Which parameters might help to predict an impact on reactivity for mixed fissile units in a storage array?

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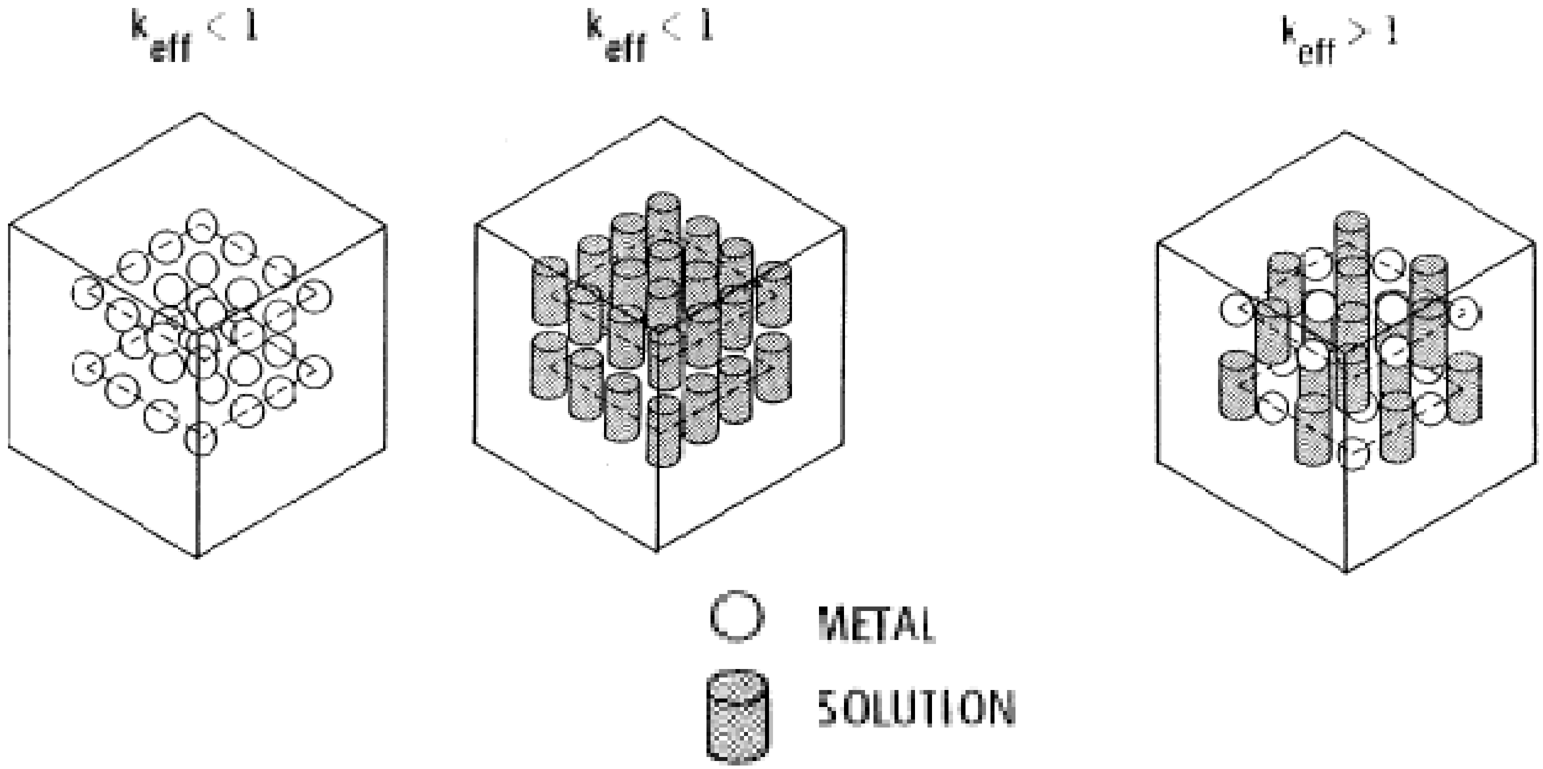
Content

- Why such a study?
- Description of the calculation model
- Parameters studied:
  - Part 1: fissile medium
  - Part 2: geometry of the containment vessel
  - Part 3: structural material

Clayton's study on anomalies of nuclear criticality (1979)



Early in the past, the mixing effect has been well known.

Main conclusion of previous studies

According to previous studies, the following parameters have an impact on reactivity of mixed array:

- Neutron spectrum,
- Shape of fissile medium,
- Interstitial moderation,
- Structural materials.

But, in most storage in facilities, the packages (or fissile units) are very different:

- The content (metal, oxide, moderated…),
- The shape of the containment vessel (safe or unsafe geometry),
- The packaging materials (neutron poison…).

➔ In such configuration, it is not possible to conclude easily and quickly on mixing effect.

Reason of this study

In calculation output (in this case APOLLO2-MORET 4 from CRISTAL V1.2), we have access to:

Keff with different estimators

ESTI.	SOURCE-CHOC	0.94961	+/-	0.00044
ESTI.	SOURCE-CORDE	0.94984	+/-	0.00052
ESTI.	SOURCE-ABSORPTION	0.95012	+/-	0.00037
ESTI.	BILAN-CHOC	0.95001	+/-	0.00037
ESTI.	BILAN-CORDE	0.95005	+/-	0.00040
ESTI.	BILAN-ABSORPTION	0.95012	+/-	0.00037

But also:

Mean energy of absorption, collision, fission in each volumes

VOLUME	% ABSORPTIONS	GROUPE MOYEN D'ABSORPTION	ENERGIE MIN DU GR. MOY. (EN MEV)	ENERGIE MAX DU GR. MOY. (EN MEV)
1	48.8686 +/- 0.0288	156.05	0.9500E-07	0.1000E-06
2	0.3978 +/- 0.0004	117.05	0.1123E-05	0.1150E-05
3	12.6778 +/- 0.0140	80.86	0.1945E-04	0.2260E-04
4	12.6761 +/- 0.0137	80.81	0.1945E-04	0.2260E-04
30	12.6959 +/- 0.0139	80.90	0.1945E-04	0.2260E-04
40	12.[illegible] +/- 0.0142	80.[illegible]5	0.1945E-04	0.2260E-04

EALF, % thermal (neutron energy up to 4 eV) flux, % thermal fission, etc

```
--> Dans tous les [illegible]
Distance parcourue (cm) / neutron = 0.76612E+03 -- % de flux thermique          = 20.151
Nb Collisions / neutron           =    73.57854 -- % de collision thermique     = 52.330
Nb Absorptions / neutron          =     0.99652 -- % d'absorption thermique     = 63.443
Nb Productions / neutron          =     0.94984 -- % de production thermique    = 35.330
Nb Fuites / neutron               =     0.00411 -- % de fuite thermique         = 82.683
                                      Lethargie moyenne   Energie correspondante (eV)
  des neutrons emis par fission       :    1.94414            0.14311E+07
  des neutrons absorbes               :   14.83510            0.36074E+01
  des neutrons induisant une fission  :   10.76591            0.21107E+03
  des neutrons qui ont fuit           :   16.98756            0.41917E+00
  de disparition des neutrons         :   14.84393            0.35757E+01
Densite de ralentissement a la coupure thermique =    0.63561
```

Is it possible to use these outputs to predict mixing effect?

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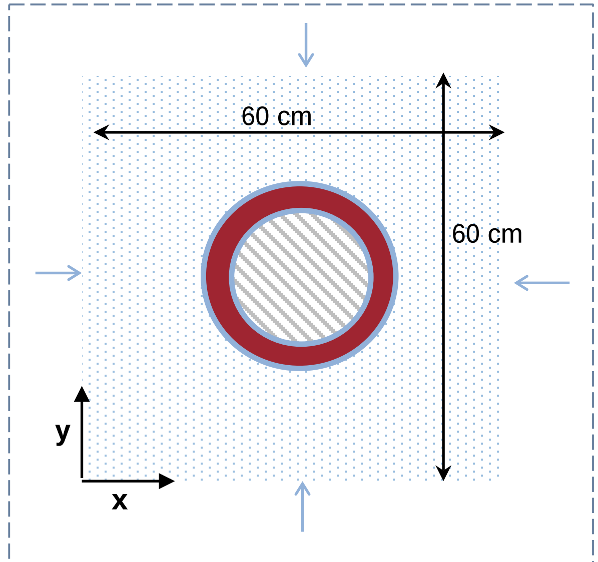
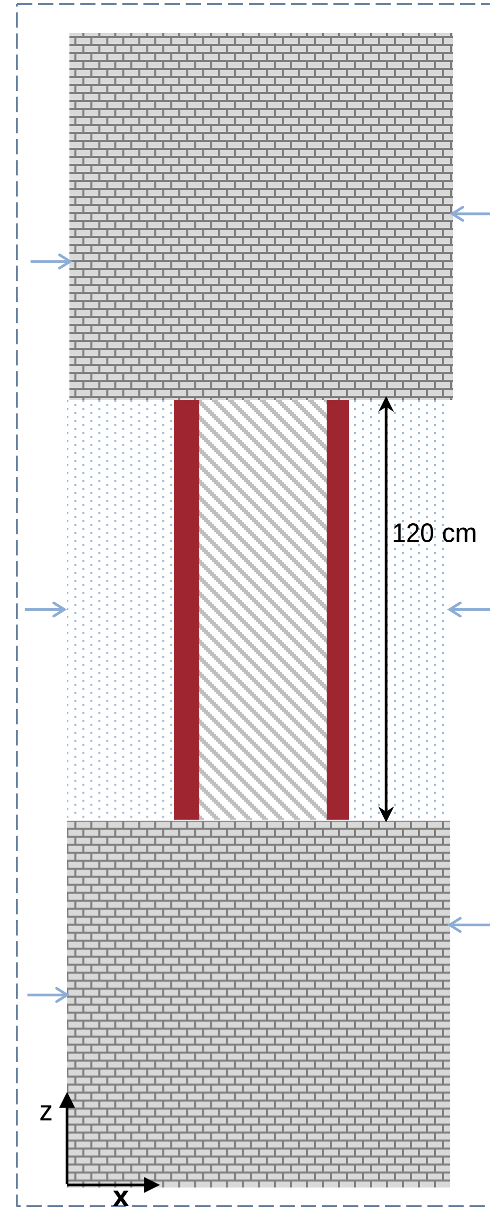
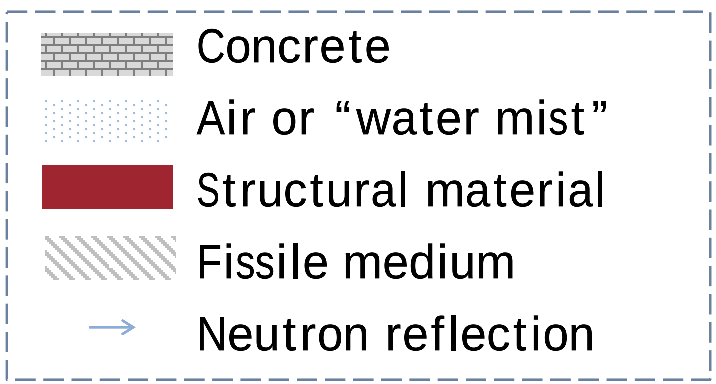
Calculation model

- Infinite planar array on 1 level
- Cylindrical shape for the containment vessel (Φ = 12 cm, H = 120 cm)
- Presence of structural material (only in part 3)
- 2 situations: either air or interstitial moderation (“mist”) between packages
- Checkerboard arrangement for mixed arrays







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Part 1: fissile medium / description of fissile media

Name	Physical form	Moderator	Isotopic composition	Mass U+Pu (g)	Configuration studied
Pu-mod	Metal	Water	100 % ^{239}Pu	461	Both
U-mod	Metal	CH_2 (d=0.96)	4 % ^{235}U	No limit	Both
UO_2-wet_A*	Oxide (d=3.5)	Water (10wt%)	26 % ^{235}U	No limit	Air
UO_2-dry_A	Oxide (d=max)	None	24 % ^{235}U	No limit	Air
UO_2-wet_IM**	Oxide (d=3.5)	Water (10wt%)	15.5 % ^{235}U	No limit	Interstitial moderation
UO_2-dry_IM	Oxide (d=max)	None	11.5 % ^{235}U	No limit	Interstitial moderation

* Air ** Interstitial Moderation

Keff for non-mixed configuration ~ 0.950

All usual penalizing hypothesis are considered

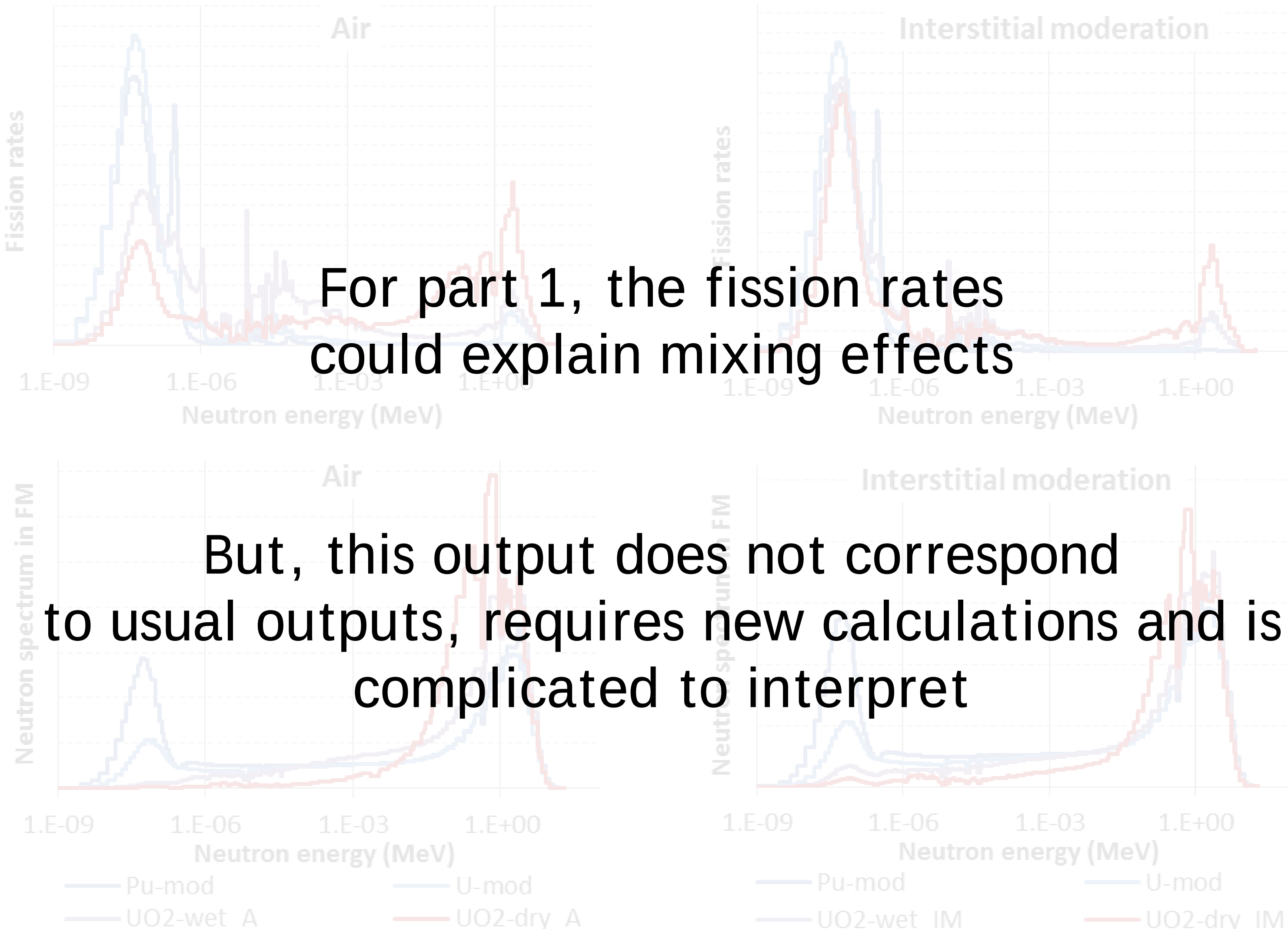
Part 1: fissile medium / results

Result = Keff_mixed_units_AB – Max (Keff_unit_A, Keff_unit_B)

Air between fissile media				
Name	**Pu-mod**	**U-mod**	**UO_2-wet_A**	**UO_2-dry_A**
Pu-mod	0	-	-	-
U-mod	0.5%	0	-	-
UO_2-wet_A	4.5%	1.4%	0	-
UO_2-dry_A	7.2%	3.1%	0.6%	0

Interstitial moderation between fissile media				
Name	**Pu-mod**	**U-mod**	**UO_2-wet_IM**	**UO_2-dry_IM**
Pu-mod	0	-	-	-
U-mod	0.5%	0	-	-
UO_2-wet_IM	1.0%	-0.6%	0	-
UO_2-dry_IM	1.0%	-0.3%	0.1%	0

Part 1: fissile medium / analysis of results



For part 1, the fission rates could explain mixing effects

But, this output does not correspond to usual outputs, requires new calculations and is complicated to interpret

Part 1: fissile medium / analysis of results

Name	EALF (eV)*	% thermal neutron in all media**	% thermal neutron in FM	% thermal fission***	Mean energy of collision in the interstitial area (eV)
Pu-mod	0.059	42%	32%	97%	1.5
U-mod	0.2	35%	20%	87%	2.7
UO_2-wet_A	8	24%	4.6%	56%	34
UO_2-dry_A	1230	20%	0.85%	30%	140
UO_2-wet_IM	0.75	40%	8.7%	77%	1.1
UO_2-dry_IM	7.4	41%	3.7%	65%	1.1

* Energy corresponding to Average Lethargy of neutrons causing Fission.
** Fraction of neutron with an energy lower than 4 eV in the whole model.
*** Fraction of fission due to neutron with an energy lower than 4 eV.

2 indicators seem to predict mixing effect for part 1:

- **% thermal neutron in all media**
- **Mean energy of collision in the interstitial area**

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Part 2: geometry / description of fissile media

Name	Diameter (cm)	Height (cm)	Isotopic composition	Mass U+Pu (g)	Configuration studied
Pu-mod_D8.5_A	8.5	120	100 % ^{239}Pu	1614	Air
Pu-mod_D12	12	120	100 % ^{239}Pu	461	Both
Pu-mod_H60	17	60	100 % ^{239}Pu	373	Both
Pu-mod_D17	17	120	50 % ^{239}Pu 50 % ^{nat}U	883	Both
Pu-mod_D8.5_IM	8.5	120	100 % ^{239}Pu	1396	Interstitial moderation
UO_2-dry_D12_A	12	120	24 % ^{235}U	No limit	Air
UO_2-dry_H60_A	17	60	23.8 % ^{235}U		
UO_2-dry_D17_A	17	120	13.2 % ^{235}U		
UO_2-dry_D24_A	24	120	9.1 % ^{235}U		
UO_2-dry_D12_IM	12	120	11.5 % ^{235}U		Interstitial moderation
UO_2-dry_H60_IM	17	60	18.5 % ^{235}U		
UO_2-dry_D17_IM	17	120	5 % ^{235}U		
UO_2-dry_D24_IM	24	120	3.2 % ^{235}U		

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Part 2: geometry / results

Air between fissile media									
Name		Pu-mod				UO_2-dry			
		D8.5	D12	H60	D17	D12	H60	D17	D24
Pu-mod	D8.5	0							
	D12	1.1%	0						
	H60	1.7%	0.2%	0					
	D17	2%	0.1%	0.1%	0				
UO_2-dry	D12	2.6%	7.2%	7.4%	9%	0			
	H60	2%	5.6%	5.9%	7.1%	0.1%	0		
	D17	4.2%	9.1%	9.2%	11.3%	0.3%	0.5%	0	
	D24	5.4%	10.4%	10.4%	12.7%	0.8%	1%	0.2%	0

High effect for mixed array of moderated and dry units.

No/limited mixing effect for array with only moderated or dry units

➔ **Mixing effect only due to geometry is not observed.**

Part 2: geometry / results

Interstitial moderation between fissile media									
Name		Pu-mod				UO_2-dry			
		D8.5	D12	H60	D17	D12	H60	D17	D24
Pu-mod	D8.5	0							
	D12	0.5%	0						
	H60	1%	0.2%	0					
	D17	1.6%	0.1%	0.1%	0				
UO_2-dry	D12	-0.9%	1%	2%	3.9%	0			
	H60	0.1%	2.8%	3.4%	5%	0%	0		
	D17	-0.5%	0.7%	1.4%	3.3%	0%	-0.1%	0	
	D24	-0.1%	0.7%	1.2%	2%	0.1%	-0.2%	-0.2%	0

Contrary to part 1, there is still a mixing effect in some cases when interstitial moderation is considered between units.

Part 2: geometry / analysis of results

Name	EALF (eV)	% thermal flux in all media	% thermal flux in FM	% thermal fission	Mean energy of collision in the interstitial area (eV)
Pu-mod_D8.5_A	0.24	31%	11%	88%	5.3
Pu-mod_D12	0.059	42%	32%	97%	1.5
Pu-mod_H60	0.054	45%	36%	97%	1.4
Pu-mod_D17	0.046	49%	45%	97%	1.1
Pu-mod_D8.5_IM	0.18	40%	13%	90%	1.8
UO_2-dry_D12_A	1230	20%	0.85%	30%	140
UO_2-dry_H60_A	1850	22%	0.73%	25%	410
UO_2-dry_D17_A	1560	18%	0.88%	21%	530
UO_2-dry_D24_A	3310	17%	0.72%	16%	1000
UO_2-dry_D12_IM	7.5	41%	3.7%	65%	1.1
UO_2-dry_H60_IM	68	38%	1.7%	50%	1.2
UO_2-dry_D17_IM	5.9	42%	5%	67%	1.0
UO_2-dry_D24_IM	8.3	41%	5.2%	66%	1.0

Based on these spectrum indicators, it is possible to classify units which explain the presence or absence of mixing effect.

But, indicators of part 1 do not explain part 2 results.

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Part 3: structural material / fissile media

Name	Structural material	Isotopic composition	Mass U+Pu (g)	Configuration studied
PuO_2-mod-No	-	100 % ^{239}Pu	461	Air
PuO_2-mod-steel	Stainless steel (0.5 cm)	100 % ^{239}Pu	604	
PuO_2-mod-poison	Colemanite concrete (2 cm)	100 % ^{239}Pu	13911	
PuO_2-mod-CH_2	Polyethylene (2 cm)	100 % ^{239}Pu	631	
UO_2-dry-No_A	-	24 % ^{235}U	No limit	Air
UO_2-dry-steel_A	Stainless steel	30 % ^{235}U		
UO_2-dry -poison	Colemanite concrete (2 cm)	61 % ^{235}U		Air
UO_2-dry -CH_2	Polyethylene (2 cm)	19.25 % ^{235}U		
UO_2-dry-No_IM	-	11.5 % ^{235}U		Interstitial moderation
UO_2-dry-steel_IM	Stainless steel (0.5 cm)	26.25 % ^{235}U		

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Part 3: structural material / results

Air between fissile media									
Name		PuO_2-mod				UO_2-dry			
		No	Steel	Poison	CH_2	No_A	Steel_A	Poison	CH_2
PuO_2-mod	No	0							
	Steel	-0.6%	0						
	Poison	-5.6%	-3.6%	0					
	CH_2	1.7%	0.8%	-4.3%	0				
UO_2-dry	No_A	7.1%	6.6%	1.3%	14%	0			
	Steel_A	3.9%	4.1%	0.8%	9.3%	0.1%	0		
	Poison	-7.4%	-4.7%	0.2%	-5%	-0.4%	-0.8%	0	
	CH_2	0.6%	0%	-4.9%	0.5%	9.5%	5.5%	-6.8%	0

Interstitial moderation between fissile media								
Name	PuO_2-mod				UO_2-dry			
	No	Steel	Poison	CH_2	No_IM	Steel_IM	Poison	CH_2
UO_2-dry_No_IM	1%	0.6%	-2.9%	9.4%	0	-0.5%	-5.6%	3.6%
UO_2-dry_Steel_IM	2.3%	2.6%	-0.3%	8.2%	-0.5%	0	-2.3%	4.1%

Steel has a limited effect compared to no material.

The presence of neutron poison leads to a negative mixing effect.

Hydrogenated material may lead to a high positive mixing effect.

Part 3: structural material / analysis of results

Name	EALF (eV)	% thermal flux in all media	% thermal flux in FM	% thermal fission	Mean energy of collision in the interstitial area (eV)
PuO_2-mod-No	0.059	42%	32%	97%	1.5
PuO_2-mod-steel	0.072	36%	27%	97%	2.6
PuO_2-mod-poison	9.2	20%	4.4%	56%	81
PuO_2-mod-CH_2	0.059	56%	31%	97%	0.93
UO_2-dry-No_A	1240	20%	0.86%	30%	140
UO_2-dry-steel_A	4250	21%	0.59%	23%	68
UO_2-dry -poison	98200	19%	0.07%	1.6%	210
UO_2-dry -CH_2	32.7	47%	2.5%	47%	1.2
UO_2-dry-No_IM	7.5	41%	3.7%	65%	1.1
UO_2-dry-steel_IM	232	33%	1.3%	41%	1.7

Few differences in spectra indicators between steel and no material.

No spectrum indicators could predict alone a mixing effect.

When air is present between fissile units, indicators of part 1 seem good predictors of "mixing effects"

Conclusion

Mixing effect only due to geometry is not observed.

Interstitial moderation between fissile media does not nullify mixing effect.

Based on a comparison of several spectrum indicators, it seems possible to predict mixing effect.

Conclusion

But, no spectrum indicators, present in the usual output results of CRISTAL V1.2, could predict alone the mixing effect.

Another spectrum parameter which provides indication on the energy of neutron in the interstitial area could be tested.

Such indicators are not easily accessible in usual results from APOLLO2-MORET 4 (CRISTAL V1.2 package) but are directly accessible in results files of new APOLLO2-MORET 5 (CRISTAL V2 package).

Thank you for your attention

Question?