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A Method for Radiological Characterization based on Fluence Conversion Coefficients

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Radiological Characterization

- Radiological characterization of components needed
    - Maintenance
    - Transport
    - Handling
    - Selection of proper disposal pathway
- Hazard factor often a weighted sum of specific activities
    - Radionuclide specific weighting coefficients

Common methods - Introduction

$$H = \sum_b \frac{1}{w_b} A_b = \sum_b \frac{1}{w_b} \sum_r \sum_e T_{br}\, P_{re}\, m_e \qquad (1)$$

$$P_{re} = \frac{N_A}{M_e} \sum_{i=\mathrm{p,n},\pi^+,\pi^-} \int \phi_i(E)\, \sigma_{i,e,r}(E)\, dE \qquad (2)$$

- Event based
  - FLUKA - RESNUCLE: production yields or activities for given irradiation profile
  - FLUKA & DORIAN: `usrrnc` and `ftelos` user routines, time evolution offline, allows binning not based on regions
  - PHITS - T-Yield: time evolution offline (option DCHAIN-SP)
- Fluence spectra based
  - Monte Carlo code to compute fluence spectra (region based)
    - FLUKA - USRTRACK
    - PHITS - T-Track
  - Post-processing with various codes (JEREMY, ActiWiz, ...)

Common methods - Comparison

Method	Pros	Cons
Event based	Built-in capability with reduced human error probability Very good for small number of regions close to main interaction zone Uses cross-sections from MC code Material compositions from MC input	Convergance can be slow for regions away from main interaction zone Region-based: Mass normalization has to be done *manually* Visualization difficult Cumbersome for large number of regions
Fluence spectra based	Better convergance properties Possibility to evaluate alternative material compositions	Cross-sections decoupled from MC code Region-based: Volume normalization has to be done *manually* Visualization difficult Cumbersome for large number of regions Higher post-processing needs

- Clear need for an alternative method with **fast convergance**, **automatic normalization** and **good visualization** for large number of cells

Fluence conversion coefficients - Principle

$$
\begin{aligned}
H &= \sum_b \frac{1}{w_b} \sum_{r,e} T_{br}\ P_{re}\ m_e \\
&\approx \sum_b \frac{1}{w_b} \sum_{r,e} T_{br} \left(\frac{N_A}{M_e} \sum_{i=\mathrm{p,n},\pi^+,\pi^-} \sum_E \Phi_{i,E}\, \sigma_{i,e,r}(E) \right) m_e \\
&= \sum_{i=\mathrm{p,n},\pi^+,\pi^-} \sum_E \Phi_{i,E} \underbrace{\left(\sum_{b,r,e} \frac{1}{w_b}\ T_{br}\ \frac{N_A}{M_e} \sigma_{i,e,r}(E)\ m_e \right)}_{K_{i,E}}
\end{aligned}
\tag{3}
$$

- Fluence conversion coefficients (FCCs) $K_{i,E}$ precomputed and then applied online during radiation transport

Fluence conversion coefficients - Implementation

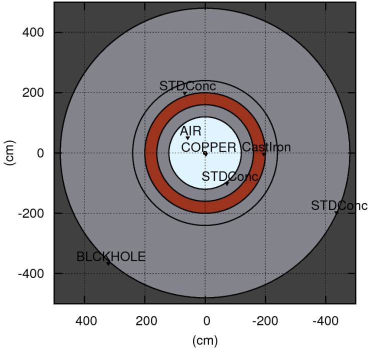
- Dedicated code **FCC-generator** to compute fluence conversion coefficients
- Monte Carlo code side
  - FLUKA:
    - FCCs from FFC-generator written out in F77 source code format
    - included in dedicated `fluscw` user routine and linked to produce FLUKA executable
    - USRBIN scoring
  - PHITS:
    - FCCs from FFC-generator written out in PHITS input file format for built-in multiplier sections
    - T-Track with associated multipliers for scoring

Fluence conversion coefficients - FCC-generator Code

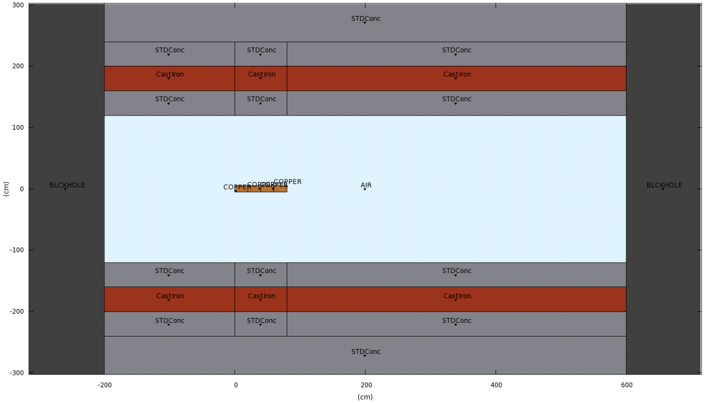
- User input
  - Material composition
  - Irradiation profile
  - Radionuclide specific weight coefficients for hazard factor
- Output
  - FFCs (as lists)
  - FCCs can be written out as F77 source code snippet or PHITS input file snippet
- Python code based on the JEREMY code
  - <300 LOC
  - scriptable
  - can easily be extended (e.g. weight coefficient sets)
  - designed so that it can be easily interfaced with other cross-section sets or time evolution engines

Validation

- Validation against built-in capabilities of FLUKA and PHITS
- 1 GeV proton beam on cylidrical copper target (5cm radius, 80cm length)
- Cylindrical-symmetric geometry of air, concrete, cast iron and concrete



Validation - Geometry

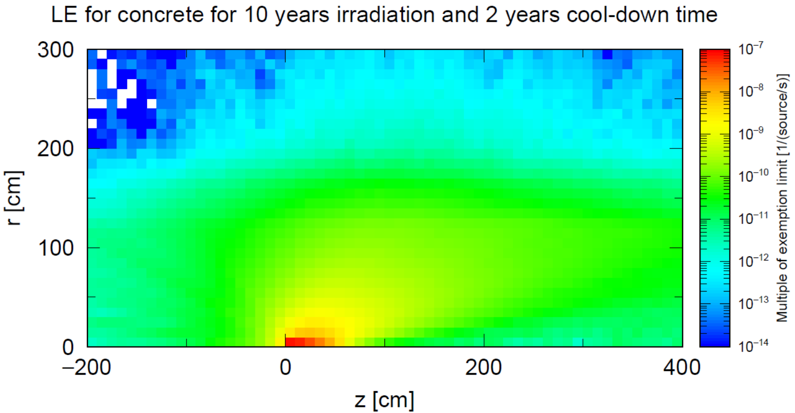


Validation - Results

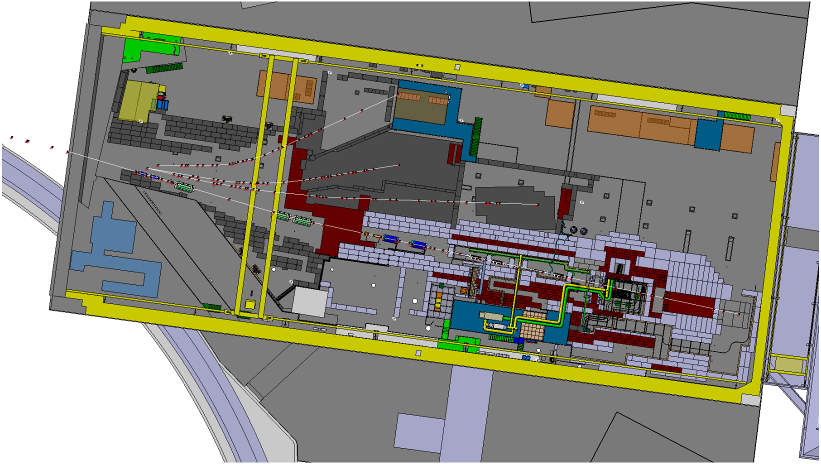
Radiological Quantity		Material	Region	FLUKA*	FFCs*	FLUKA/FCCs
Co-60	Production Yield	Copper	T1	1.98e-06±0.8%	1.536e-06±0.1%	1.29 ± 0.81%
			T4	5.82e-09±14%	4.897e-09±2.1%	1.19 ± 14%
Na-24	Production Yield	Concrete	Sh1	2.91e-09±3.3%	2.668e-09±0.4%	1.09 ± 3.3%
			Sh3	8.02e-11±16%	8.680e-11±2%	0.924 ± 16%
	Specific Activity (10y, 2d)	Concrete	Sh1	3.15E-10±3.3%	2.885e-10±0.4%	1.09 ± 3.3%
			Sh3	8.67E-12±16%	9.385e-12±2%	0.924 ± 16%
Na-22	Specific Activity (10y, 2y)	Concrete	Sh1	1.20E-10±2.8%	1.443e-10±0.3%	0.832 ± 2.8%
			Sh3	2.25E-12±16%	3.251e-12±1.8%	0.692 ± 16%
Mn-54	Specific Activity (10y, 2y)	Cast Iron	Sh2	1.78e-10±1.5%	1.641e-10±1.7%	1.08 ± 2.3%
Multiple of Swiss Exemption Limit (10y, 2y)		Concrete	Sh1	1.48e-10±3.1%	1.539e-10±0.2%	0.962 ± 3.1%
			Sh3	4.16e-12±5.7%	4.575e-12±0.9%	0.909 ± 5.8%
		Cast Iron	Sh2	2.37e-10±2.9%	2.339e-10±0.5%	1.01 ± 2.9%

* Production Yields in [nucl/primary]
Specific Activities in [(Bq/g)/(primary/s)]
Multiple of Swiss Exemption Limit in [1/(primary/s)]

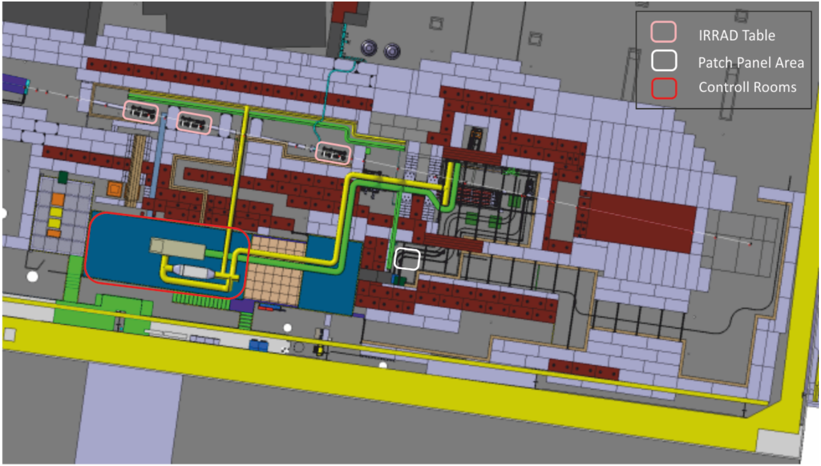
Examples - PHITS



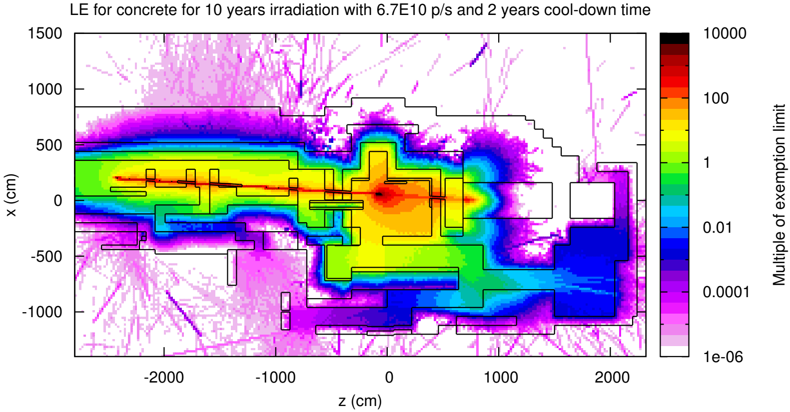
Examples - IRRAD & CHARM



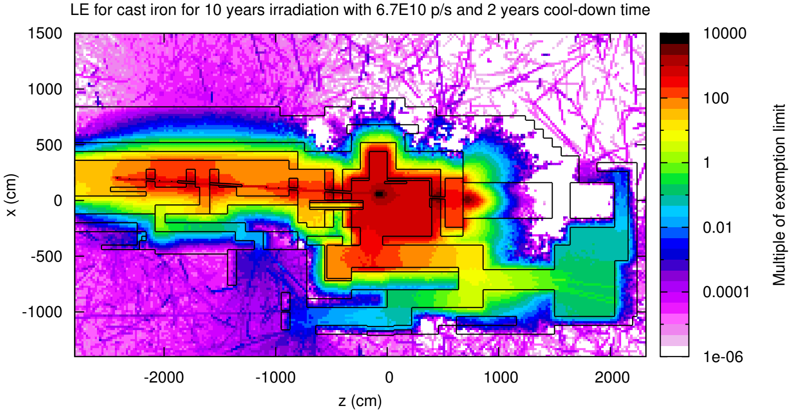
Examples - IRRAD & CHARM



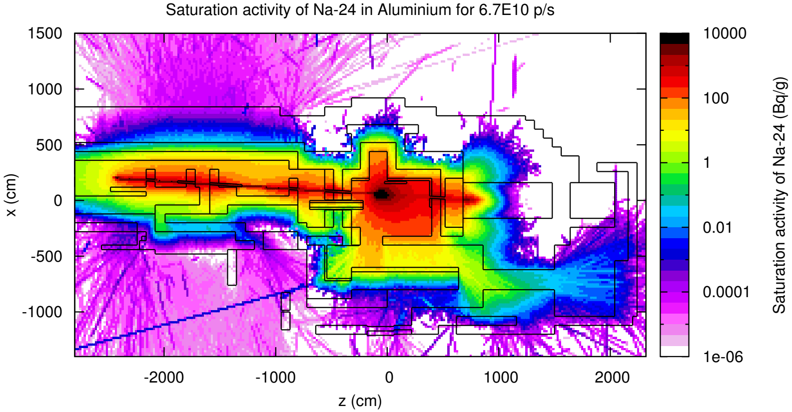
Examples - IRRAD & CHARM



Examples - IRRAD & CHARM



Examples - IRRAD & CHARM



Comparison to common methods

Method	Pros	Cons
Event based	Built-in capability with reduced human error probability Very good for small number of regions close to main interaction zone Uses cross-sections from MC code Material compositions from MC input	Convergance can be slow for regions away from main interaction zone Region-based: Mass normalization has to be done *manually* Visualization difficult Cumbersome for large number of regions
Fluence spectra based	Better convergance properties Possibility to evaluate alternative material compositions	Cross-sections decoupled from MC code Region-based: Volume normalization has to be done *manually* Visualization difficult Cumbersome for large number of regions Higher post-processing needs
Fluence conv. coeff. based	Fully integrated into existing toolchain Very good visualization of larger number of regions Automatic mass normalization Better convergance properties	Cross-sections decoupled from MC code Higher pre-processing needs

Future applications

- Radiological waste characterization
- Clearance zoning (part of radiological characterization at the source)
- Earth activation: Derived activation limits due to drinking water limits
- Tight spatial coupling: α-induced and t-induced reactions
- Planning of irradiation experiments

Summary

- Fluence conversion coefficients based radiological characterization
  - Complementary to common methods
  - Fast convergance
  - Automatic normalization
  - Good visualization for large number of cells
- Implementation
  - FCC-generator code
  - FLUKA (user routine) or PHITS (multiplier)
- Promising future applications

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