^f_{max}	x^f_{min}	y^f_{max}	y^f_{min}	z^u_{max}	z^f_{max}
Lower hardware	x^f_{max}	x^f_{min}	y^f_{max}	y^f_{min}	z^f_{min}	z^l_{min}
Cask	x^c_{max}	x^c_{min}	y^c_{max}	y^c_{min}	z^c_{max}	z^c_{min}
Global	x^g_{max}	x^g_{min}	y^g_{max}	y^g_{min}	z^g_{max}	z^g_{min}

Intervals – requires 11 parameters to define how fine or coarse

Region Between:		x	y	z
Fuel		n^f_x	n^f_y	n^f_z
Upper hardware	Fuel	n^f_x	n^f_y	n^u_z
Lower hardware	Fuel	n^f_x	n^f_y	n^l_z
Cask	Upper hardware	n^c_x	n^c_y	n^c_z
Global	Cask	n^g_x	n^g_y	n^g_z



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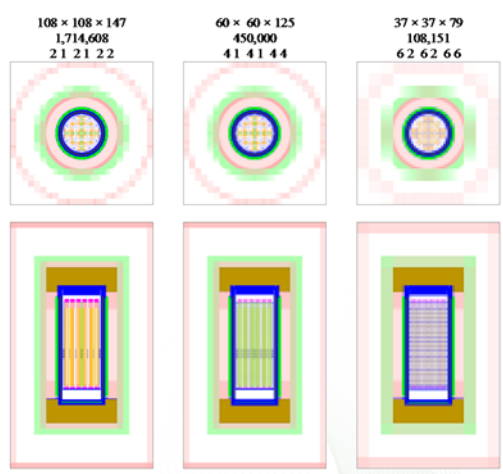
Optimizing Dose Rate Calculations – Mesh Grid

- Mesh grid
  - Fine, medium, coarse
  - Change macromaterial parameters as well
- Results
  - Not much difference in MC performance
  - Choose lower values to decrease memory requirement and run time



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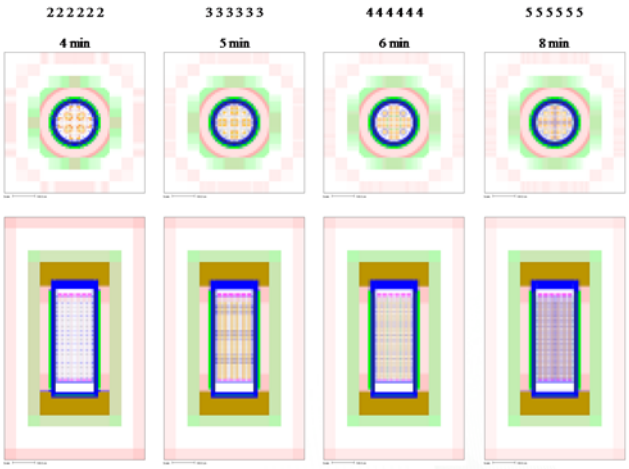
Optimizing Dose Rate Calculations - Macromaterials

- Macromaterials
  - Small improvement in MC performance
  - Small impact on Denovo input file creation
  - Helps preserve fuel fractions



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Optimizing Dose Rate Calculations - Other

- Quadrature and Legendre scattering expansion
  - Not much difference in MC performance
  - Large impact on Denovo memory requirements and run time
  - Choose lower values to decrease memory requirement
- Subcell sampling for meshed source creation
  - Slight improvement in MC performance with more subcell sampling
  - Small increase in Denovo input file creation time
  - Choose more subcell sampling to preserve fuel fractions

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Activated Hardware

- Biggest contributor is ^{60}Co
- Added discrete distributions to Monaco

```
distribution 1
   title="cobalt-60 gammas/decay"
   discrete   347140   826100 1173228 1332492  2158570    2505692 end
   truepdf  0.000075 0.000076 0.9985 0.999826 0.000012 0.00000002 end
end distribution
```

- Keywords to pull from ORIGEN gamma database

```
distribution 1
   title="cobalt-60 gammas/decay"
   special="origensDiscreteGammas"
   parameters 27 60 end
end distribution
```

- Keep the total number of gammas as part of the strength

```
src 7
   title="top nozzle Co-60 source"
   photons
   useNormConst  multiplier=37e9
   zCylinder 71.0 212.8 203.9
   mixture=10
   eDistributionID=1
end src
```

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Summary

- Many improvements to SCALE for detailed dose rate calculations of realistic as-loaded spent fuel casks
  - New ORIGAMI code - for axial-dependent source terms
  - MAVRIC – improved processing for many sources
  - MAVRIC Utilities – more utilities for more flexible analysis

- UNF-ST&DARDS system
  - Uses templates to create SCALE input for dose rate analysis for
    - *any* licensed storage or transportation cask
    - at *any* time after last discharge
  - using
    - carrying actual loadings of spent nuclear fuel assemblies
    - realistic inventories for the actual power history that was experienced
    - including axial dependence

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Questions?

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