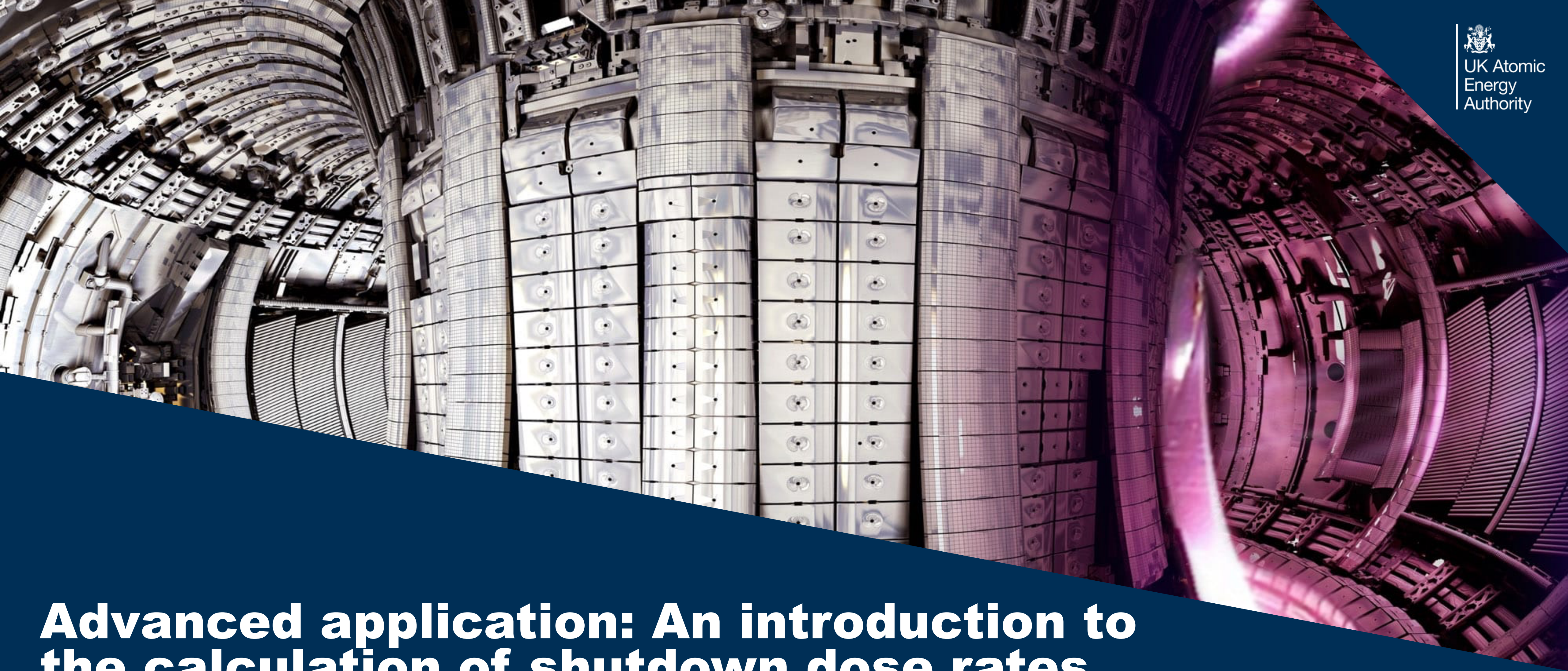

UK Atomic Energy Authority

Advanced application: An introduction to the calculation of shutdown dose rates using FISPACT-II

By T. Eade

Outline

- What are shutdown dose rates? Why are they important
- How FISPACT-II can be used to provide estimates of shutdown dose rates and an overview of the R2S process
- Description of the UKAEA's MCR2S code
- Advanced methods within MCR2S to take account of movement of components
- Current and future developments

Shutdown dose rates

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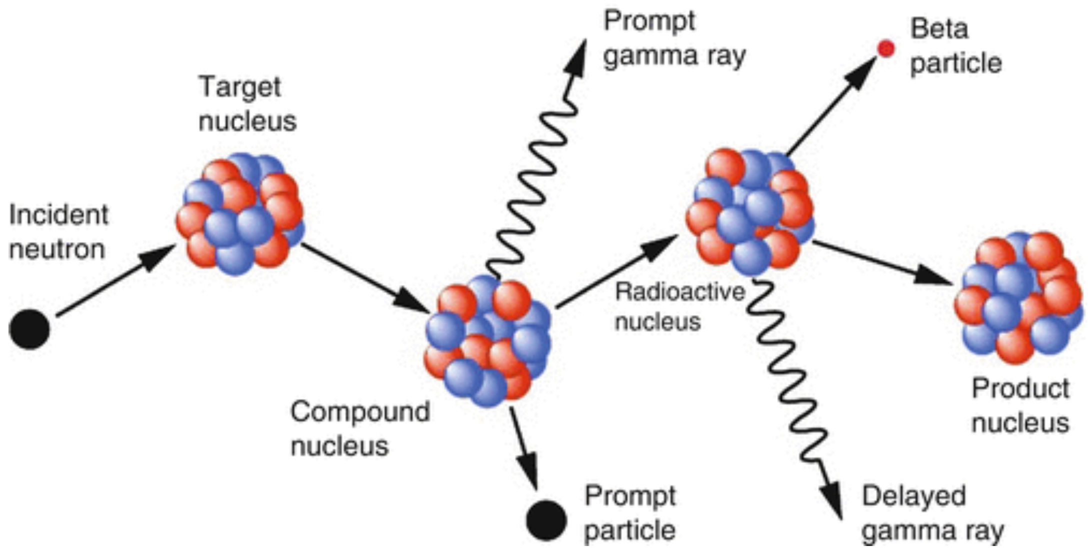
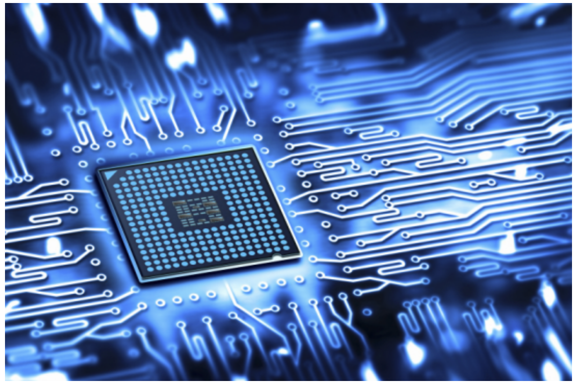
- Emission of radiation during periods that the reactor is switched off
- During on-load operation neutrons (or other charged particles e.g. protons) interact with material leading to transmutation
- Unstable daughter nuclei decay leading to gamma emission
- Decay continues after irradiation has ended
- Gamma emission can lead to dose rates
- Occur in fusion and fission reactors (and other accelerator driven systems)



Shutdown dose rates cont.

- Why do we care about trying to calculate shutdown dose rates?
  - Allows dose to personnel to be estimated
  - Allows dose to sensitive equipment/remote handling equipment to be estimated
- Feed into:
  - safety cases
  - system and component engineering design
  - maintenance
  - lifetime assessments



FISPACT-II

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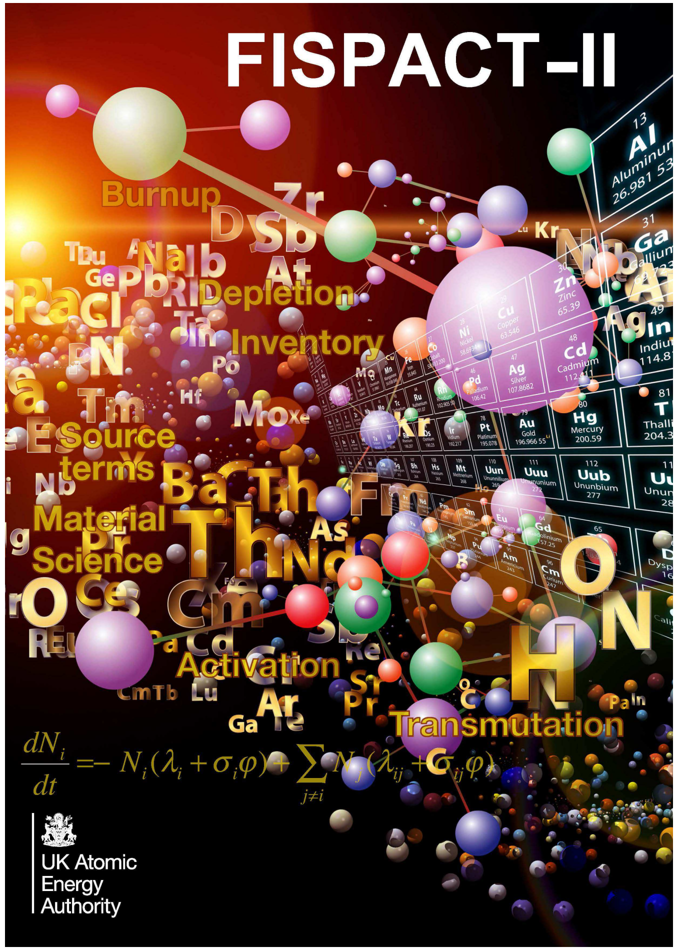
- How can FISPACT-II, a 1D code inventory code be used to help calculate shutdown dose rate in a 3D model?
- Input requirements:
  - Neutron Flux
  - Material composition
  - Irradiation schedule
  - Decay times
  - Nuclear data
- Outputs
  - Gamma spectrum ɣ/s/cm^3 or MeV/s (default 24 energy groups, although can be arbitrary)



R2S Calculations

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- Rigorous-2-Step calculations can be used to estimate SDDR
- Advantages
  - Does not need prior knowledge of the important nuclides
  - Can take account of secondary activation effects
  - Allows for other activation quantities to be ascertained
- Disadvantages
  - Requires geometry and energy to be discretised
  - Requires 2x radiation transport + ?x inventory calculations

Step 1 Neutron Transport Calculation

↓

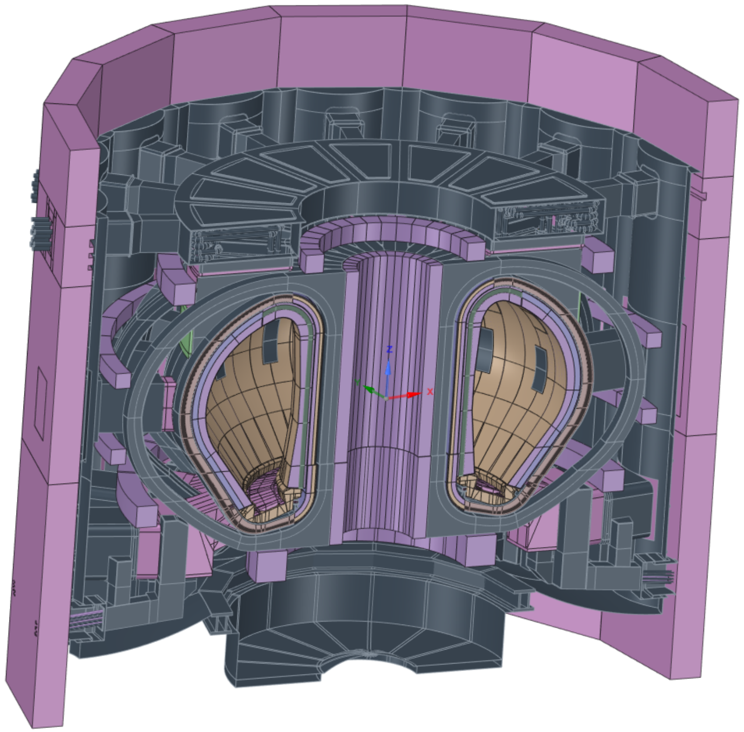
Inventory Calculation

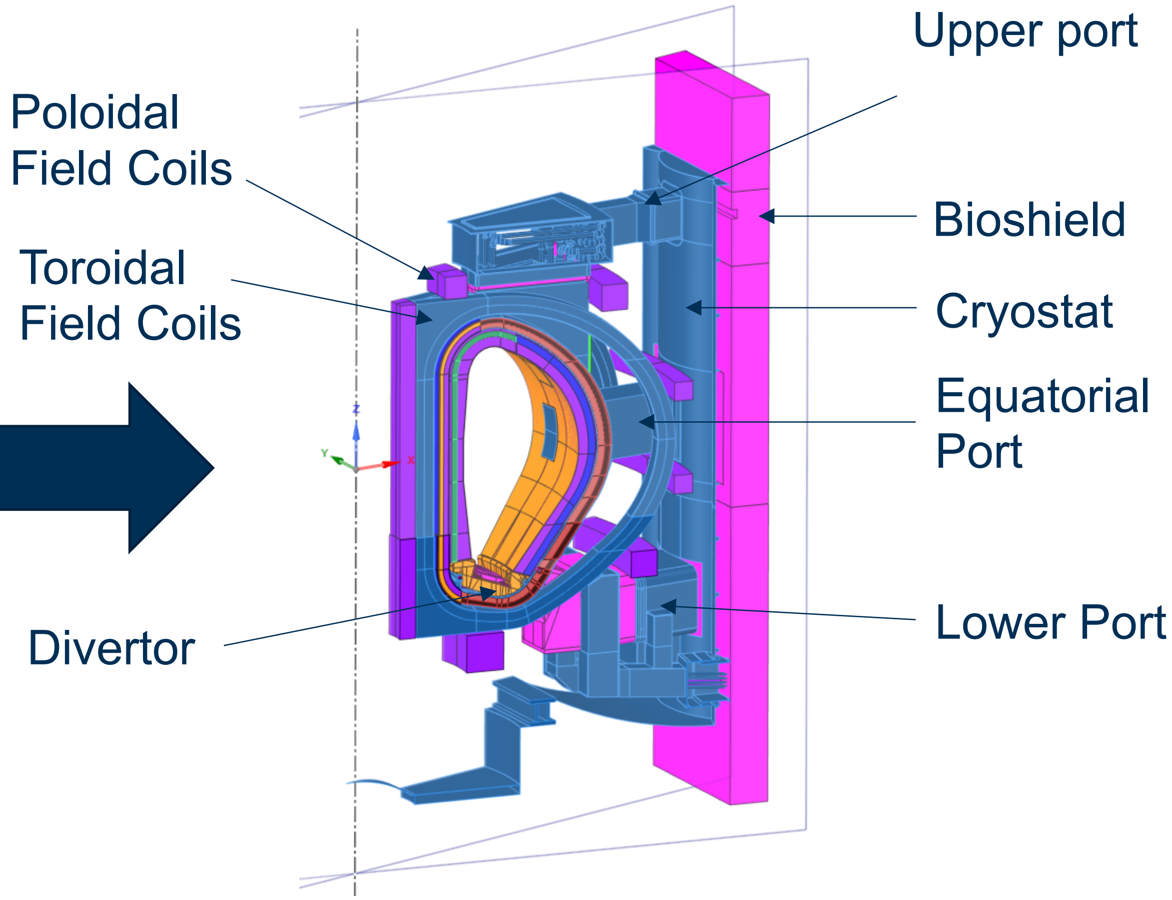
↓

Step 2 Gamma Transport Calculation

Example

- How do we go about calculating the shutdown dose rate using an R2S technique in and around a reactor?
- Firstly we need a model of the reactor:





Step 1 - Neutron Transport

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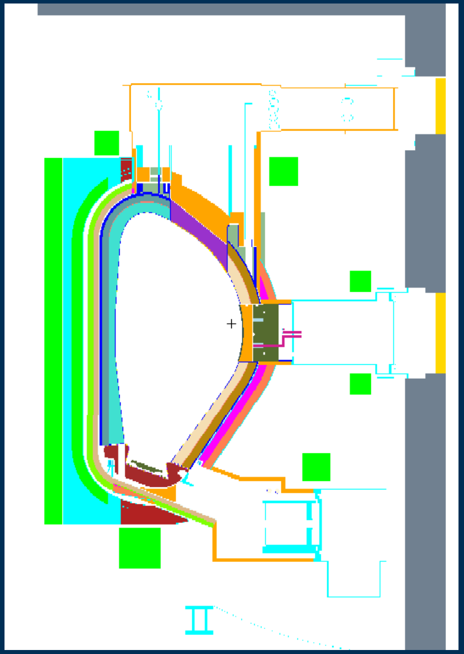
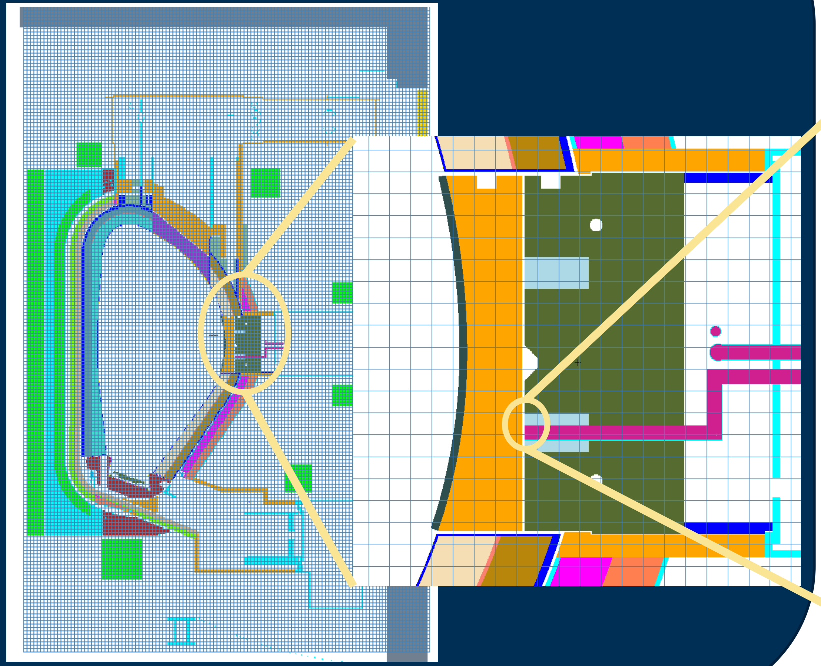
- Use a monte-carlo transport code, such as MCNP, to estimate the neutron flux and spectra
- How do you take account of the variation in flux and material around your model?

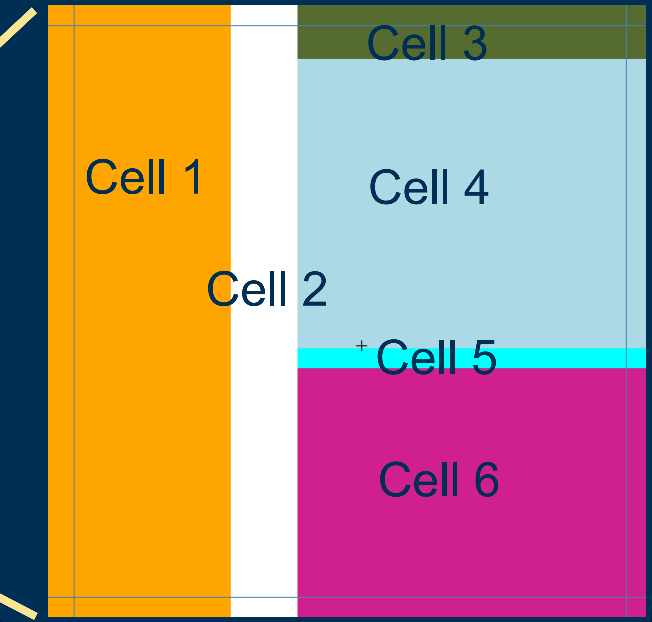
Cell-based tallies



Mesh-based tallies

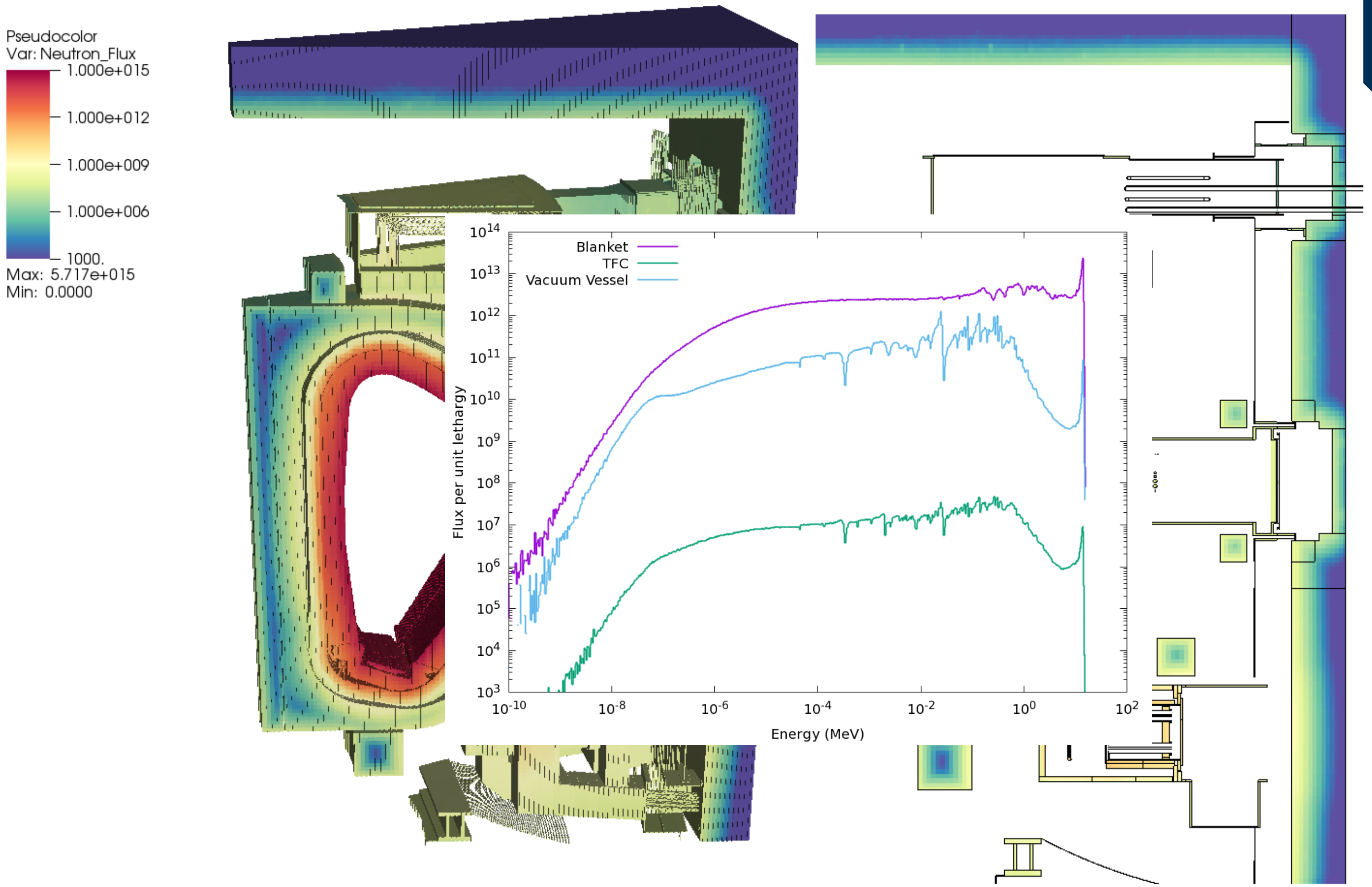


Mixture of both (Cell-Under-Voxel)



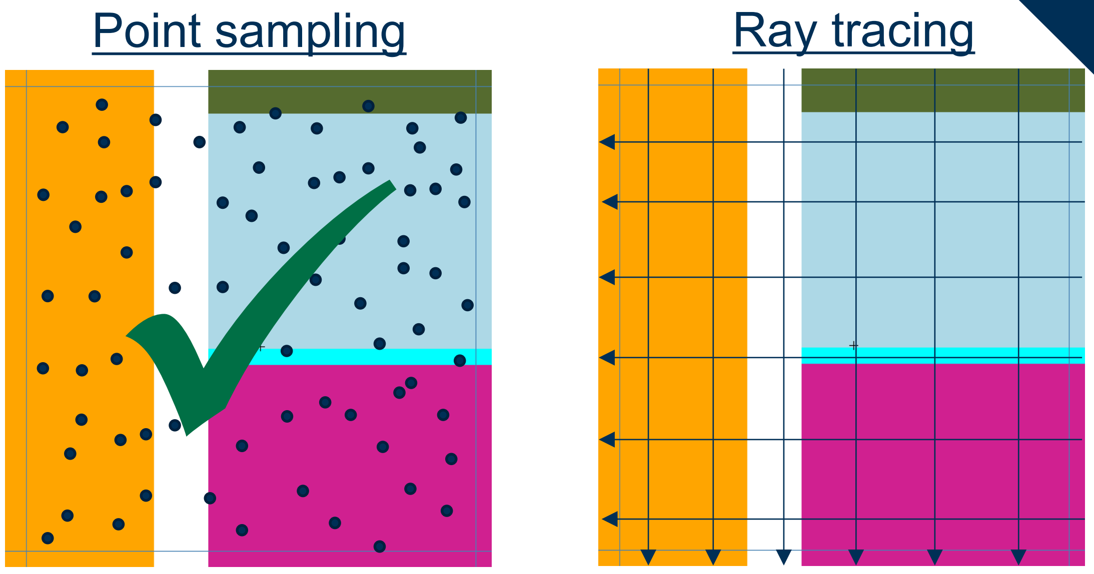
Step 1 – Neutron Transport Example

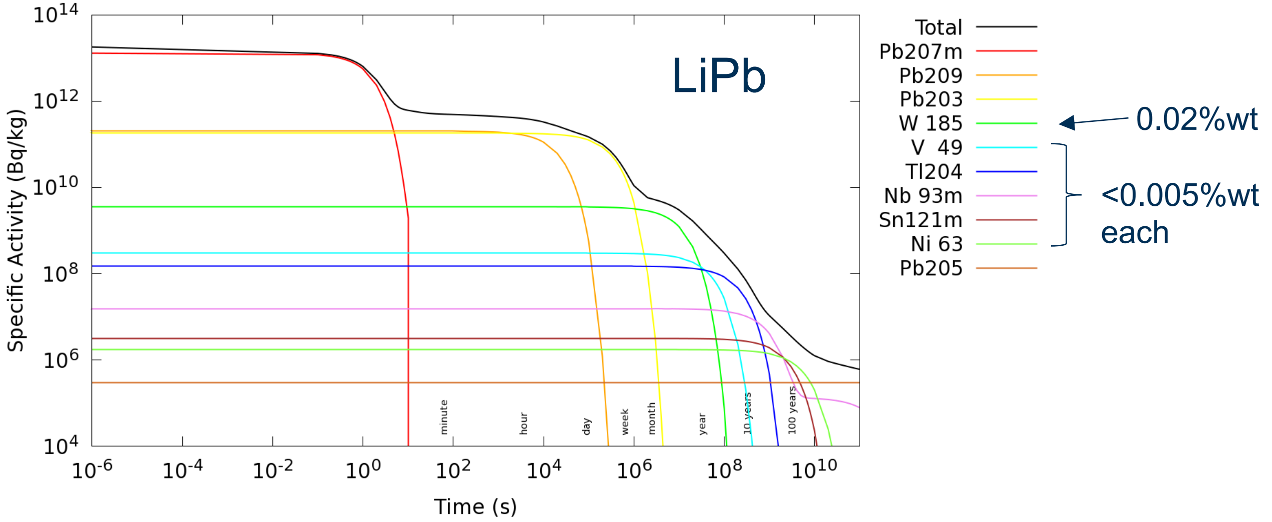
- Record the neutron flux across the DEMO reactor
- Mesh voxel size ~17x20x17 cm
- Cell under voxel method
- To save on memory neutron flux not recorded in the void
- Visualisation developed to allow finer resolution plots for CuV
- Neutron spectra in each voxel recorded



Step 1 – Material assignment

- Require knowledge of materials/cells under each mesh voxel
- Options:
  - Point sampling
  - Ray-tracing
- Can be automatically performed as a pre-transport calculation step (point sampling currently used in MCR2S)
- Material definitions required – including impurities





Inventory Calculations - MCR2S Code

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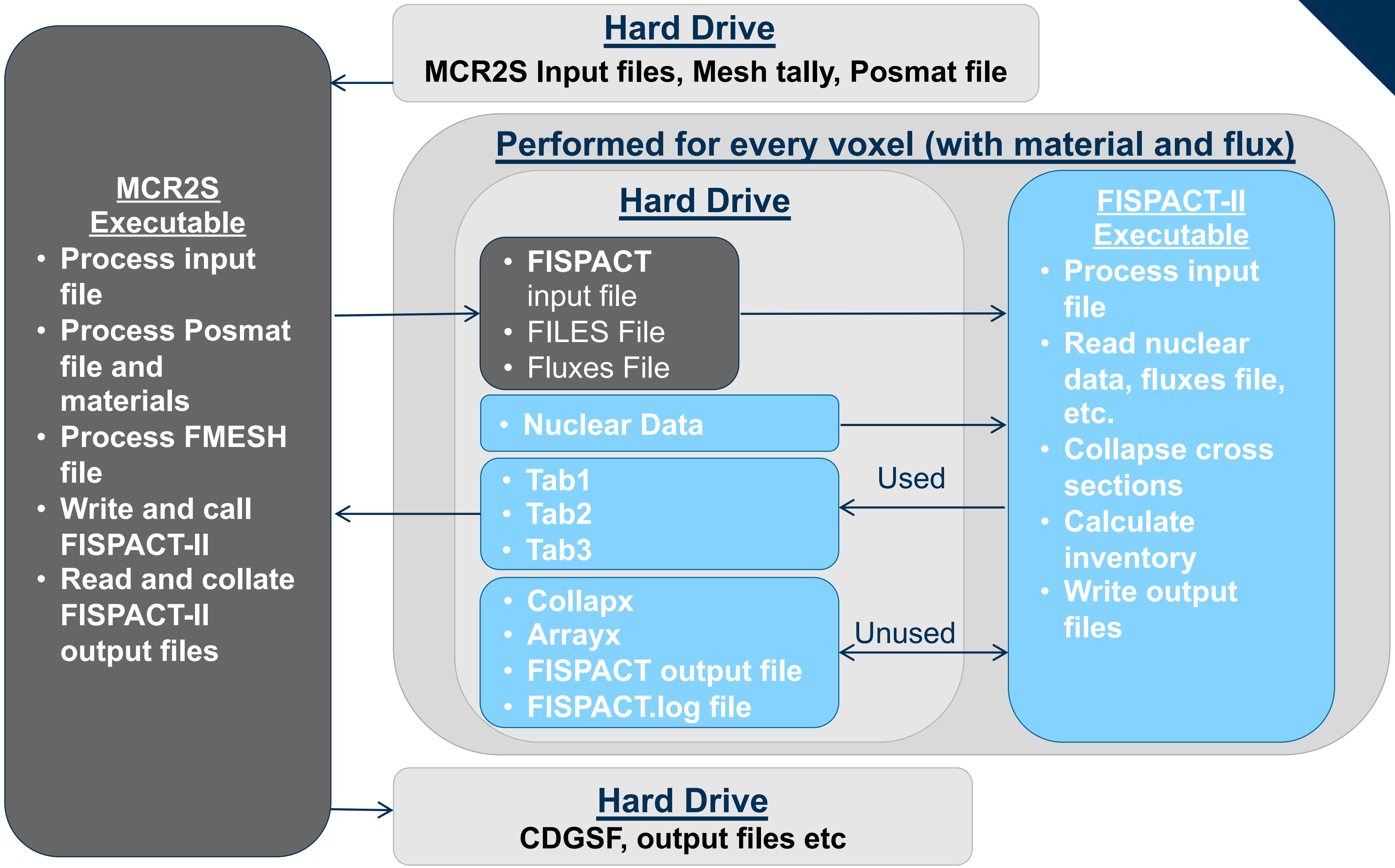
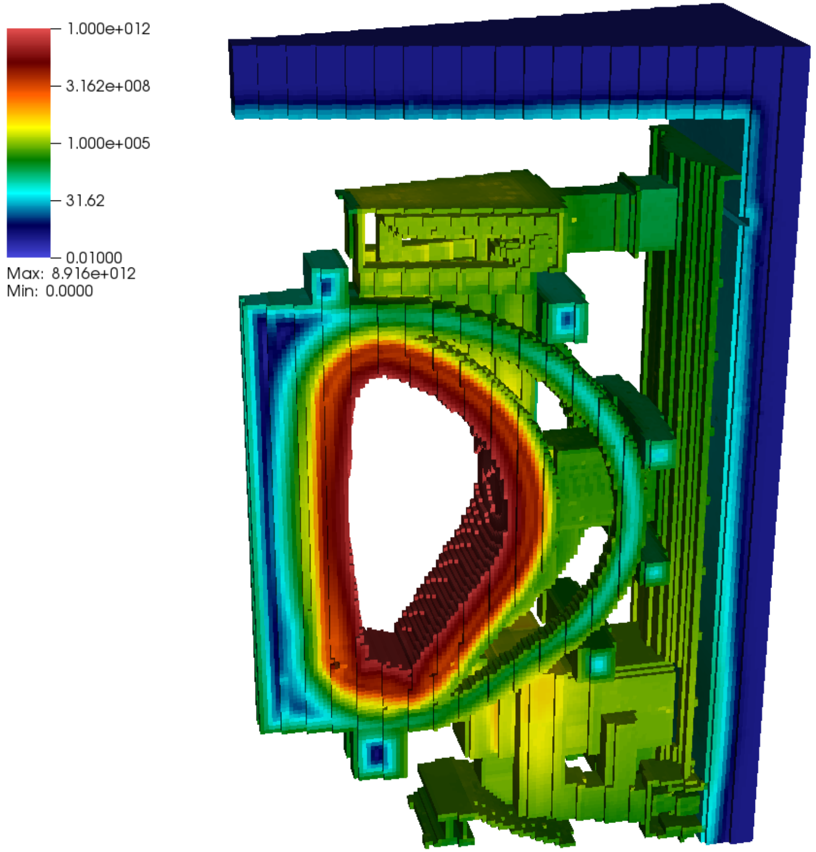
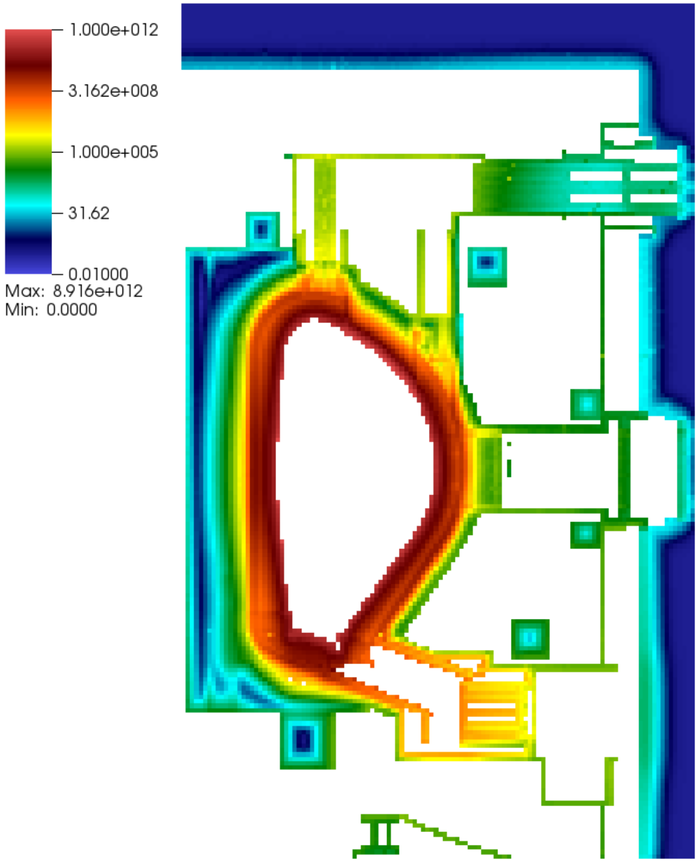
- UKAEA developed a Mesh-Coupled Rigorous 2 Step method (MCR2S)
  - Uses a mesh based approach for spatial separation
  - Takes neutron flux in the form of a mesh tally (can be from MCNP, Serpent 2 or OpenMC)
  - Uses FISPACT-II for inventory calculation



Inventory Calculations – Gamma Source Example

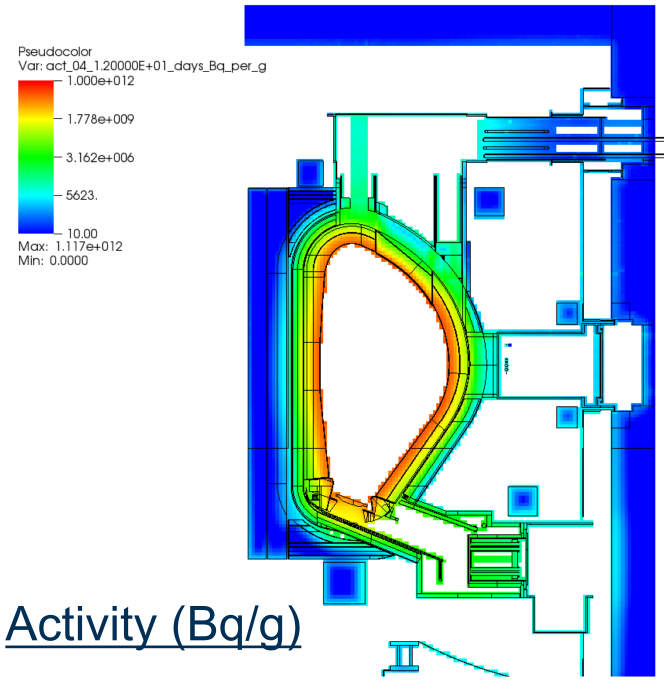
- MCR2S output a CDGS file for each decay step
- Number of gamma's per voxel/cell
- Energy spectrum (default 24 groups) but can be arbitary
- Source at 12 days after shutdown following a 20 DPA to FW irradiation schedule (g/cm^3/s)



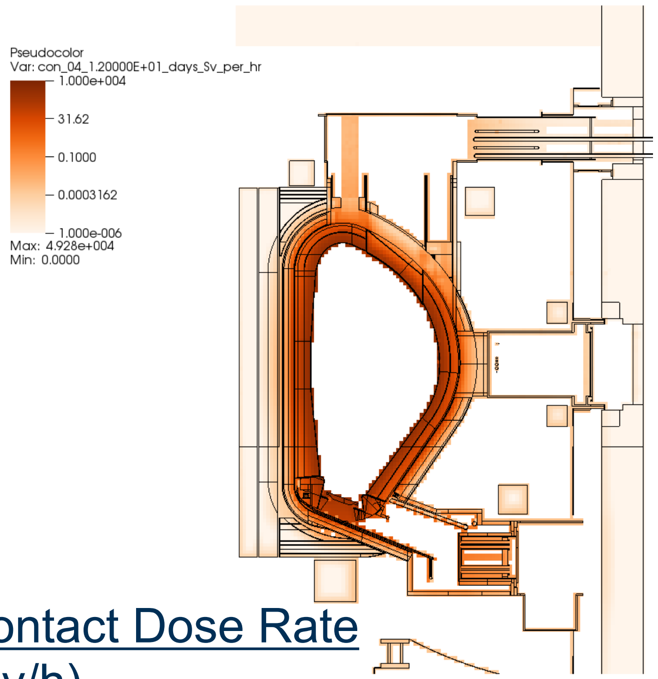


Inventory Calculation – Other outputs

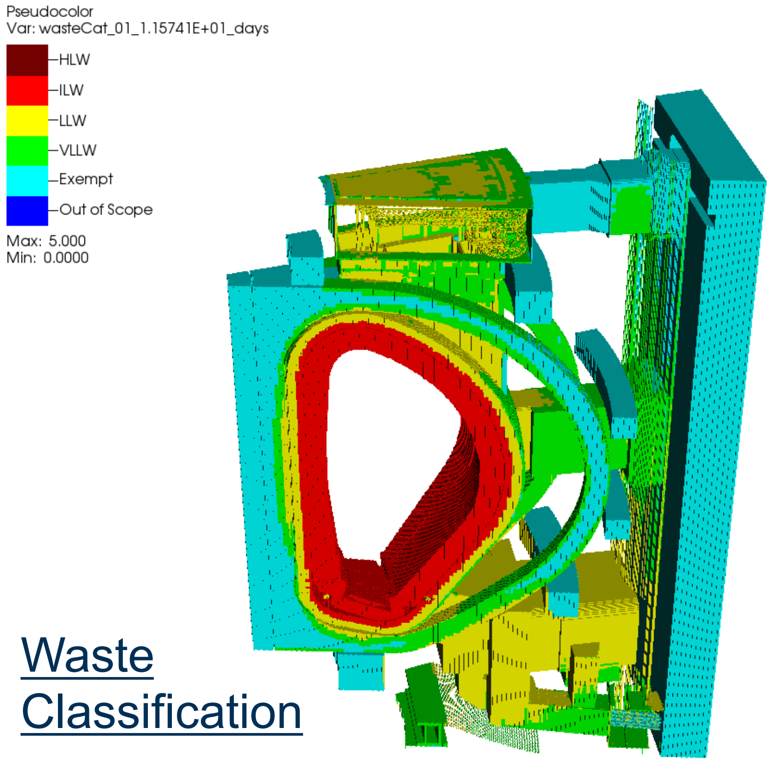
- As well as gamma source file MCR2S can output 3D maps of:
  - Decay heat
  - Activity
  - Contact dose rate (from either a point source or semi-infinite slab approximation)
  - Waste Categories



Activity (Bq/g)



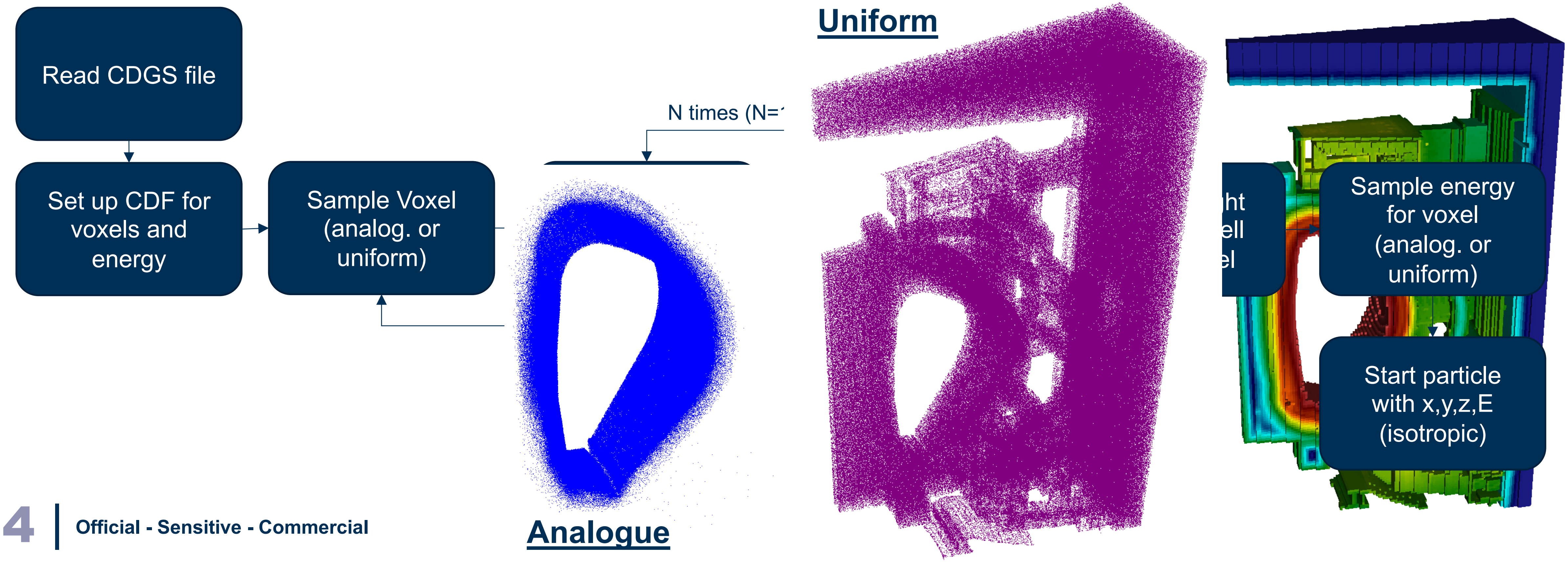
Contact Dose Rate (Sv/h)



Waste Classification

Step 2 – Gamma Transport

- How do we use the CDGS file to start particles in a gamma transport run?
- Reader and sampling library – written in Fortran with C-bindings to allow for use in radiation transport codes such as MCNP, OpenMC and Serpent 2



Step 2 – Gamma Transport Example

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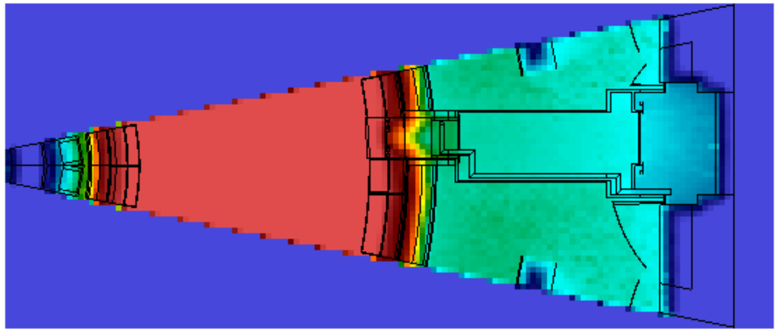
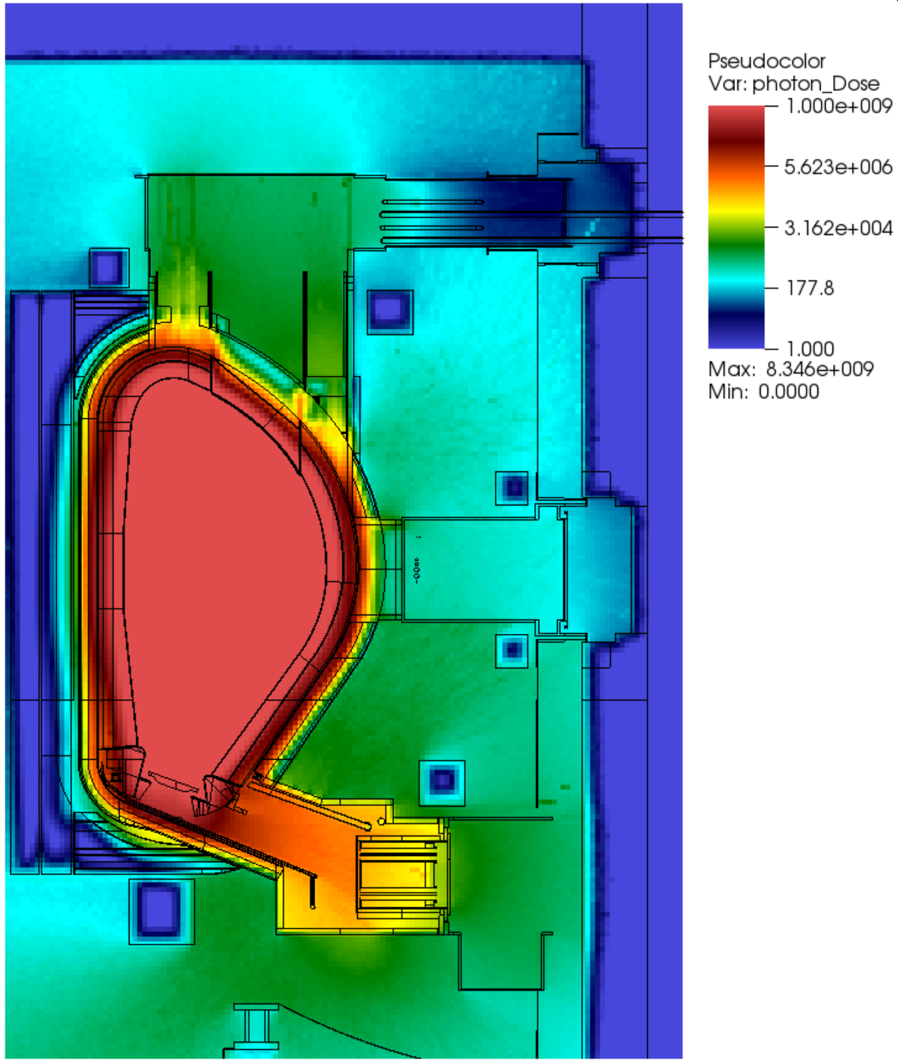
- 3D map of shutdown dose rate can be calculated
- Dose rate at 12 days after shutdown (µSv/h)
- Other quantities e.g. dose to electronics can be calculated.



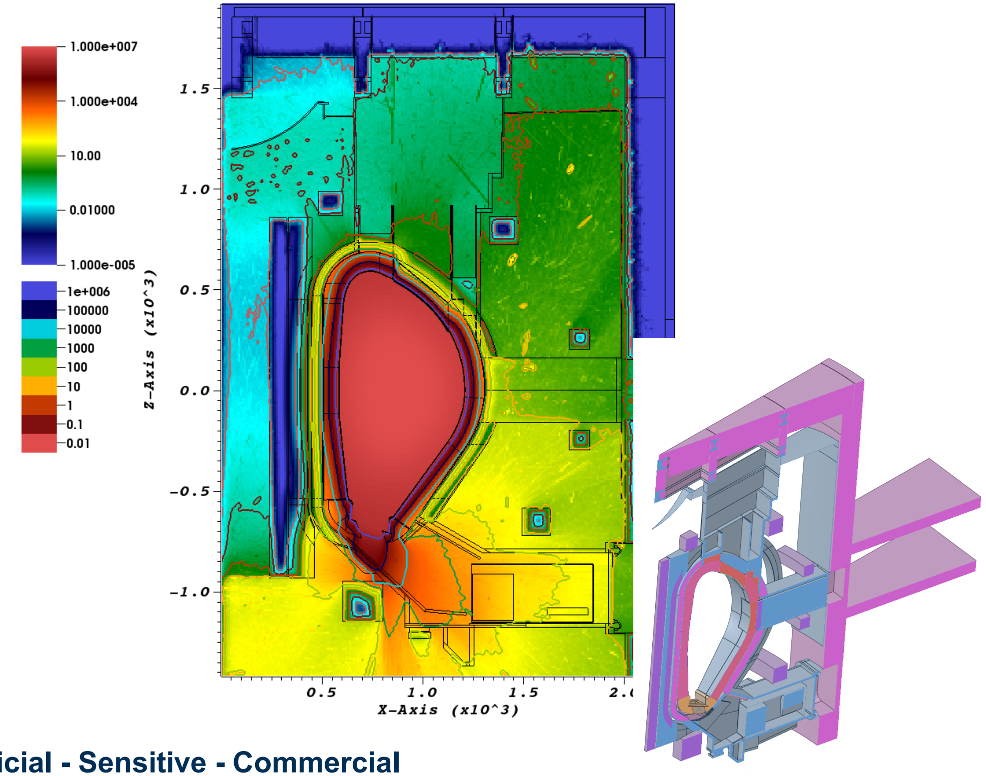


Movement of Components

- During shutdown things can move. How can these be taken into account?
- R2S allows for different models between the on-load and off-load transport calculations.

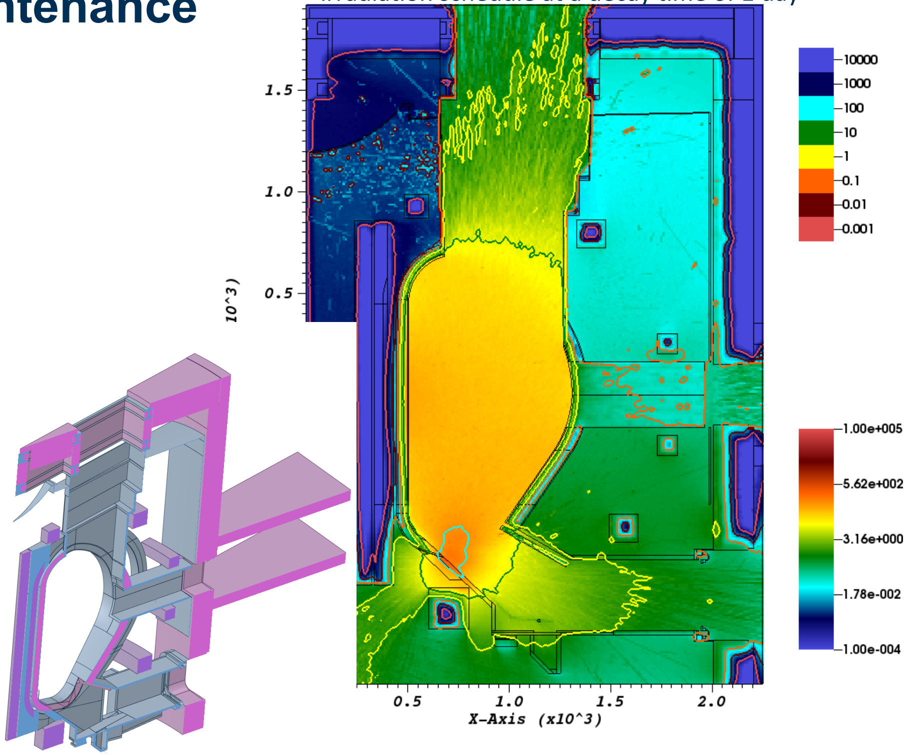
On-load

Dose to silicon (Gy/Hr)



During maintenance

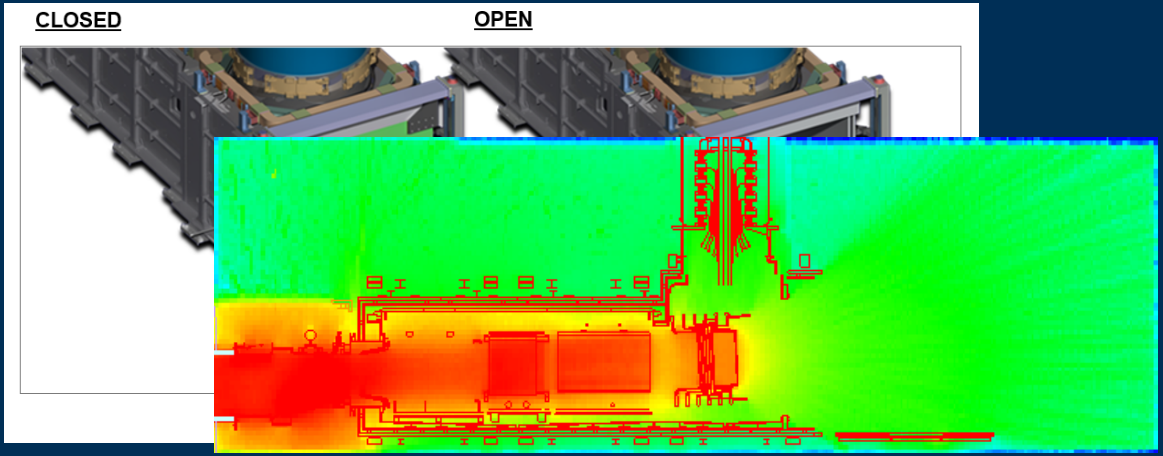
Dose to silicon (Gy/Hr) for the 1 dpa irradiation schedule at a decay time of 1 day



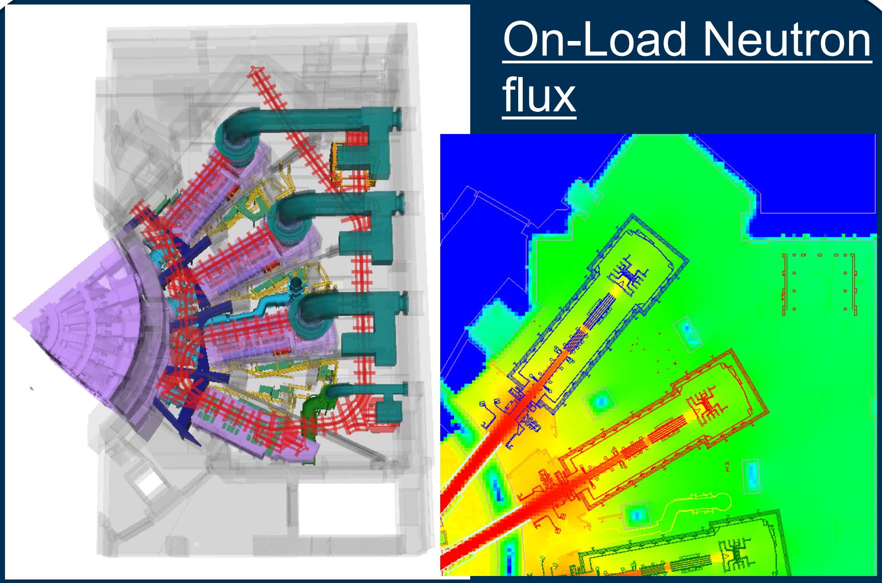
Movement of Components cont.

- ITER NBI Maintenance
- Calculation of dose rate when accessing the NBI source
- Calculations of dose rate when accessing beam line components
- Taking account of the movement of components
- T. Eade et. al Fusion Engineering and Design 98–99(2015)2130–2133

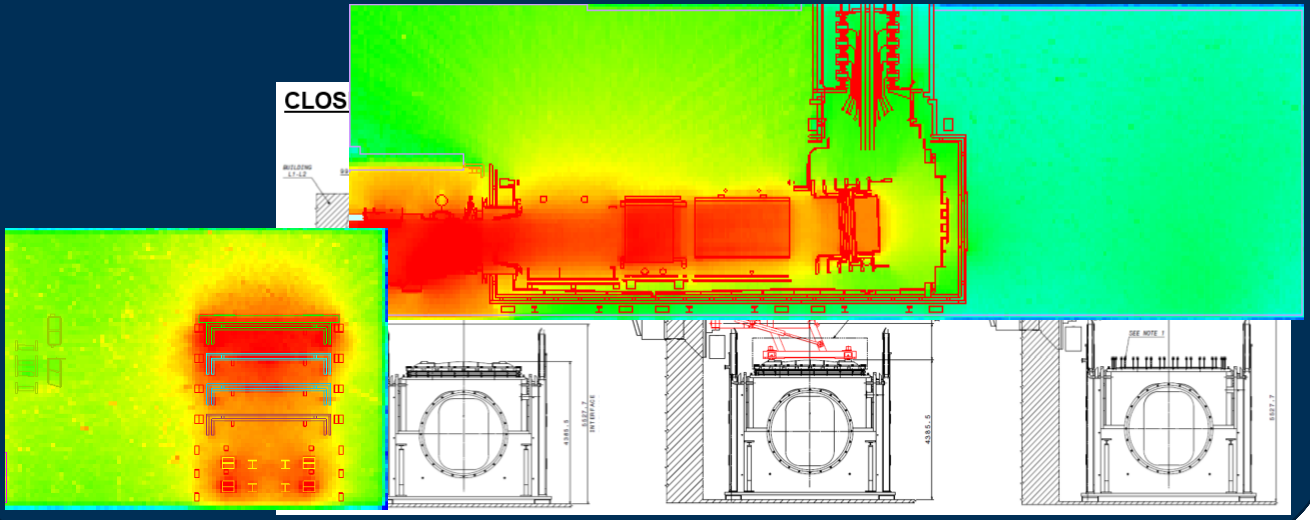
SDDR access to the source



On-Load Neutron flux

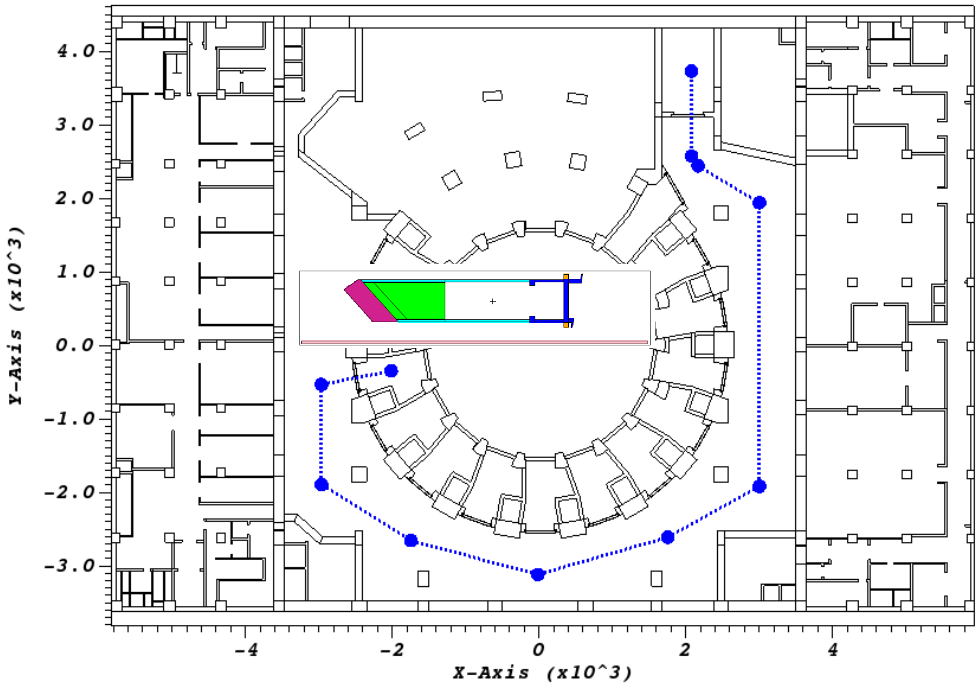


SDDR access to beam line components

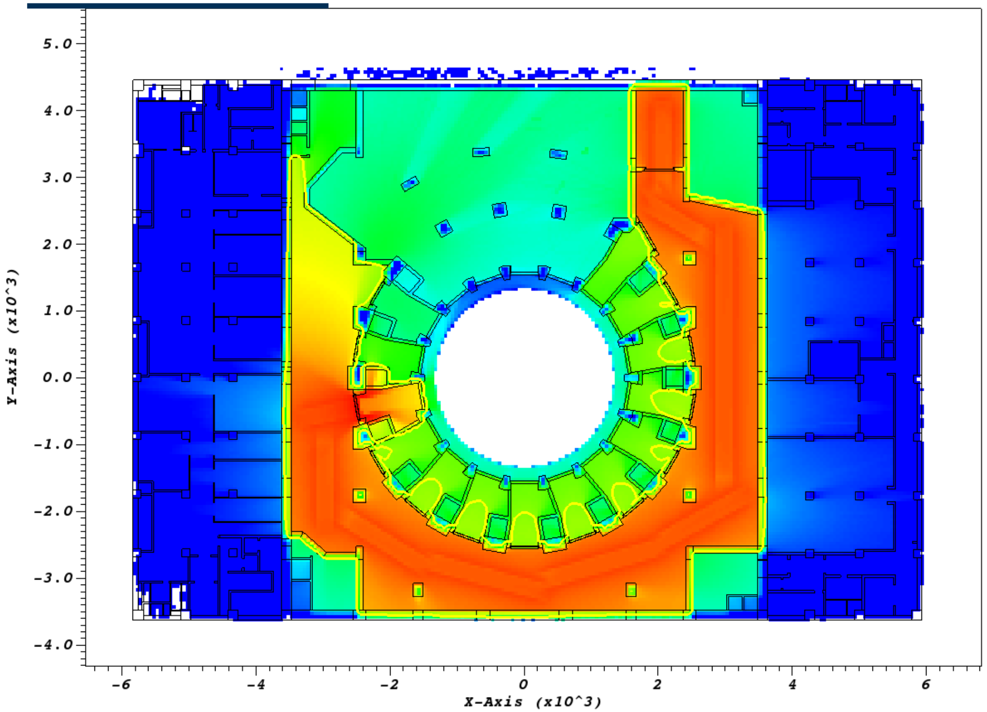


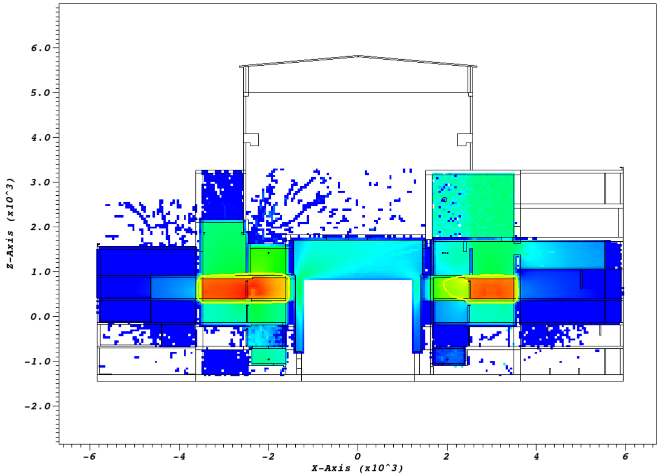
Movement of Components Cont.

- ITER Radiation maps
- Calculate the time integrated dose
- During movement of cask containing upper port plug



Gamma dose



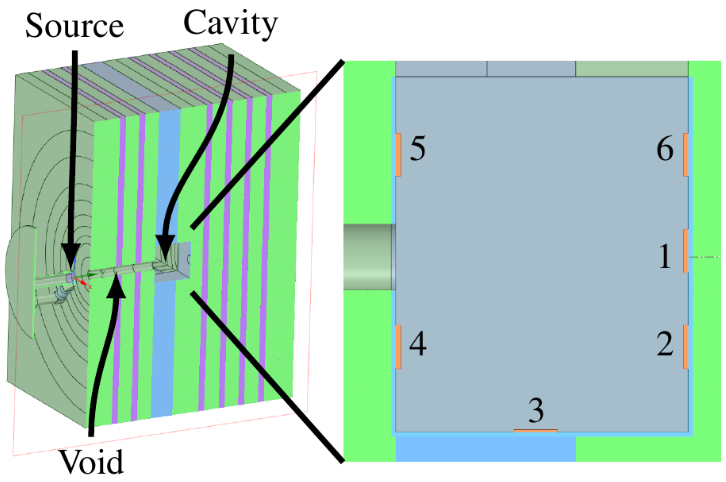


Developments – MCR2S use with other transport codes

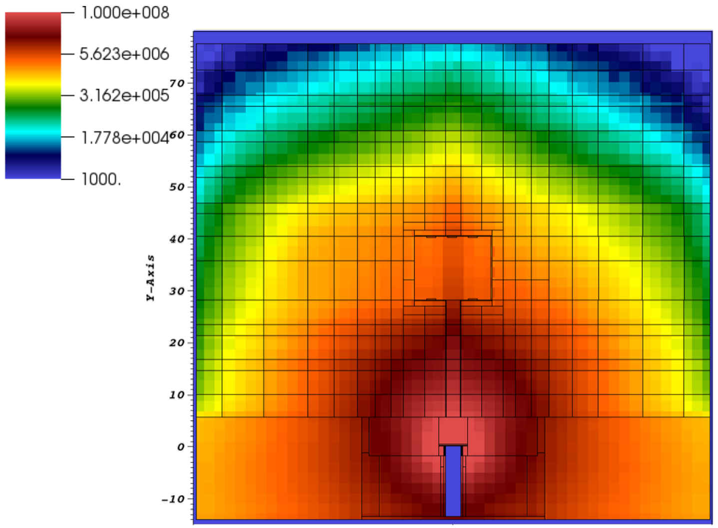
- MCR2S has been extended to Serpent 2 and OpenMC
  - Currently only support rectangular meshes and basic (non-CuV) method
- New material sampling processes written for Serpent 2 and OpenMC
- New routines for reading Serpent 2 and OpenMC neutron flux meshes
- New code independent common decay gamma source library created
  - Written in Fortran 90
  - C-bindings to allow it to be used by transport codes written in other languages
  - Starts gamma particles from the gamma source generated by MCR2S
- MCR2S compatibility with other transport codes - T. Eade et al 2020 Nucl. Fusion 60 056024

Developments – MCR2S use with other transport codes

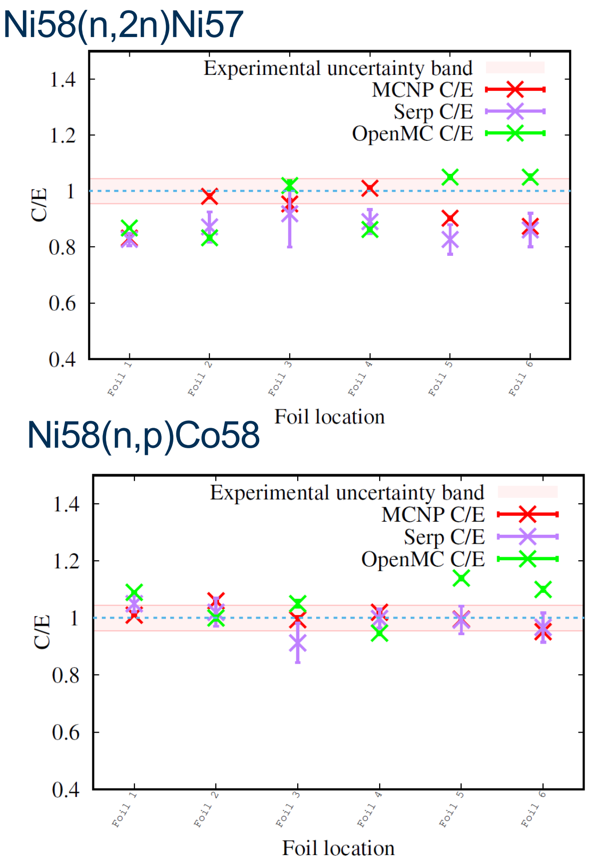
- Calculations performed for the FNG SDDR benchmark for Campaigns 1 and 2
- MCNP, Serpent 2 and OpenMC used to calculate results
- MCR2S used to calculate gamma source across rectangular mesh
- Reaction rates for foils, SDDR and gamma spectrum calculated.



Neutron Flux (n/cm²/s)



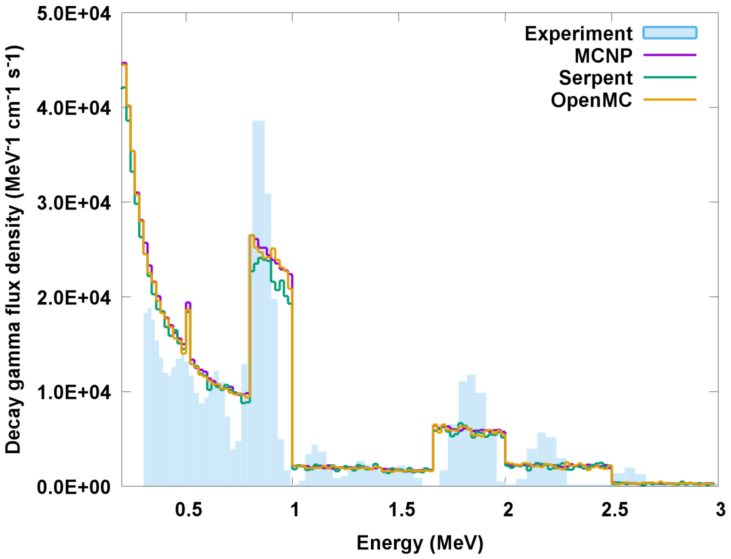
On-load Reaction Rates



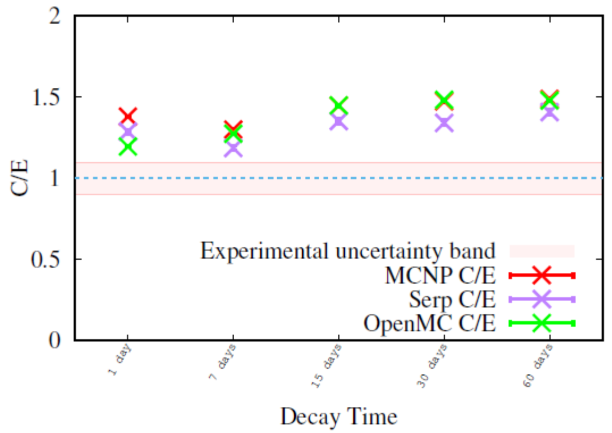
Developments – MCR2S use with other transport codes

- All SDDR results compare reasonably well
- Serpent predicts slightly lower dose rates than MCNP and OpenMC; most likely due to the different photon physics used

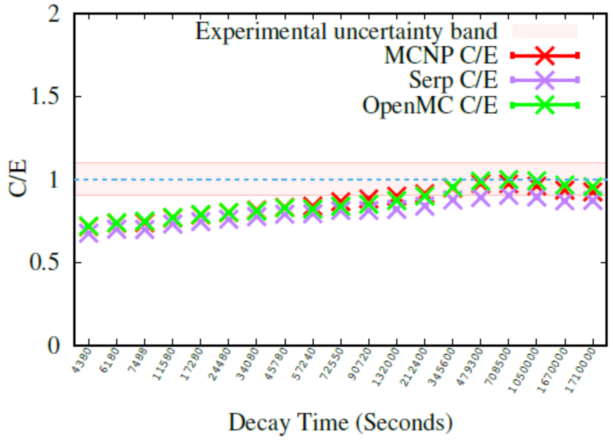
Campaign 2 Gamma Spectra (@ 7488 s)



Campaign 1 (Shutdown dose rate (C/E))

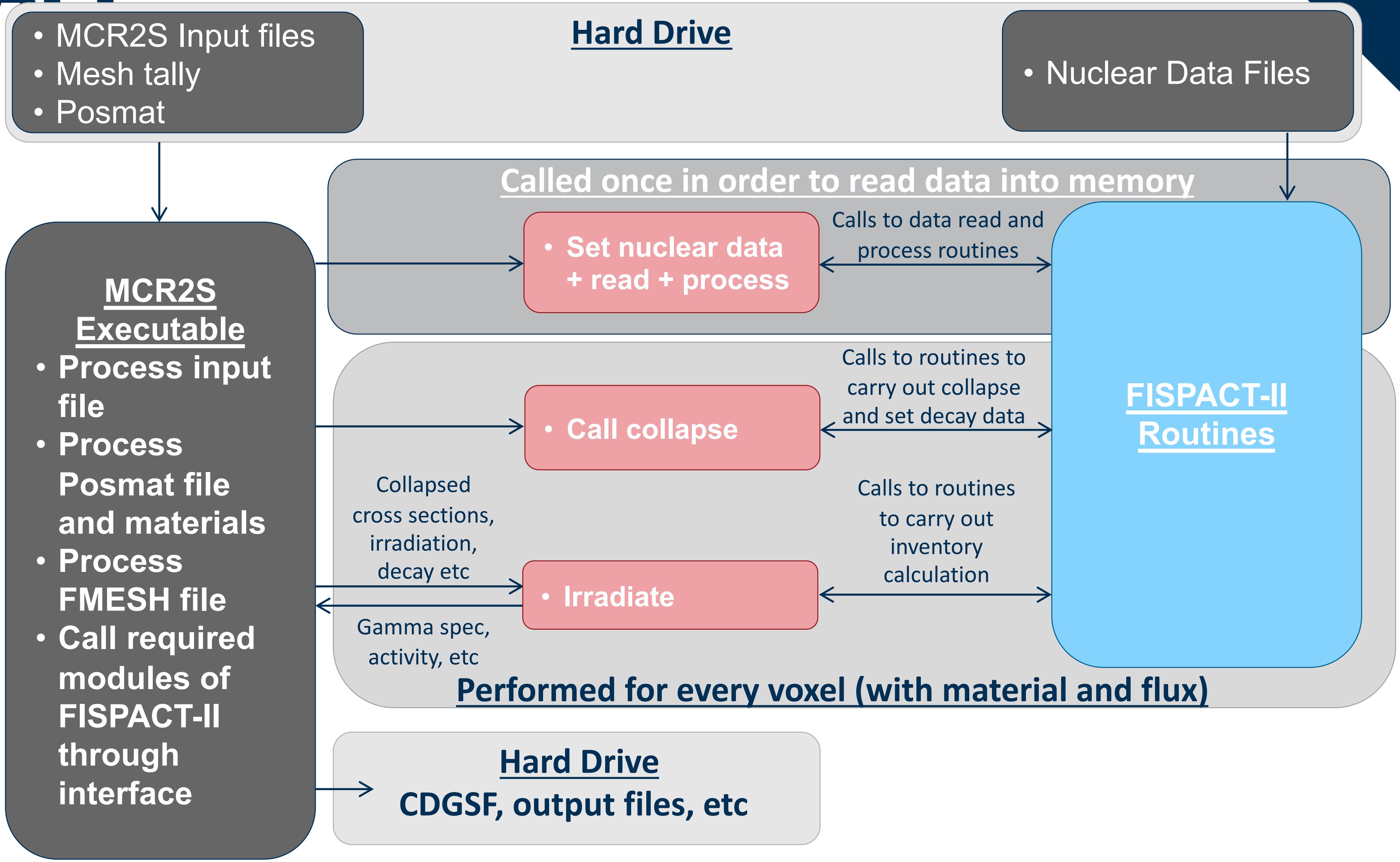


Campaign 2 (Shutdown dose rate (C/E))



Developments – MCR2S use with the FISPACT-II API

- MCR2S has been updated to use FISPACT-II API
- No intermediate output files
- Nuclear data read in once
- MCR2S can output FISPACT-II input file for a given voxel



Summary

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- FISPACT-II can be used as part of R2S calculations to predict the shutdown dose rate
- MCR2S has been written to couple MCNP and FISPACT-II
- R2S calculations allow flexibility to model differences in geometry between on-load and off-load scenarios
- MCR2S has been updated to be able to use OpenMC and Serpent-II
- MCR2S has also been updated to use the FISPACT-II API