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Flow and radionuclide transport calculations for highly heterogeneous radioactive waste disposal in clay

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Outline

- Introduction
- Objectives
- Reduced calculation domain
- Flow and transport data
- Performed calculations
- Results
- Conclusions



Introduction (1/4)

Geological disposal appears as a possible way to isolate radioactive waste from biosphere.

Principle: delay radionuclide arrival to the biosphere while radionuclide amount decreases with radioactive decay.

As water is the vehicle for radionuclide transport in porous media, geological disposal concept is based on the choice of:

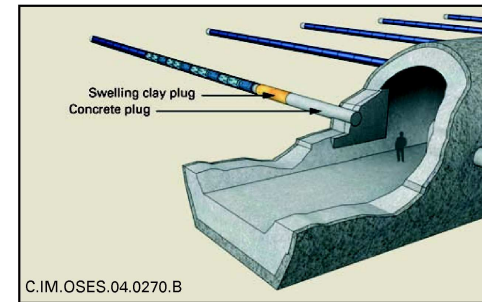
- a deep geological layer,
- a small geological layer permeability (to ensure slow water movement),
- a multi-barriers approach (waste matrix, engineered barriers, geological media).

Introduction (2/4)

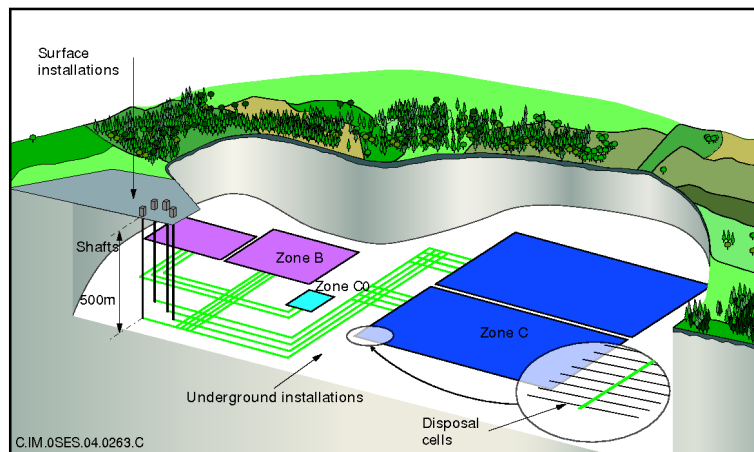
Vitrified waste disposal in clay concept description (French concept).



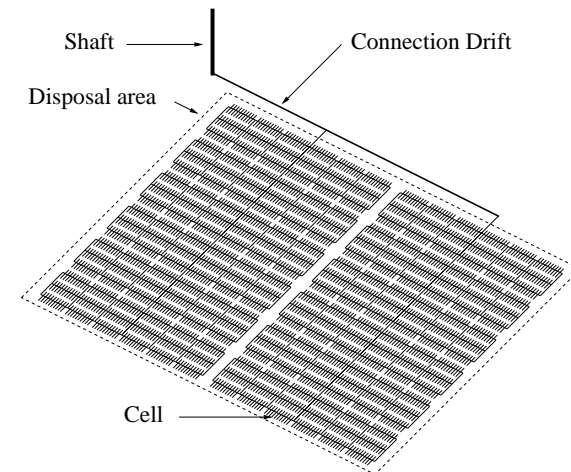
Vitrified waste canister
 $1.3\text{ m} \times \varnothing 0.43\text{ m}$



Repository cell $30\text{ m} \times \varnothing 0.7\text{ m}$



Geological disposal
 $20\text{ km} \times 20\text{ km}$



Vitrified disposal area
 $2\text{ km} \times 2\text{ km}$



Introduction (3/4)

Radioactive waste disposal safety assessment must include radionuclide transport modeling because we have to take into account:

- large time scale (at least 1 million years),
- large space scale (geological layers over tens of kilometer extension).

Equations to solve:

- Flow:
$$\begin{cases} \operatorname{div} \mathbf{U} & = & 0 \\ \mathbf{U} & = & -\bar{K} \nabla h \end{cases}$$
- Radionuclide transport:
$$\omega \frac{\partial C}{\partial t} = \nabla \cdot (\bar{D} \nabla C - C \mathbf{U})$$

with particular properties:

- objects of meter scale embedded in objects of kilometer scale,
- highly heterogeneous and anisotropic tensors (\bar{K} , \bar{D})



Introduction (4/4)

Main simplifications of the performed radionuclide calculations:

- smallest objects are not represented,
- square section geometry used,
- no computation convergence study,
- box to box calculations.



Objective

What is the error induced by geometric simplifications ?

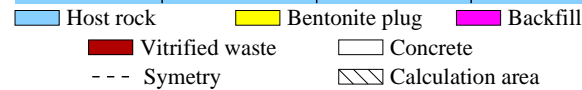
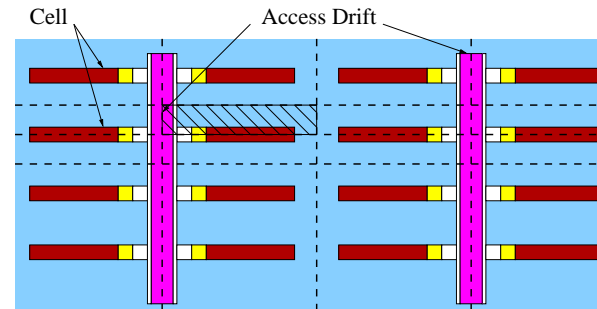
→ One objective of the Euratom project PAMINA (Performance Assessment Methodologies IN Application to guide the development of the safety case) (2006-2009)

<http://www.ip-pamina.eu>

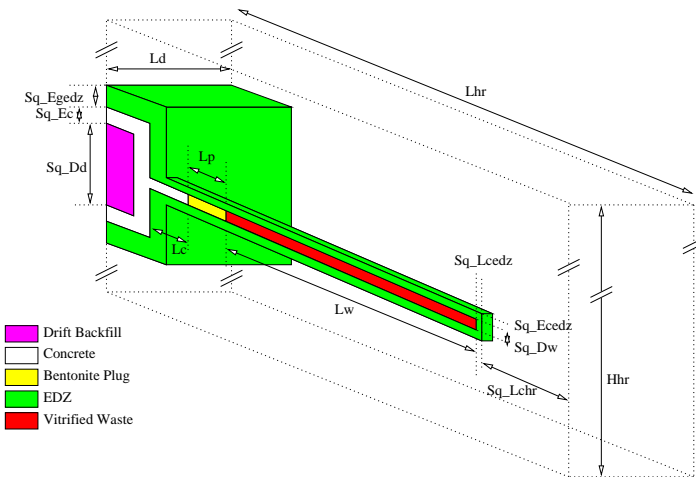
The objective of this work is to evaluate the error induced by using square section geometry instead of cylindrical one.

Reduced calculation domain

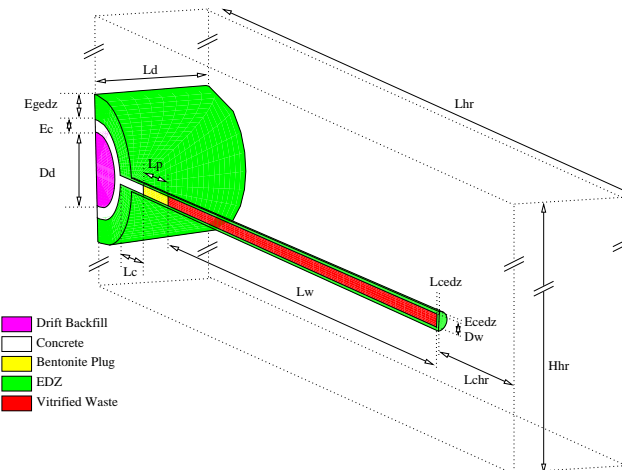
Reduced calculation domain was extracted considering symmetries and periodicity of the disposal area.



Reduced calculation domain selection



Square



Cylindrical



Flow and transport data

Material property values for flow and transport calculations.

Material	Permeability ($m.s^{-1}$)	Porosity	Effective Diffusion ($m^2.s^{-1}$)
Host Rock	10^{-13} (v) / 10^{-12} (h)	0.06	$6 \cdot 10^{-13}$
EDZ	$5 \cdot 10^{-11}$	0.20	$2 \cdot 10^{-11}$
Vitrified wastes	10^{-8}	0.10	10^{-11}
Concrete	10^{-10}	0.20	$2 \cdot 10^{-11}$
Bentonite	10^{-11}	0.20	$2 \cdot 10^{-11}$
Gallery backfill	10^{-6}	0.40	$4 \cdot 10^{-11}$

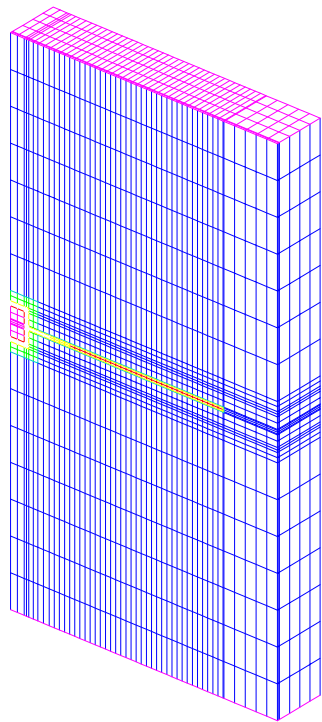


Performed calculations

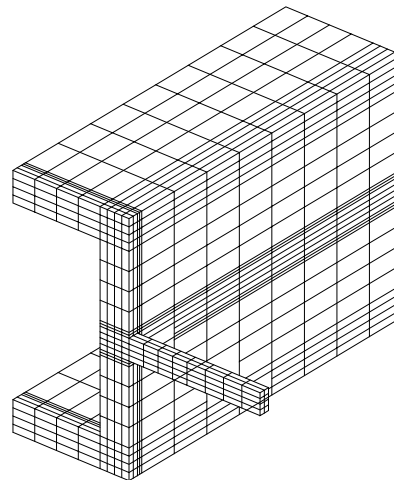
- Calculations performed on three levels of mesh refinement.
- Calculations performed over 2 million years using 11, 44 and 176 time steps.
- Finite Volume (MPFA) scheme.
- Fully implicit time scheme.
- Bi-CGSTAB with ILUT preconditioner solver.
- AMD Opteron processor (2.6 Ghz - 64 Go RAM).

Used Meshes (1/2)

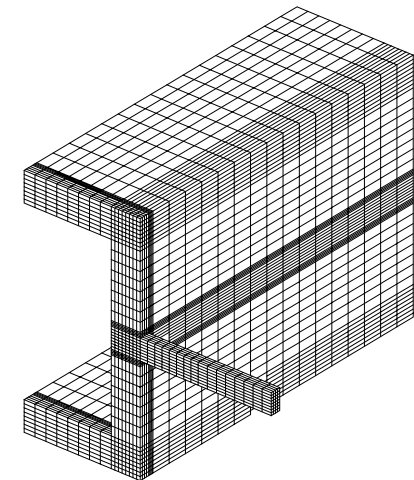
Three levels of mesh refinement were used on the basis of smallest object discretization (EDZ radial extension around canisters).



First level refinement
mesh (8,640 (1))



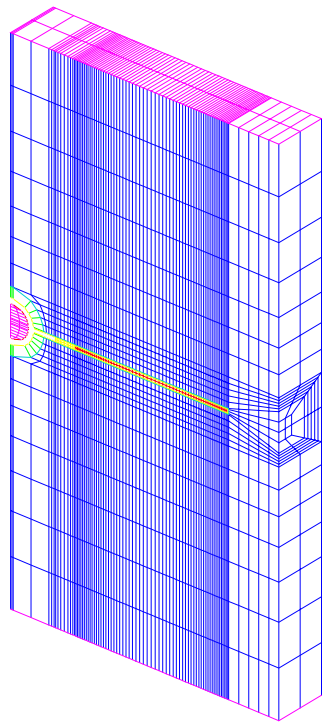
Second level refinement
mesh (69,120 (2))



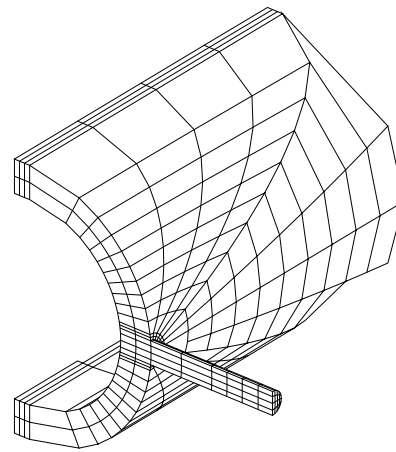
Third level refinement
mesh (552,960 (4))

Used Meshes (2/2)

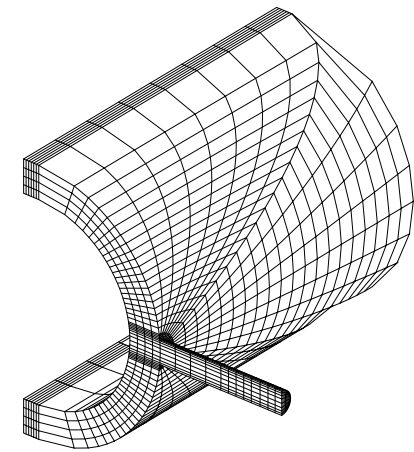
Three levels of mesh refinement were used on the basis of smallest object discretization (EDZ radial extension around canisters).



First level refinement
mesh (5,536 (1))



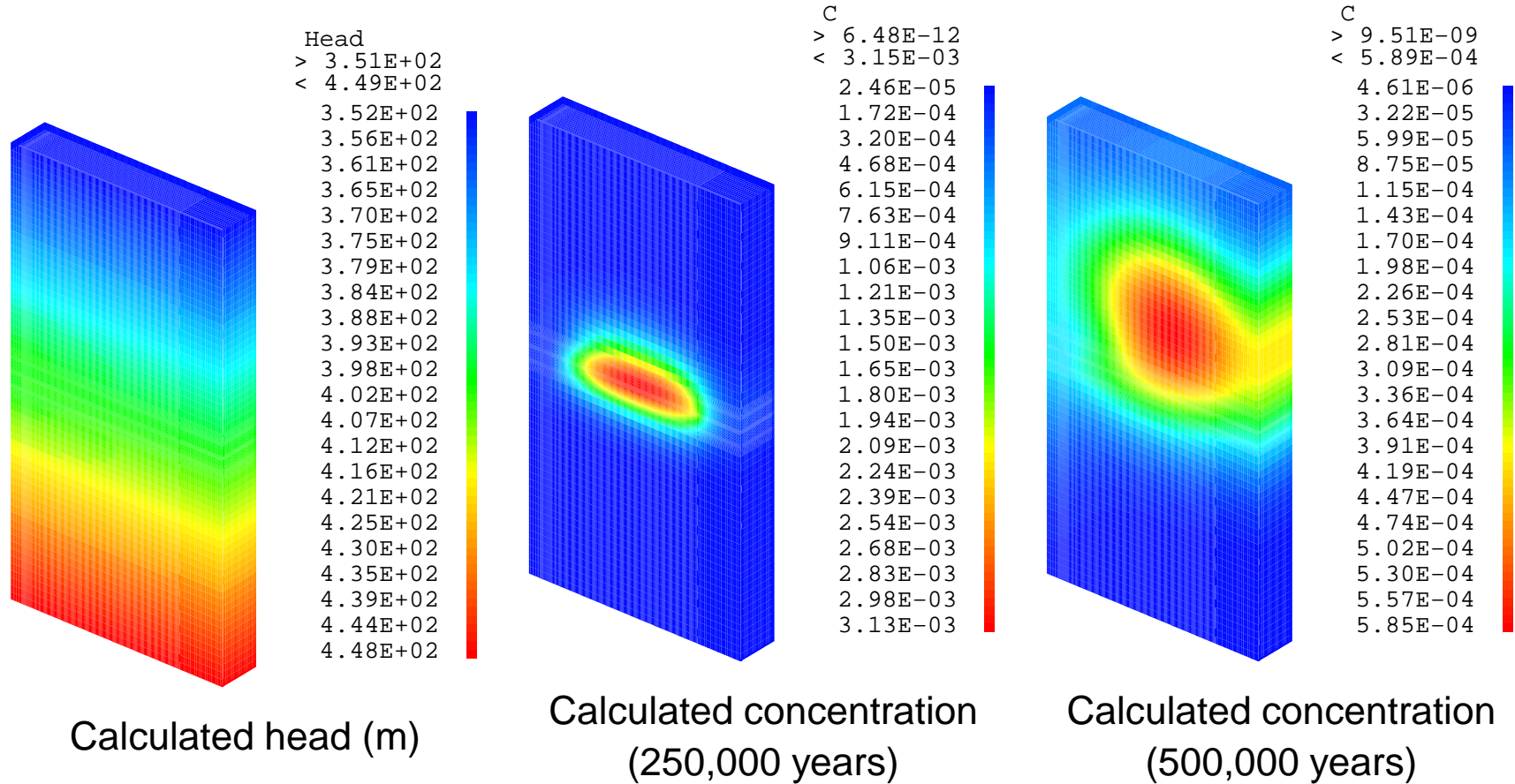
Second level refinement
mesh (44,288 (2))



Third level refinement
mesh (354,304 (4))

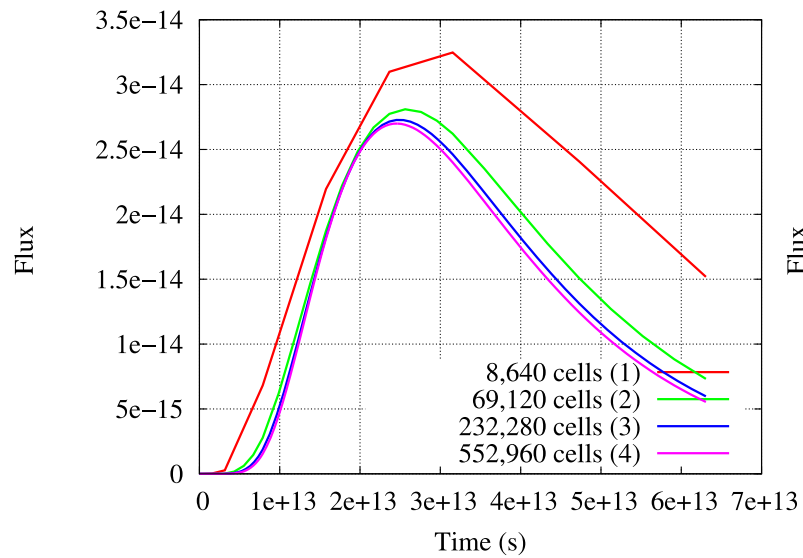
Results (1/4)

Flow and transport results.

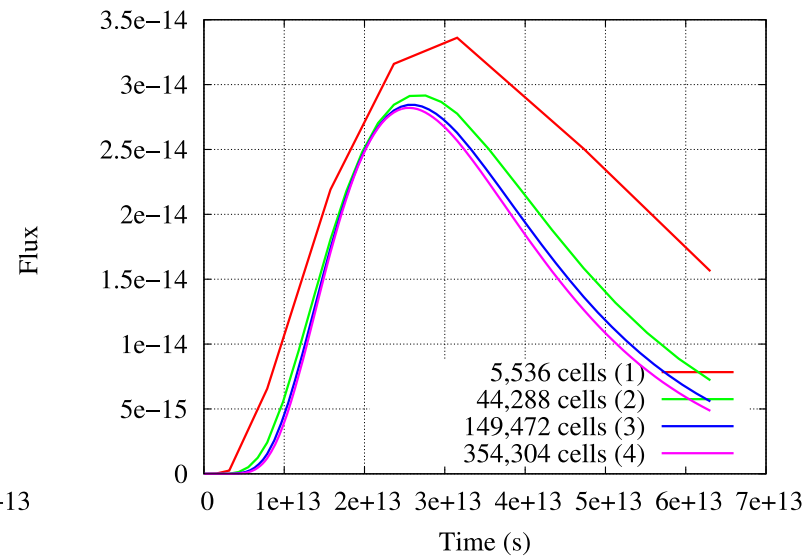


Results (2/4)

Mesh and time step refinement convergence test.
 Radionuclide flux at the upper boundary condition (aquifer) is used.



Square



Cylindrical

Results (3/4)

Mesh and time step refinement convergence test.

- Considering $f_n^{dt}(t_i)$ the calculated flux at times t_i using a refinement level n and a time step dt , $f_{2n}^{dt/4}(t_i)$ the calculated flux at times t_i using a refinement level $2n$ and a time step $dt/4$ and $f_\star^*(t_i)$ the analytical flux at times t_i .

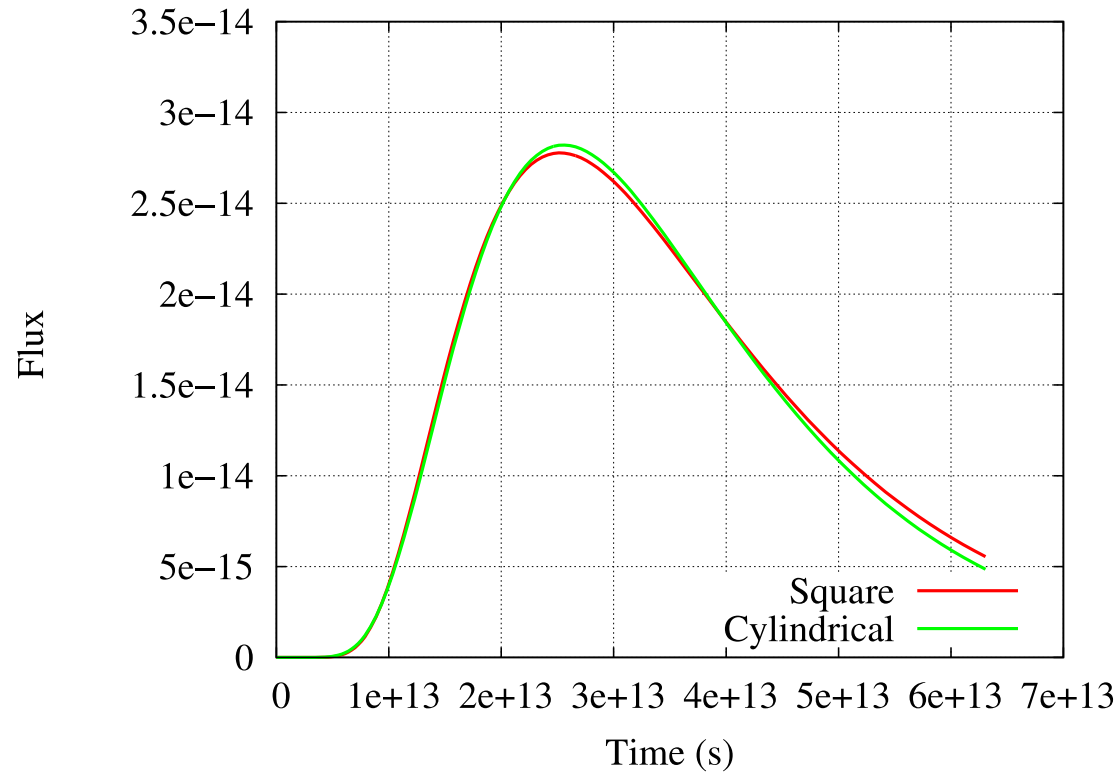
- Considering the quadratic error $E_n^{dt} = \sqrt{\frac{\sum_i |f_\star^*(t_i) - f_n^{dt}(t_i)|^2}{\sum_i |f_\star^*(t_i)|^2}}$.
- Considering a second order spatial scheme and a first order time scheme allow to estimate a majoring of error $R_{2n}^{dt/4}$ given by relation (1)

$$R_{2n}^{dt/4} = \sqrt{\frac{\sum_i |f_\star^*(t_i) - f_{2n}^{dt/4}(t_i)|^2}{\sum_i |f_{2n}^{dt/4}(t_i)|^2}} < \frac{1}{\sqrt{3}} \sqrt{\frac{\sum_i |f_{2n}^{dt/4}(t_i) - f_n^{dt}(t_i)|^2}{\sum_i |f_{2n}^{dt/4}(t_i)|^2}} \quad (1).$$

- → Estimated error:
 - $R_{354,304} < 0.0329$ (Cylindrical)
 - $R_{552,960} < 0.0295$ (Square)

Results (4/4)

Quantification of geometry simplification.



L2 error induced by geometrical simplification $E=0.054$.



Conclusion

The use of a simplified geometry (square section) underestimate the radionuclide output flux of about 5% in the presented case.