
Design modelling tool for fuel blocs management and application to Uranium and Plutonium cores

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- ❑ Introduction
- ❑ Description of the “slab” method
- ❑ Validation/results
- ❑ Advantages
- ❑ Application to an actinide burner core
- ❑ Conclusion

- Fuel cycle studies of HTR require to :

- Correctly calculate main « neutronics » characteristics

- ✓ Impact of graphite reflectors on core neutronics (lack of assembly block calculations, large migration area of the neutrons,...)
- ✓ Fuel double heterogeneity

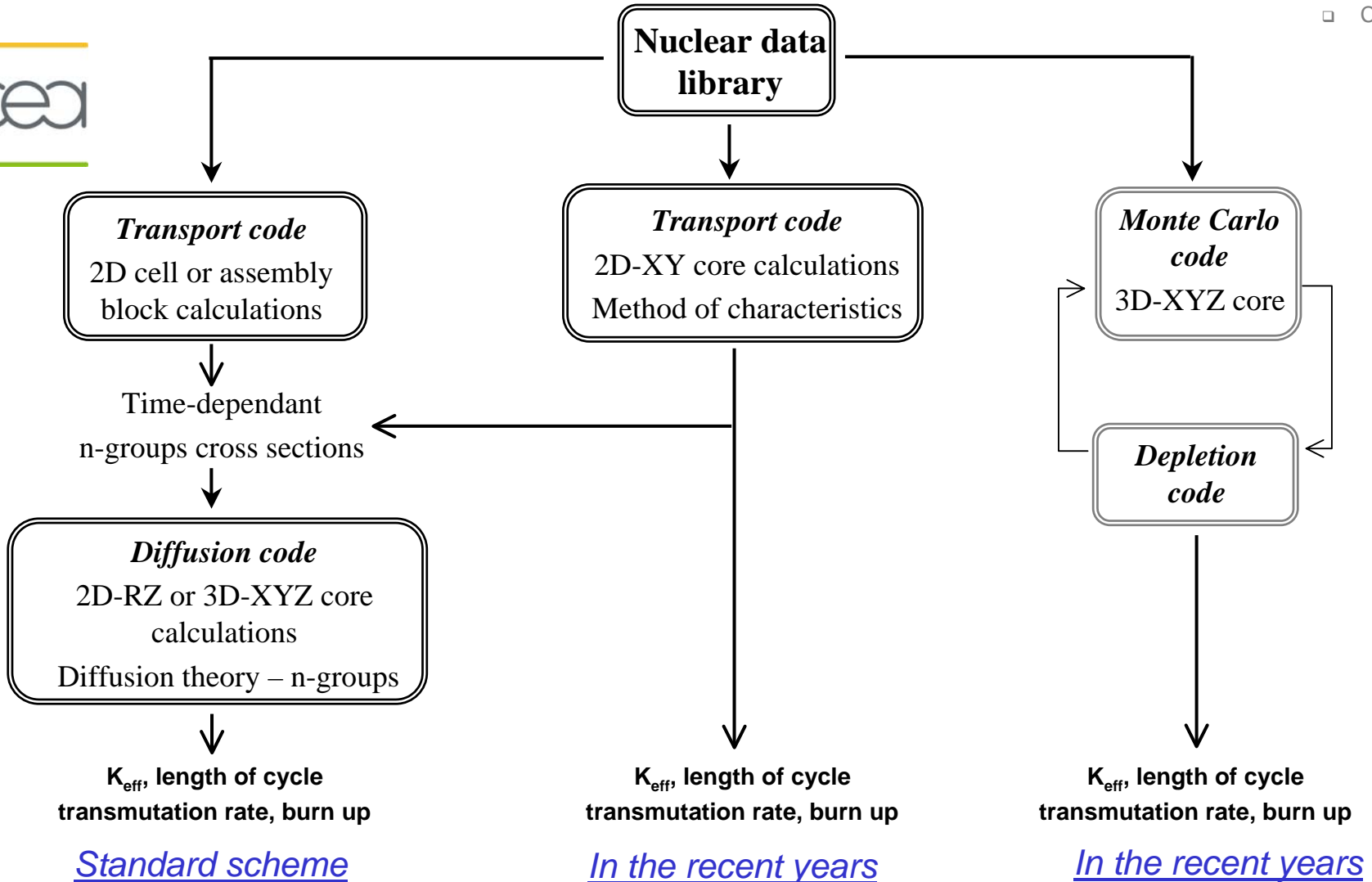
- Allow parametric and/or exotic preliminary fuel cycle studies

- ✓ Covering a large range of configuration:
 - Fuel particles (size, different types of fuel,...)
 - Assembly (different fuel compacts, fuel/helium ratio,...)
 - Core and reflectors geometry and dimensions
- ✓ In a reasonable calculation time
- ✓ With input data easy to change

- Take into account different fuel pattern schemes

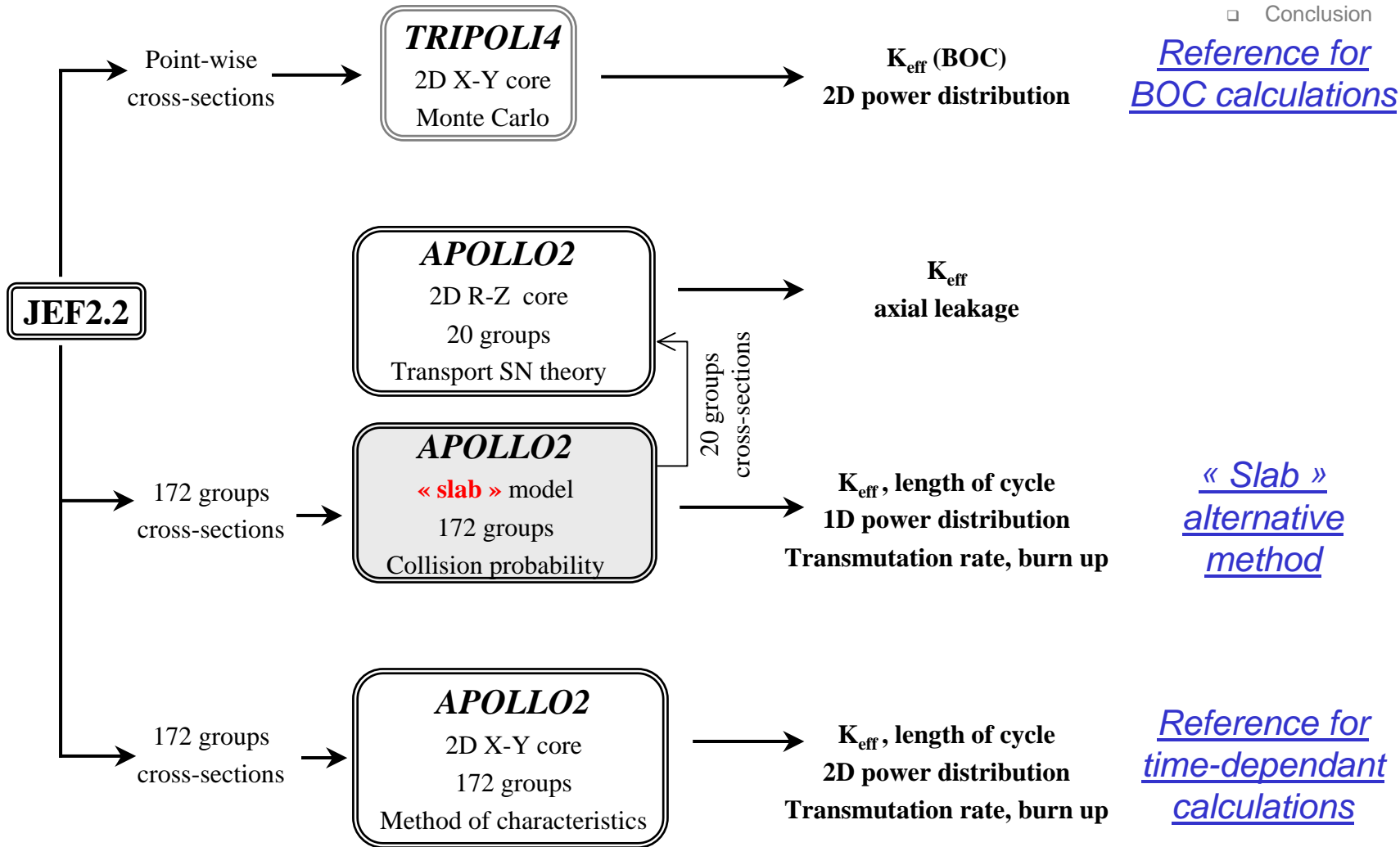
Introduction

- Main calculation routes for HTR fuel cycle studies



Introduction

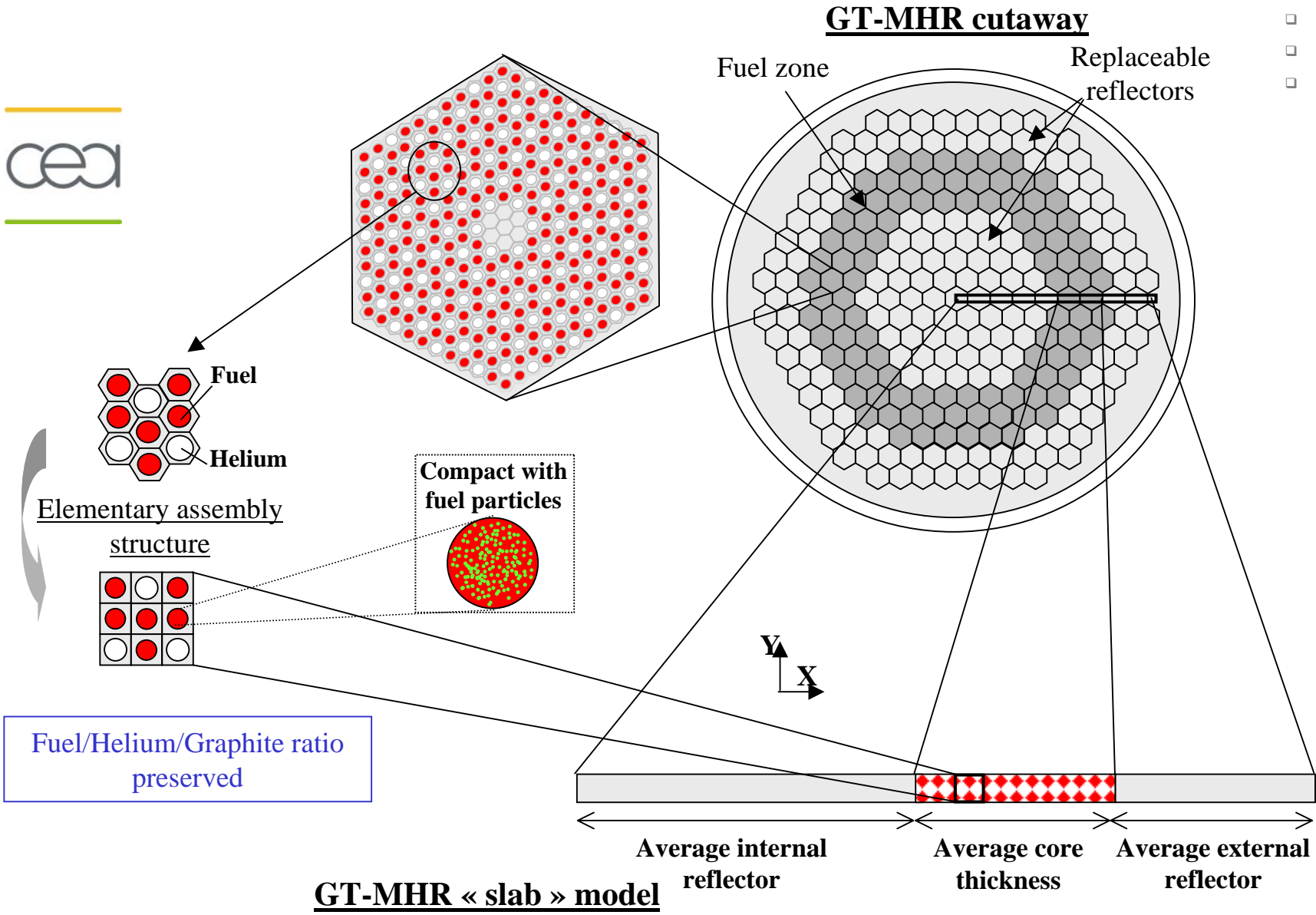
• Calculation tools used in this work



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Description of the « slab » geometry

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Description of the « slab » method

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□ Computational options

- ✓ 172 group cross sections processed from Jef2.2 library
- ✓ Explicit description of the particles - Double heterogeneity formalism
- ✓ Collision probability method for flux and self shielding calculations
- ✓ Boundary conditions: all reflection except X-right = leakage

□ Approximations

- ✓ No burnable poisons (replaced by fuel compact)
- ✓ No cavities for control rods
- ✓ Hexagonal elementary cells replaced by square cells
- ✓ Plane geometry

□ Running « slab » calculations

- ✓ Depletion calculations with fine space-dependant cross sections
- ✓ Generation of 20 groups flux-weighted cross sections for 2D R-Z SN calculations
- ✓ Irradiation stops at $k_{eff} = 1$
- ✓ Fuel management with radial refueling scheme up to equilibrium

□ Output

- ✓ $k_{eff}(t)$, length of cycle, burn up by batch
- ✓ Transmutation rate, mass balances
- ✓ Radial peak power

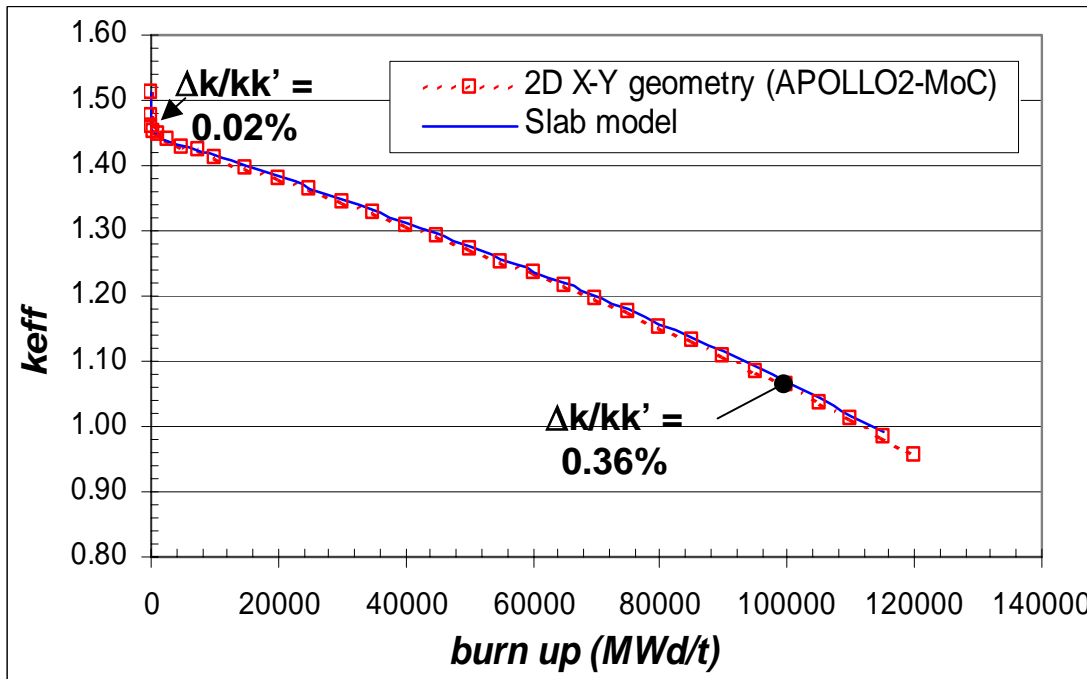


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Validation on uranium core

Uranium core main characteristics

- U5/U = 15%
- Heavy metal (in fresh core) = 4451 kg
- 216 fuel compacts / assembly



Monte-Carlo	$k_{eff} = 1.51663$
Slab model	$\Delta k/kk' = -0.2\%$

1 neutron production	U235 fission	U238 abs.
Monte-Carlo	0.405	0.088
Slab model	+1.0%	+2.9%

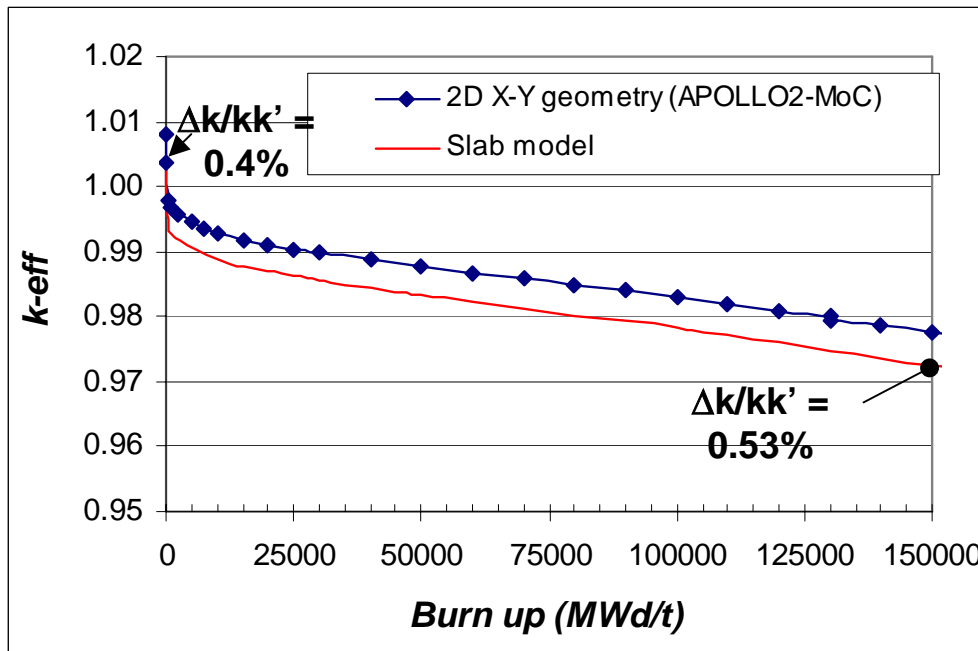
→ Good results for uranium core

Validation on actinide burner core

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Actinide burner main characteristics

- driver (Pu+Np) fuel from LWR = 1125 kg
- transmuter (Pu+MA) fuel from driver reprocessing and LWR = 687 kg
- 144 driver / 72 transmuter compacts / assembly



Transmutation rate (%)

	slab	2D-XY MoC
Pu239	-32	-31.7
Pu240	-13.9	-15.1
Pu241	19.1	20.8
Pu242	4.9	4.1
Am241	-26.1	-26.5

→ Acceptable results for actinide burner core

Remark : $\Delta k/kk' < 0.33\%$ at 600 GWd/t in a CEA/ANL benchmark (physor2006)

Impact of « slab » approximations

- **Plane geometry** : comparisons between 1D-cylindrical and 1D-plane geometry (SN transport with 20 groups cross sections) including reflectors

Uranium core	$\Delta k/kk' = 0.20\%$
MA core	$\Delta k/kk' = 0.27\%$

- **Axial leakage**: inter comparisons between 1D-cylindrical and 2D R-Z geometry (SN transport with 20 groups cross sections)

Uranium core	$\Delta k/kk' = 0.60\%$
MA core	$\Delta k/kk' = 0.41\%$

- **Elementary square cells**: inter comparisons between slab geometry made of square cells or hexagonal cells: $\Delta k/kk' < 0.08\%$

- **No burnable poison**: penalty on reactivity assumed to be negligible

→ Approximations are valid



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Computation time

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Computation time as a function of calculation scheme

	slab	MoC	Monte-Carlo
Computer	Linux PC	CCRT	IBM 44P
Uranium core - flux step calculation	< 2 minutes	~10 hours	~10 days ($1\sigma < 100$ pcm)
Minor actinides core - flux step calculation	< 4 minutes	>> 10 hours	~10 jours
1 cycle	< 60 minutes	> 1 mois	Not yet implemented

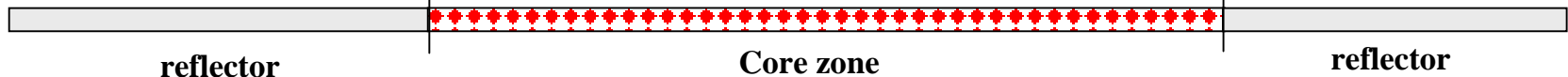
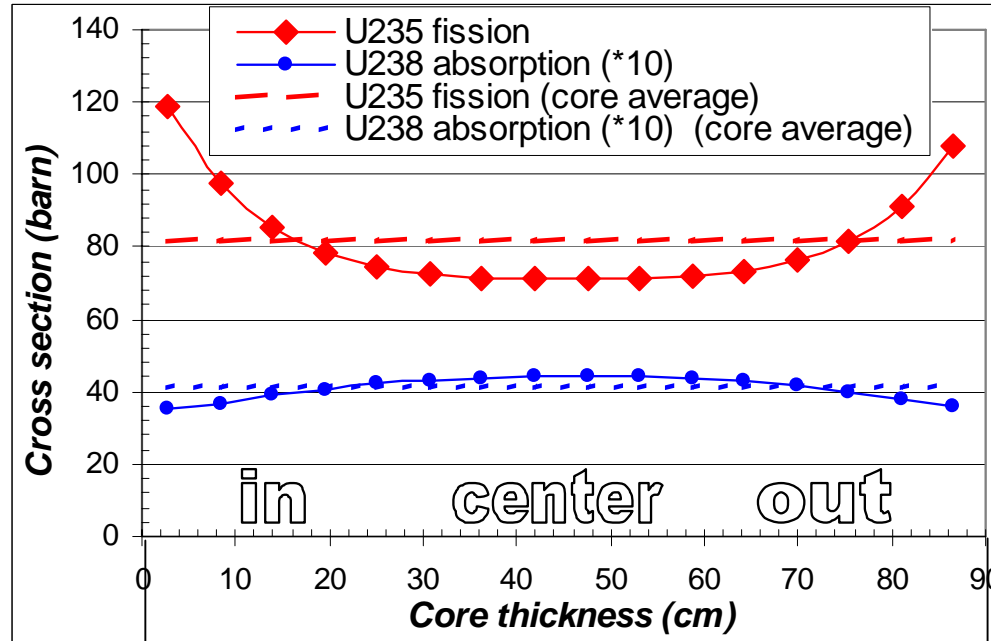


Parametric studies

Space dependant cross section

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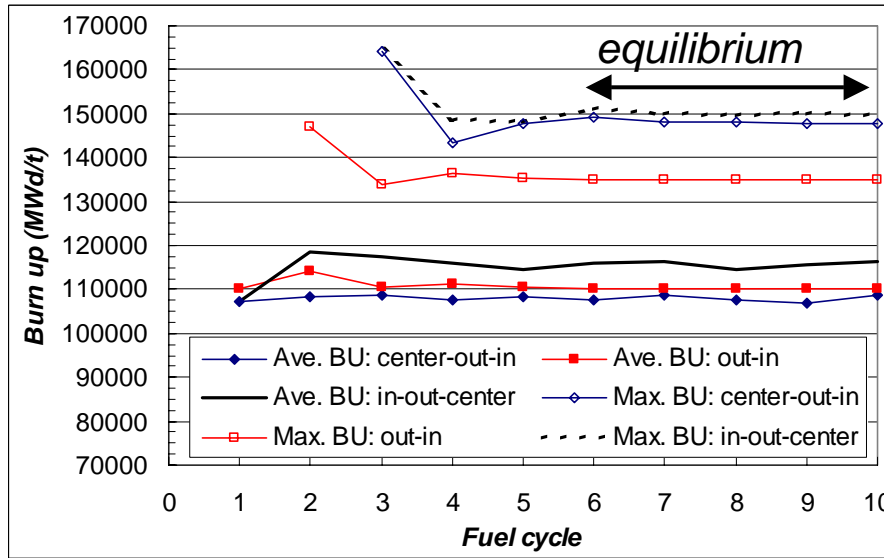
1 group cross section as a function of position in core



→ Depletion calculations are done with 1-group cross sections collapsed with space dependant neutron spectrum

Refueling and fuel management

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Burn up by batch at equilibrium

Batch 1	Batch 2	Batch 3	Total burn up (GWd/t)	Length of cycle (d)	Radial peak power
Center-out-in					
61 GWd/t	53 GWd/t	34 GWd/t	148	371	1.46
In-out-center					
79 GWd/t	40 GWd/t	31 GWd/t	150	383	2.39
Out-in					
85 GWd/t	50 GWd/t		135	518	1.92

→ Space dependant cross section and fuel loading pattern must be both taken into account to get correct fuel performances



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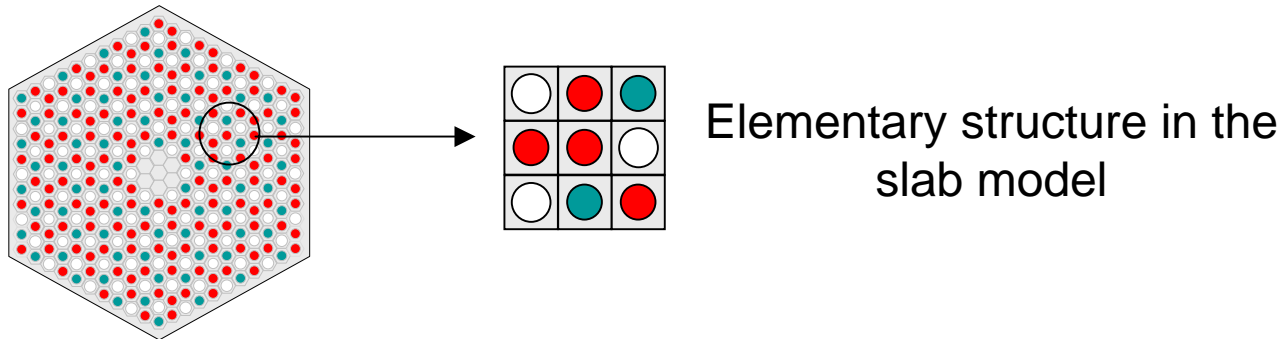
Fuel characteristics

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- Starting point: deep-burner from General Atomics & FRAMATOME
- Fuel fabrication from EPR 60GWd/t and MOX spent fuel (30 years old)



	Driver	Transmuter
Pu ⁸ / Pu ⁹ / Pu ⁰ / Pu ¹ / Pu ²	3.9/ 50.3/ 25.6/ 6.1/ 1.5/ 8.7	
Np ⁷ / Am ¹ / Am ³ / Cm ³ / Cm ⁴ / Cm ⁵ / Cm ⁶		45.6/ 32.2/ 15.3/ 0.1/ 6.0/ 0.6/ 0.1
Fuel diameter	150 μm	250 μm
Compacts per assembly	144	72



- Loss of reactivity minimized with D = 600kg and T = 200 kg in an standard annular GTMHR core

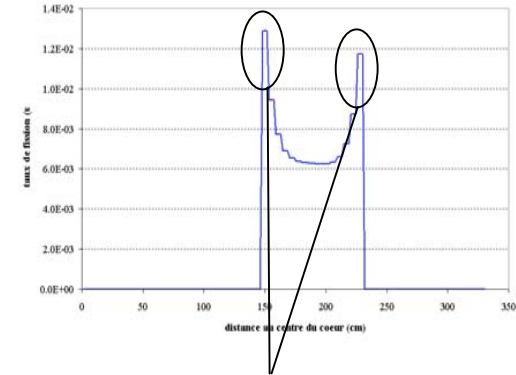
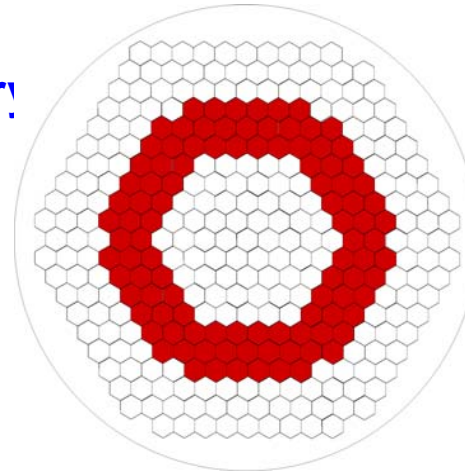
Core characteristics

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□ Standard annular geometry

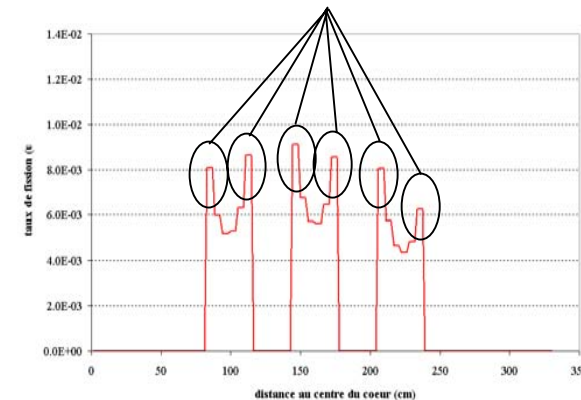
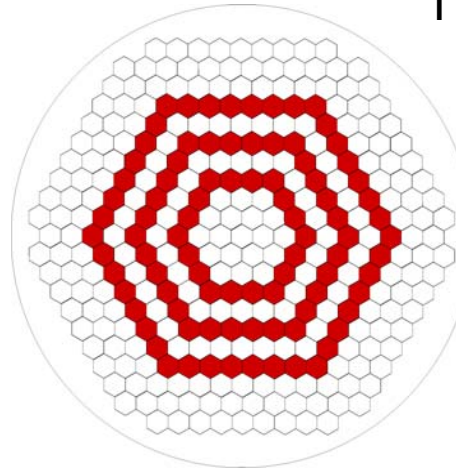
- 600 kg Driver
- 200 kg Transmuter
- 102 assembly columns
- reactivity
 - ~4500 pcm (fresh core)
 - ~2000 pcm (equilibrium)



Thermal neutron flux peaks

□ Multiple Fuel Row Core

- 600 kg Driver
- 200 kg Transmuter
- 90 assembly columns
- reactivity
 - ~17000 pcm (fresh core)
 - ~10000 pcm (equilibrium)



→ **Goal : increase the transmutation of minor actinides because of higher thermal neutron flux (including higher reactivity & lower peak power)**

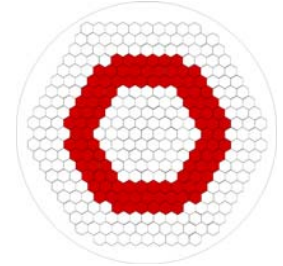
Transmutation

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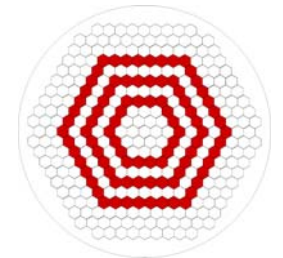
Annular core – 3*107 EFPD / 240 GWd/t

	Kg / TWhe			Kg		
	D	T	D+T	D	T	D+T
Np	0.0	-9.2	-9.2	0.0	-6.8	-6.8
Pu	-89.2	24.6	-64.6	-65.8	18.1	-47.7
Am	12.4	-21.1	-8.6	9.2	-15.5	-6.4
Cm	0.6	2.0	2.6	0.4	1.5	1.9



Multiple Fuel Row – 2*200 EFPD / 300 GWd/t

	Kg / TWhe			Kg		
	D	T	D+T	D	T	D+T
Np	0.0	-9.9	-9.9	0.0	-13.7	-13.6
Pu	-97.3	24.8	-72.5	-134.5	34.3	-100.2
Am	8.8	-21.2	-12.4	12.2	-29.4	-17.2
Cm	0.6	1.6	2.2	0.8	2.2	3.0



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Conclusions

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- The “slab” method is a simplified tool dedicated to fuel cycle studies of GT-MHR



□ Geometry description

- Simplified description of GT-MHR core (~1D) but
- Main physical aspects are taken into account :
 - Impact of graphite reflectors
 - Fuel double heterogeneity

□ Depletion calculations

- space dependant 172 groups neutron flux
 - space dependant 1-groups section for depletion calculation
- Irradiation from fresh core to equilibrium according the refueling pattern

□ Approximations

- Validation of the method with reference calculations (Monte Carlo & Method of Characteristics, benchmark)

□ Application

- Large flexibility concerning fuel, assembly or core description

□ Future work

- Application to Pebble Bed reactor ?
- Introduction of burnable poisons