Sample of EDF-R&D 2009-2012 core design studies on :

Heterogeneous sodium-cooled fast reactors with low sodium void effect.

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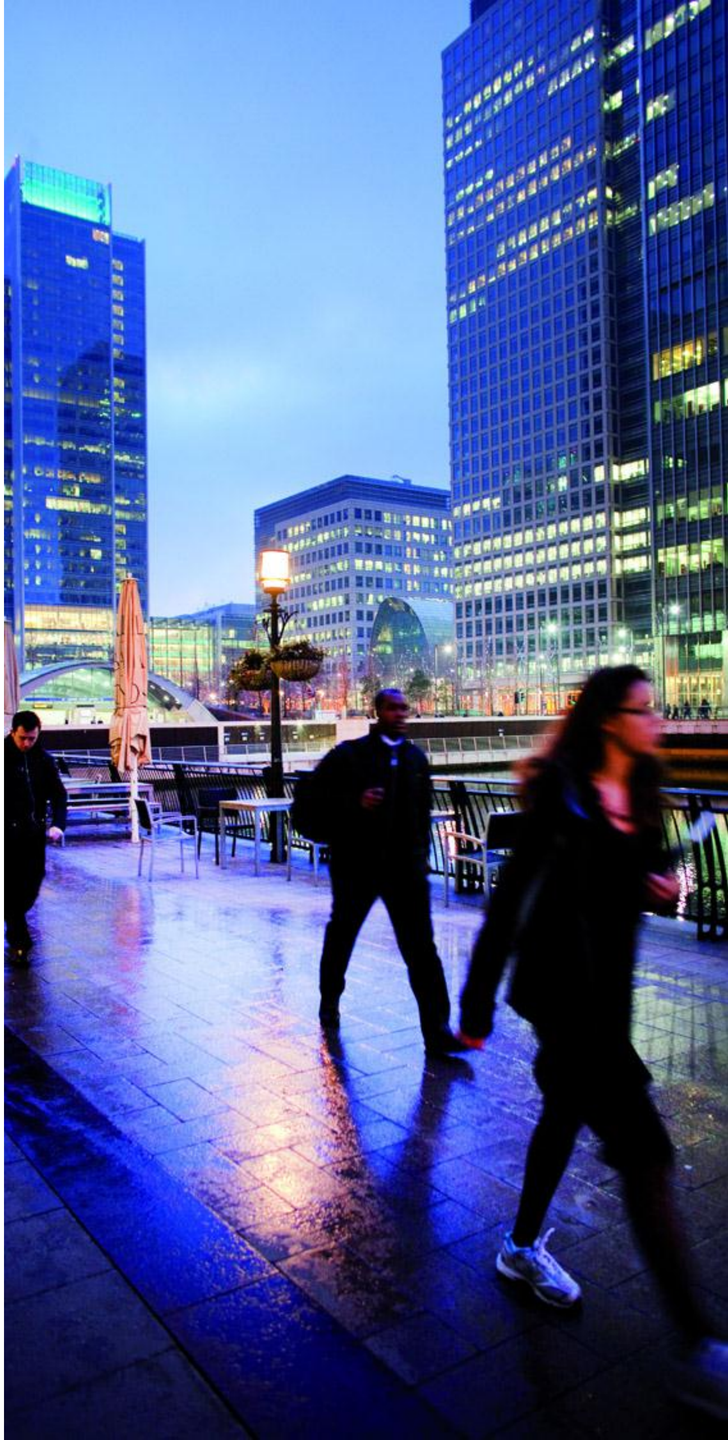
EDF-R&D

FR13 conference, Paris, 2013, 7-4 March, paper CN-199-310



Outline

Introduction

1. Axial heterogeneity : CEA CFV analysis
2. Radial heterogeneities : parametric studies
3. Finer calculations on 600 MWe designs

Conclusion

Context – EDF R&D in the French Framework

- **French partners AREVA/CEA/EDF are working together within an R&D program.**
  - → Framework for technical exchanges
  - → General SFR design development
  - → Support to the ASTRID technological demonstrator conception and safety assessment, led by CEA

- **The scale of EDF-R&D core studies program is smaller than the CEA program but aims at covering a relatively wide range of topics.**
  - → Core neutronics and design options analysis
  - → Unprotected transient behavior
  - → Severe accident analysis

- **This presentation focuses on core neutronic design studies, supported by some transient behavior results. There is two objectives :**
  - → To draw a quick overview of design activities at EDF R&D (including formerly presented results.)
  - → To give some additionnal insight on radially heterogeneous cores.

Introduction – core design activities

- **Conception work aims at improving the intrinsic behavior of the core in case of**
  - → Unprotected Loss Of Flow transients (ULOF/ULOSSP) – *main focus on sodium void worth* $\Delta\rho_{Na}$
  - → Unprotected Control Rod Withdrawal (UCRW) – *main focus on burn-up reactivity swing* $\Delta\rho_{c}$
  - → These two parameters are often antagonists

- **Former and present international works show the advantage of heterogeneous concepts.**
  - → *H.S. Khalil et al., Evaluation of Liquid-Metal Reactor Design Options for Reduction of Sodium Void Worth, ANL, Nuclear Science and Engiineering, 109, 221-226, 03/04/1991*
  - → *F.Varaine et al., Pre-conceptual design studies of ASTRID core, paper 12173, ICAPP 2012*

- **In this paper, two options will be investigated**
  - → Axial heterogeneities : fissile plate inside the fissile zone (cf. CEA CFV core)
  - → Radial heterogeneities : fissile height shifts and fertile S/A rings.

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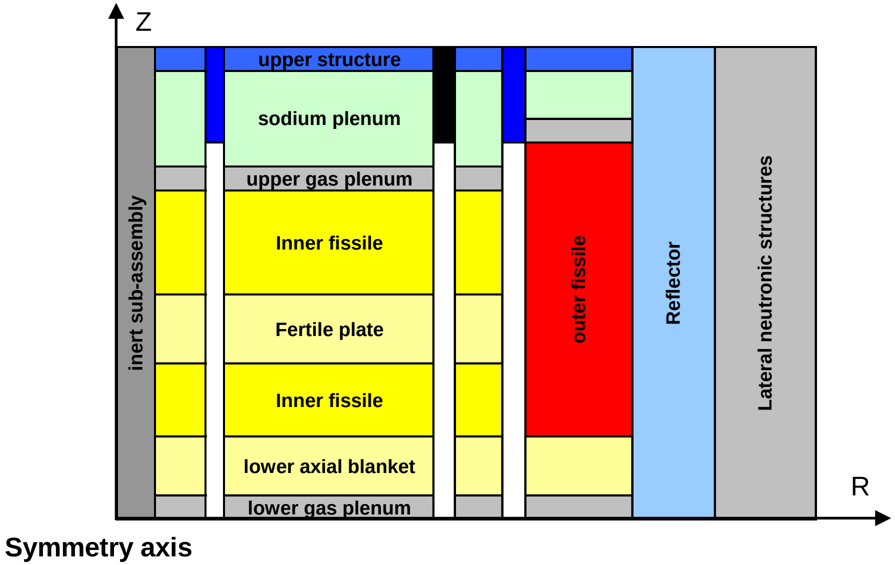
I. Analysis of the CEA CFV design

S.Poumerouly et al., Optimization of a heterogeneous fast breeder reactor core with improved behaviour during unprotected transients, proceedings of ICAPP 2012, Chicago; June 24-28, paper 12214.

Core description



Main parameters for this analysis :

- *Fissile Volume*
- *Radius of the Inner fissile zone*
- *Average Fissile Height*
- *Fissile Height Shift (« Diabolo »)*
- *Fertile plate width and location*
- ***Fissile fraction***
- ***Steel fraction***
- ***Sodium fraction***

Use of the EDF-R&D SDDS methodology

→ Systematic scan of a wide design space : simplified evaluation of ~ 2 millions core variants (neutronic performances, and rough thermal and thermo-hydraulical properties)

→ A quasi-static estimator TULOF, representative of the sodium outlet temperature at the end of a ULOF (under monophasic assumption), is used for **qualitative core comparison.**

→ Special focus : TULOF and burn-up reactivity swing

I. Analysis of the CEA CFV design

▪ Evaluation of global parameters change and Pareto Front (TULOF, $\Delta\rho_c$)

- The Pareto Front is the subset of core designs for which no characteristic can be improved without degrading another

- To be on the Pareto Front, the following designs options are required :

  No fissile height shift

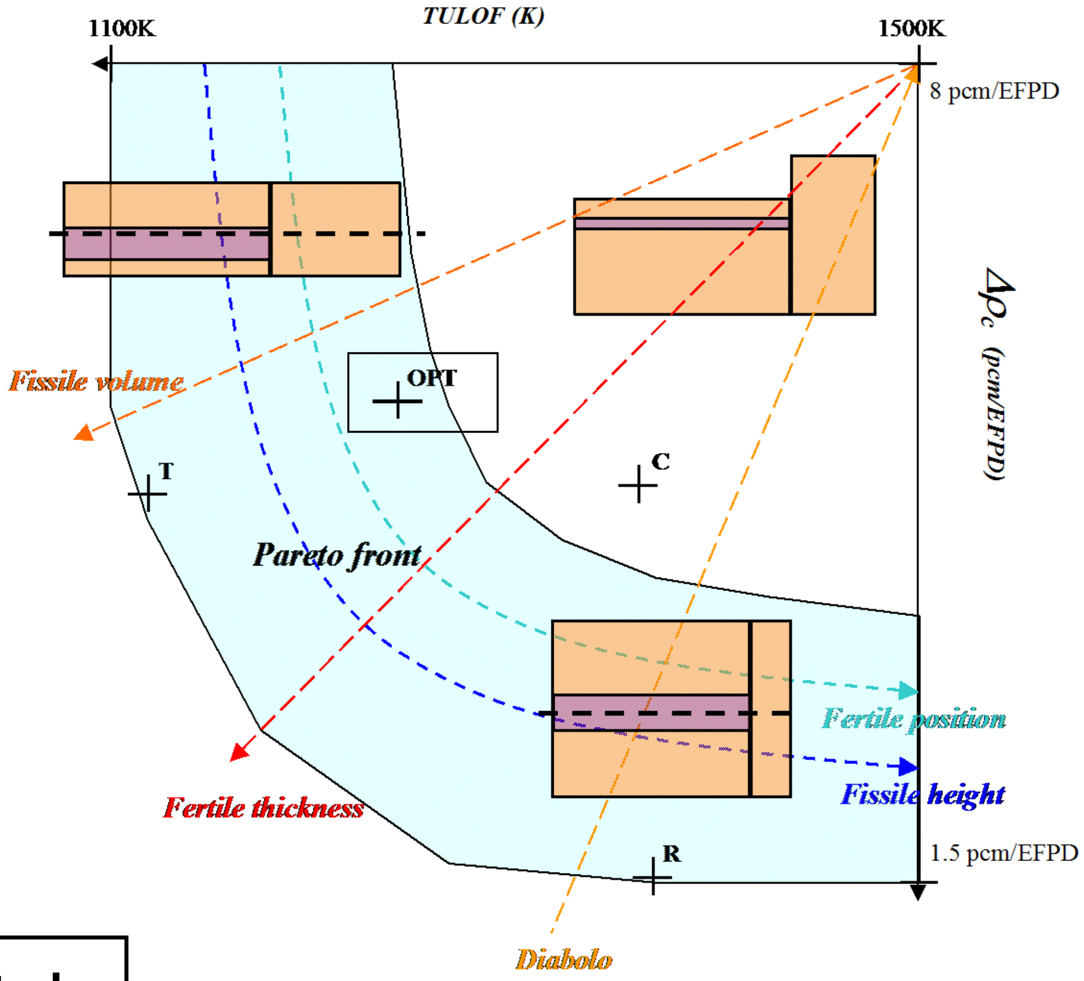
  Thick fertile plate

  High fissile volume

- To choose the trade-off between TULOF and $\Delta\rho_{c,}$ the following designs options should be changed :

  Fissile Height

  Fertile Position



The OPT core was selected

The absence of fissile height shift for optimum cores is related to control rod parking position.

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II. Radial heterogeneities : parametric studies

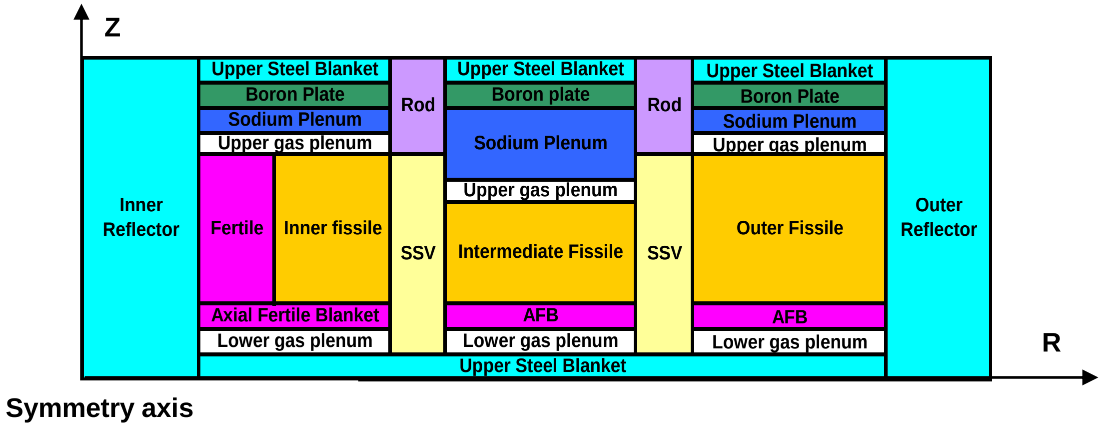
- **A first radially heterogeneous design was issued by EDF-R&D in 2010**

D.Schmitt et al., Optimization of a heterogeneous fast breeder reactor core with improved behaviour during unprotected transients, proceedings of ICAPP 2011, Nice.

→ 1200 MWe.

→ No fissile material at the center of the core

→ Sodium plenum, boron plate and fissile height shift



annular/diabolo core		
burn-up reactivity swing	pcm (10^5 dk/k)	~ 1500
EOC sodium void worth (total)	$	- 1 $

- **This design was used as a basis for low void core safety assessment.**

S.Massara et al., Behavior of an heterogeneous annular FBR core during an Unprotected Loss of Flow accident : analysis of the primary phase with the SAS-SFR code, ICAPP 2012 (EDF/KIT-INR)

II. Radial heterogeneities : parametric studies

- **The annular/diabolo core can still be improved !**

  → Safety studies have shown that sodium boiling and core degradation could not be excluded.

  → The annular shape leads to a large fissile radius (negative impact on economics/secondary system activation)

- **Two alternative optimization paths :**

  1 → Reduction of the core size and complexity

  2 → Further improvement of the safety parameters of the core ($\Delta\rho_{Na}$)

- **Exploratory parametric studies :**

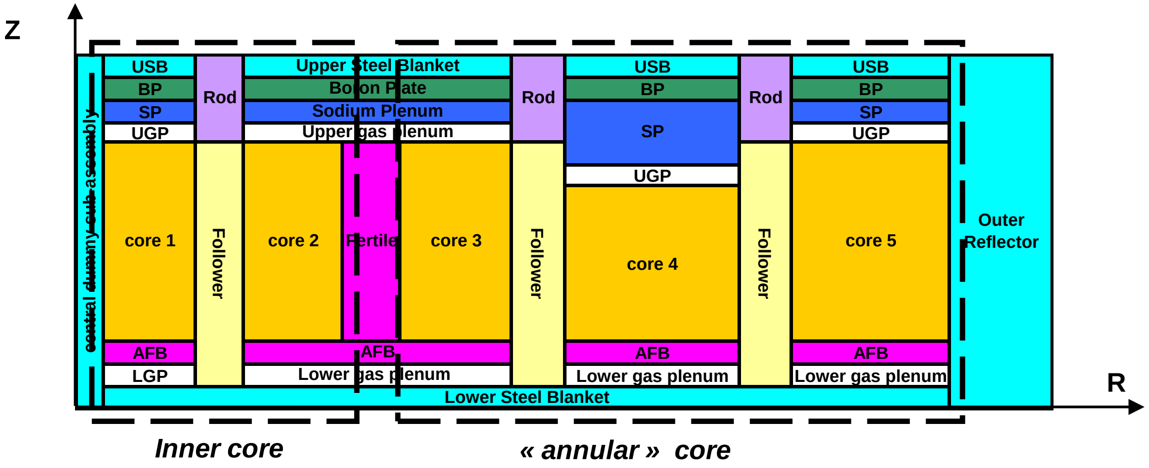
  → Homogeneous 33 gr. cell calculation / S4 RZ transport core calculation

  → Fissile height shift / annular shape / Fertile S/A rings introduction

II. Radial heterogeneities : parametric studies

→ Optimization path 1 (fissile radius reduction via inner hole filling)

▪ « Filled » annular core : RADDAR concept.



▪ Comparison with former option.

			Case 1 **annular/diabolo core**	**Case 6** **annular core filled with a small core**
outer core radius		cm	245	228
Pu content	core 1	%vol.	19.65	17.5
	core 2	%vol.	18.35	17.5
	core 3	%vol.	19.65	17.5
	core 4	%vol.	/	18.1
	core 5	%vol.	/	21.7
maximum power density		W/cm3	326	323
burn-up reactivity swing		pcm	1424	939
EOC sodium void worth (total)		$	-0.99	-0.18

Still a complex design :

→ 3 plutonium content zones

→ 2 axial height

Good safety features :

→ Near zero $\Delta\rho_{Na}$

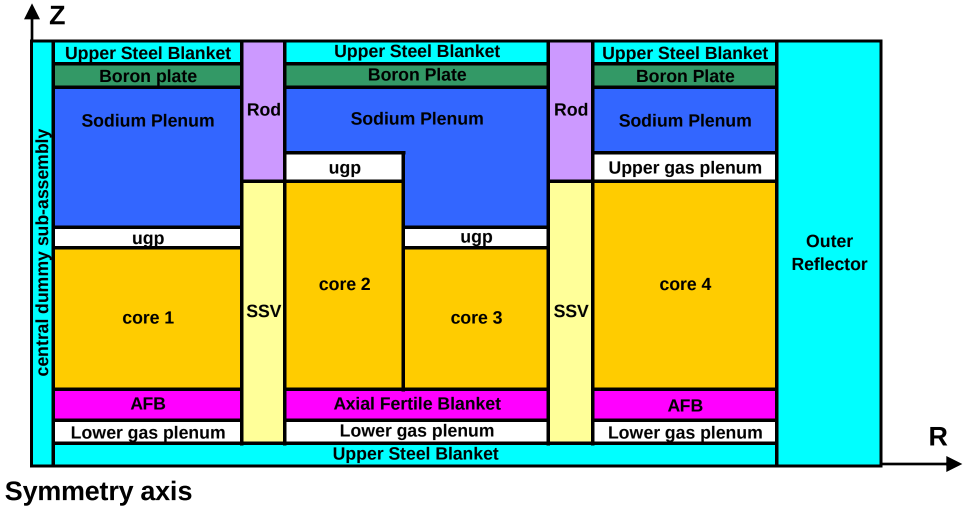
→ Moderate $\Delta\rho_c$

II. Radial heterogeneities : parametric studies

- **Introduction of additionnal S/A height shifts (without annular shape).**

Standard core with 2 diabolos

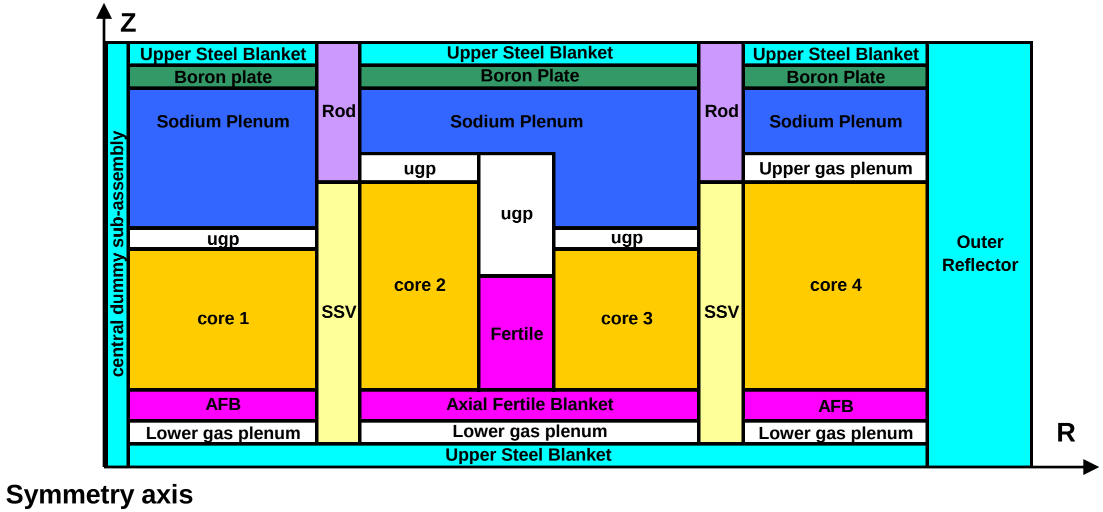
(Case 4)



- **Addition of Fertile S/A Rings**

Standard core with 2 diabolos and fertile S/As

(Case 5)



II. Radial heterogeneities : parametric studies

Comparison of Case 1, 4, 5 (main features)

			Case 1	Case 4	Case 5
			annular/diabolo core	**standard core with 2 diabolos**	**standard core with 2 diabolos and fertile ring**
outer core radius		cm	245	220	231
Pu content	core 1	%vol.	19.65	15.5	16.4
	core 2	%vol.	18.35	15.5	18
	core 3	%vol.	19.65	17.5	19.6
	core 4	%vol.	/	19	21.1
	core 5	%vol.	/	/	/
maximum power density		W/cm3	326	325	319
burn-up reactivity swing		pcm	1424	839	1103
EOC sodium void worth (total)		$	-0.99	-0.32	-1.84

Standard core with two S/A height shift

→ Lower fissile radius,

→ The sodium void worth is higher but the reactivity swing strongly decreases,

Addition of a fertile ring

→ Slight degradation of the fissile radius,

→ Very interesting set of safety characteristics.

Conclusion on standard cores with additionnal radial heterogeneities

→ Very interesting characteristics ($\Delta\rho_c$ ~ 1100 pcm / $\Delta\rho_{Na}$ ~ - 1,8 $)

→ **Too complex designs ? Where should the line be drawn ?**

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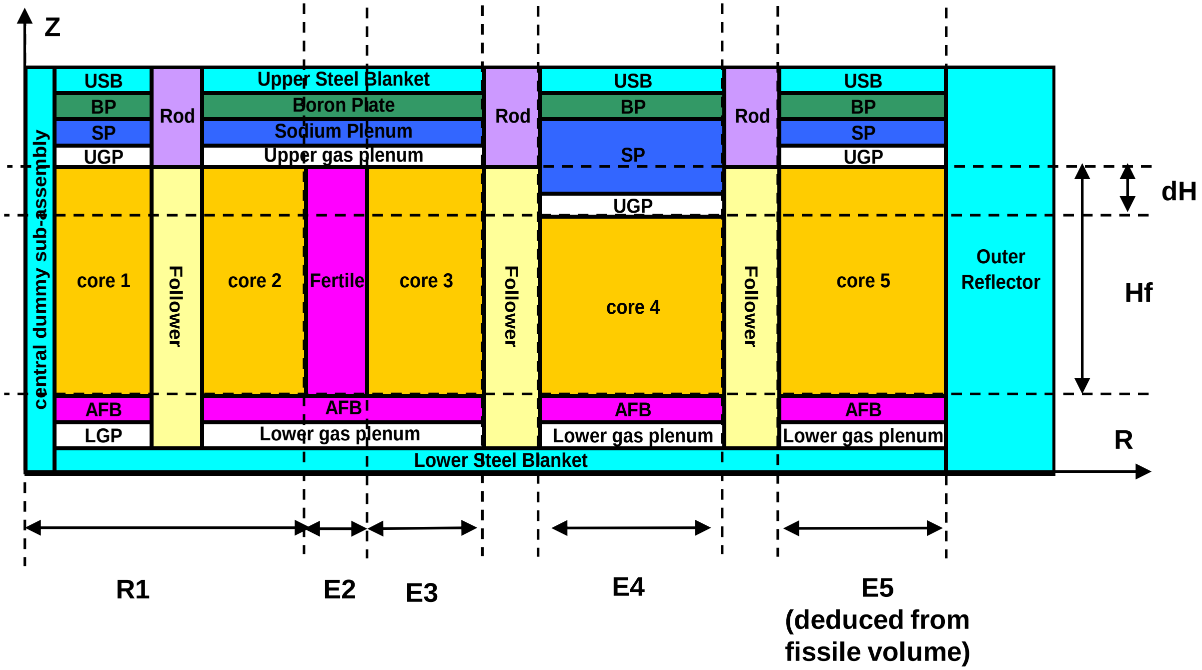
III. Finer calculations on 600 MWe designs

- **From RADDAR 1200 MWe concept to 600 MWe.**
- **Use of the SDDS methodology**



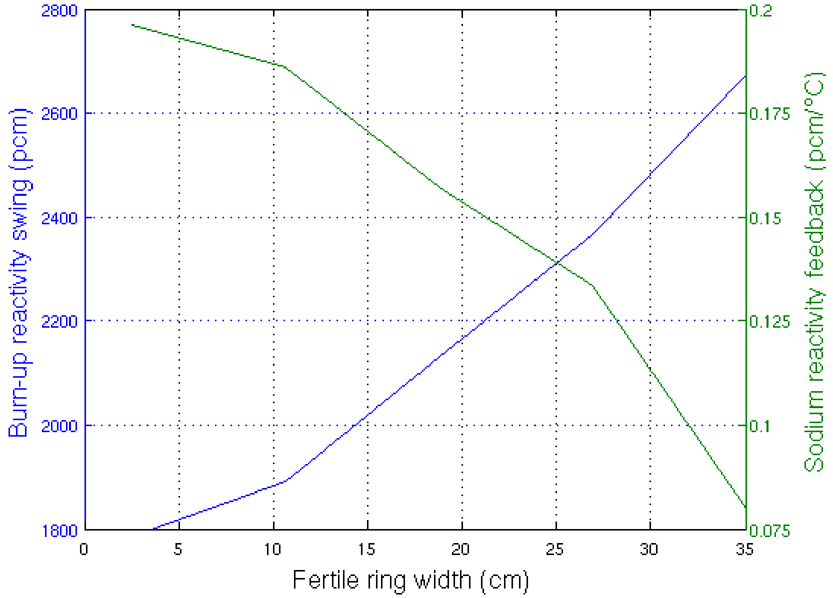
Main parameters for this analysis :

- *Fissile Volume*
- *Radius of the Inner fissile zone*
- ***Fertile ring width***
- *Width of core 3 / core 4*
- *Average Fissile Height*
- *Fissile Height Shift*
- ***Fissile fraction***
- ***Steel fraction***
- ***Sodium fraction***

- **Scan of a wide set of core variants (~ millions of cores variant), using a database of ~ 6000 simplified ERANOS calculations.**

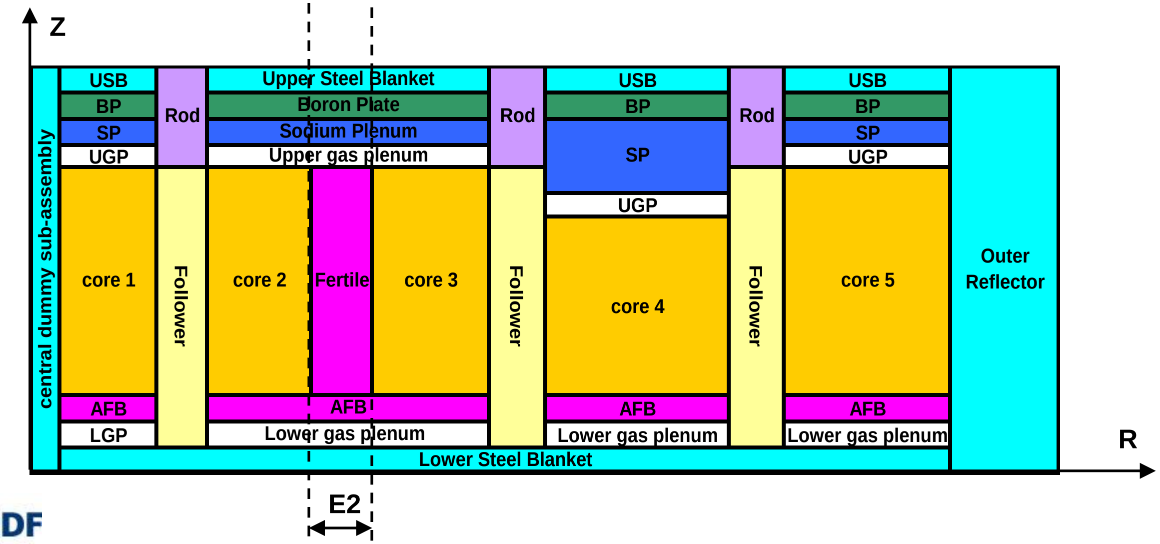
III. Finer calculations on 600 MWe designs

- **Focus on the impact of the fertile S/A ring(s)**



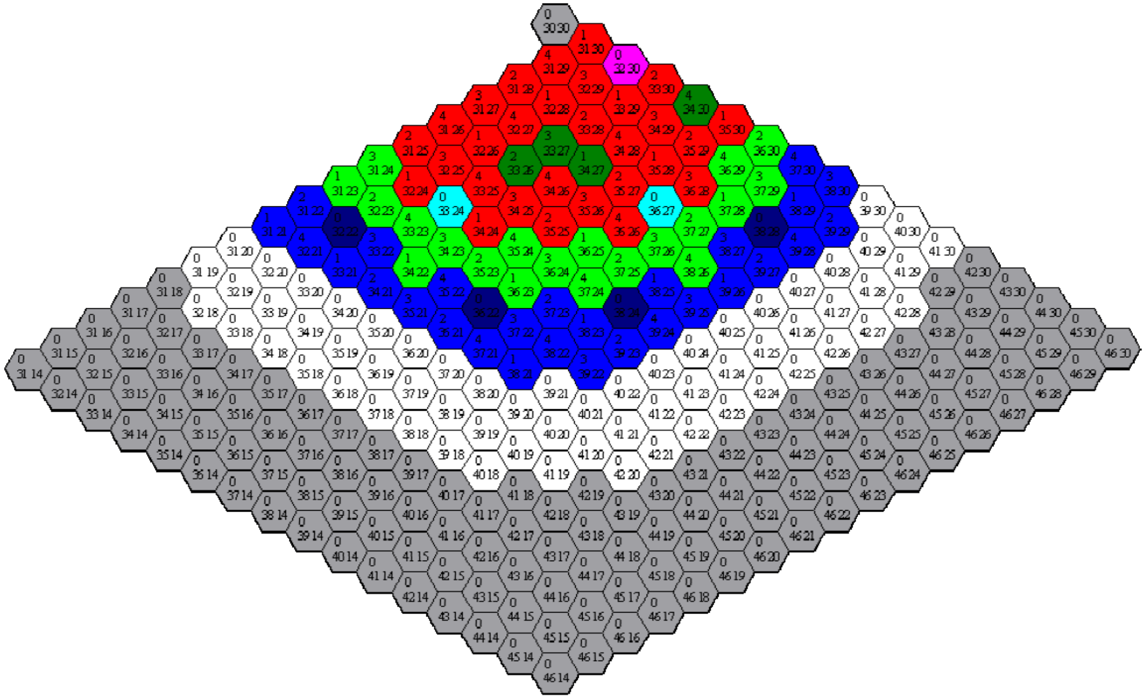
→ On average, a wider fertile ring reduces the sodium reactivity feedback, but increases the burn-up reactivity swing.

→ The burn-up reactivity swing is already high so thin fertile zones were selected. (on the Pareto Front under constraints – among which a maximum outer radius)



III. Finer calculations on 600 MWe designs

- **Selection of a core design on the Pareto Front (« RD1 » core)**



🟥 **Inner core 17.5% - high height**

🟩 **Middle core 20.2 % - low height**

🟦 **Outer core 23 % - high height**

🟩 **Fertile - high height**

🟪 **Control Rods (inner)**

🟦 **Shutdown rods**

🟦 **Control Rods (outer)**

- **Very few fertile S/A on the selected design.**
- **This core was evaluated with a finer neutronic scheme (3D Hexagonal ERANOS calculations with reloading scheme)**

III. Finer calculations on 600 MWe designs

- Design selection and comparison to the OPT design (CFV like core)

		RD1	OPT core
Mean burn-up	GWj/(hmt fissile zones)	101	92
Mean power density (EOEC)	W/cm3	256	231
Max power density (EOEC)	W/cm3	333	305
Outer fissile radius	cm	163	168
Sodium reactivity feedback	pcm/°C	0.175	0.106
Control rod expansion feedback	pcm/°C	-0.415	-0.645
EOC Total void worth (fertile plate/ring voided)	$	0.21	0
EOC Total void worth (fertile not ring voided)	$	-0.16	/
Doppler constant			
fissile (from 1500K to 453K)	pcm	-752	-550
fertile (from 900K to 453K)	pcm	-166	-359
Beta effective	pcm	365	367
Burn-up reactivity swing	pcm	1806	1824

The RD1 core shows slighly lower safety chacteristics (Sodium, rod expansion).

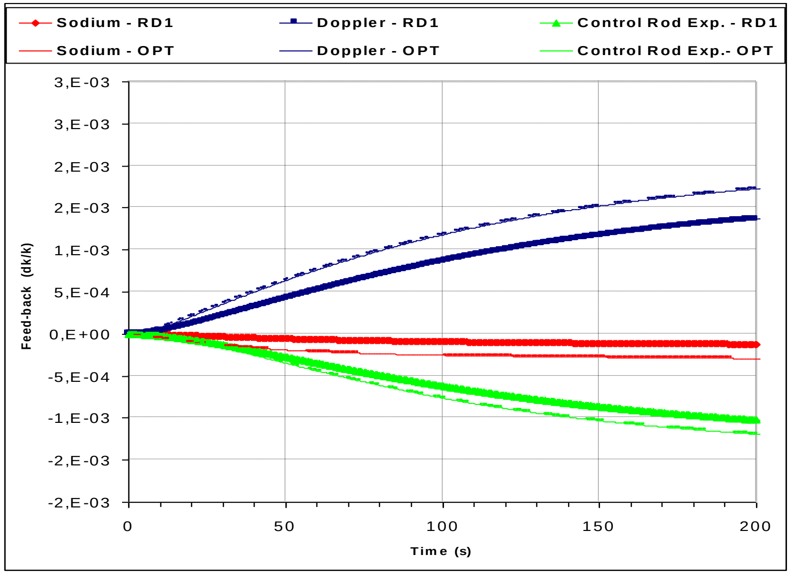
The shift to a precise neutronic scheme is responsible for +150 pcm on the burn-up reactivity swing.

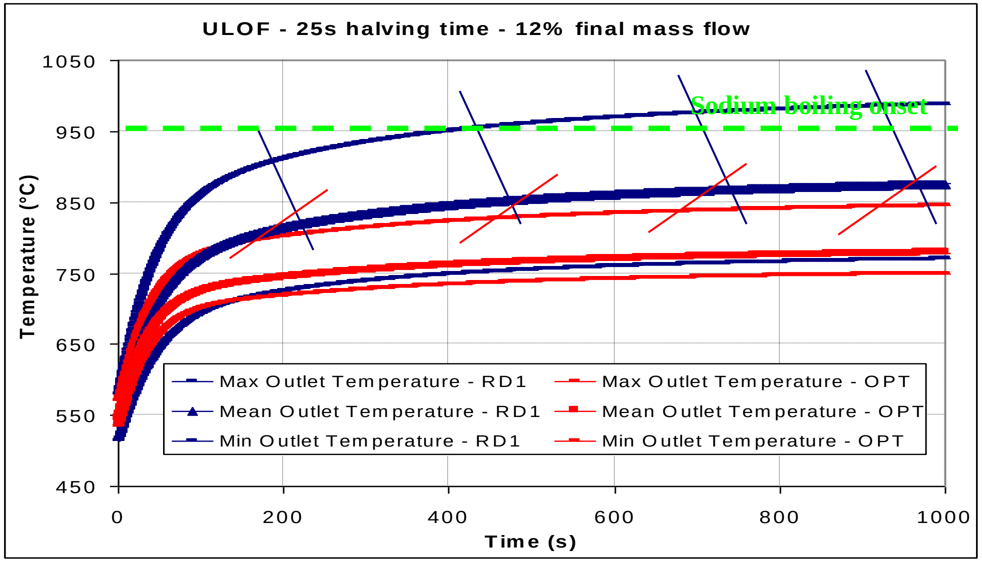
Anyway, the RD1 core still has good overall features.

III. Finer calculations on 600 MWe designs

▪ Transient evaluation with the MAT5DYN core.

G.Darmet et al., Dynamical analysis of innovative core designs facing unprotected transients with the MAT5 DYN code, proceedings of ICAPP 2012, Chicago; June 24-28, paper 12245.





→ The OPT core has a stronger rod expansion feedback coefficient,

→ Doppler and sodium effects are more favorable as well,

→ The discrepancy on sodium outlet temperature is about 100°C
(partly caused by rod expansion feedback).

→ The RD1 core is not as good as the optimized OPT core, but still has good features.

→ Other radial heterogeneous options could be studied (standard 2 diabolos ? …)

Conclusion

- **The use of axial or radial heterogeneities allows to reach negative global sodium void worth :**

  → 600 MWe radially heterogeneous cores can be designed (no annular shape, reasonable core size). But the constraint on the fissile radius might be the reason why current performances are not a breakthrough…

  → Other interesting configuration exists (standard 2 diabolos, etc.)

- **Complexity versus intrinsic safety : where should the line be drawn ?**

  → On 1200 MWe cores, it was shown that very good features can be reached. But very complex designs are needed.

- **Core design studies are still going on …**

  → The precision of global optimization method will be improved and new safety indicators added.

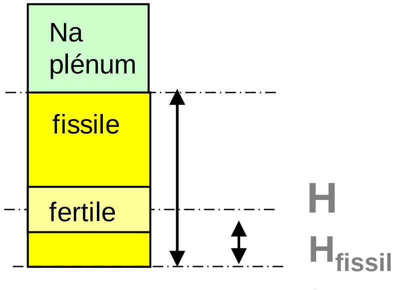
  → Optimization studies will be led on the CEA CFV design.

  → (Little) time should still be spent on alternative design options.

Additionnal slide

I. Analysis of the CEA CFV design

- **Evaluation of individual parameters change : *example of the fertile plate location.***



→ The parameter used is the relative location inside inner core.

Location = $H / H_{fissile}$

→ A quasi-static estimator TULOF, representative of the sodium temperature at the end of a ULOF, is used for **qualitative core comparison.**

- **Relative locations from 0.3 *(minimum TULOF)* to 0.5 *(minimum $\Delta\rho_c$)* are optimum.**