XFR R&D Needs:

X: SFR, LFR, GFR

Topic 1

- **Topic 1: Core and Fuels**
- Topic 2: Design and Thermal-hydraulics
- Topic 3: Materials and coolant technology
- Topic 4: Energy Conversion Systems
- Topic 5: Safety and Instrumentation

prepared by:
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G. Grasso (ENEA),

Goals of the exercise

- First: to provide input for potential future Euratom projects (draft of the work program 2016-17 includes “Safety of Gen IV reactors”).
- Second: to provide input for the ESNII+ WP6 deliverables:
  - D6.2.1-1. R&D needs for ASTRID core safety (PSI, M42)
  - D6.2.2-1. R&D needs for ALLEGRO core safety (MTA EK, M42)
  - D6.2.3-1. R&D needs for ALFRED core safety (ENEA, M42)
  - D6.2.4-1. Cross cutting and codes-related R&D and experimental needs (ENEA, M42)

Draft of the Euratom work program 2016-17 (extract)

NFRP 2 – 2016-2017: Safety of Generation IV reactors

Objective: A high level of nuclear safety is paramount in all Generation IV concepts, but designs currently under development, both in Europe and worldwide, will need to demonstrate compliance with evolving safety requirements.

In this context, a significant shift in safety is expected from new reactor coolants that may demonstrate *more favourable behaviour in the case of severe accidents*.

Safety is also strongly relying on *operational experience feedback* most of which was gained in the EU with commercially operated reactors representing a strong basis on which further safety improvements can be implemented in confidence.

The objective of this activity is to ascertain that the increased safety of Generation IV reactors can be demonstrated.

Draft of the Euratom work program 2016-17 (extract)

NFRP 2 – 2016-2017: Safety of Generation IV reactors

Scope: This activity is focused on the assessment of the safety improvements of most proven types of Generation IV reactors, such as

- *<u>core parameter optimization and reactivity control</u>*,
- *<u>reliability of automatic shut-down systems</u>*,
- diversified systems of residual power removal without common mode failure,
- demonstrable natural circulation of cooling fluids in ultimate procedures,
- *<u>advantages for safety of metallic fuel</u>*,
- improved strategy of confinement modes and molten core catching,
- in-service inspection of safety related components and leak detection of primary coolant.

These safety improvements will need to be endorsed by the EU scientific community in view of building–up the main corpus of EU technical standards for Generation IV to be used as the reference to demonstrate compliance with the amended Euratom Safety Directive.

How?

Formulate important tasks indicating the “physics”, the relevant reactor type(s); operating conditions; needs in re-evaluation of available experiments / calculational tools or developing the new ones.

“Reactor type”

- SFR (ASTRID)
- LFR (ALFRED)
- GFR (ALLEGRO)

“R&D needs”

- Experimental (available and new measurements)
- Analytical (available and new calculational tools)

“Operation conditions”

- Normal operation (Norm)
- Design-basis accidents (DBA)
- Design-extension conditions (DEC)
  - “Characterization of Fuel-Coolant-Interaction”, “Corium fragmentation and dispersion”, “Core catcher design” are discussed in PS5 “Safety and instrumentation”

At the end we can try to conclude on priorities and find synergies.

“Physics”

- Core neutronics: static (NS) or kinetics (NK)
  - “Design of control rods and safety systems” will be also addressed in PS2 “Reactor design and thermohydraulics”
  - “Reactivity control” and “Core monitoring” is addressed in PS5 “Safety and instrumentation”
- Core thermal hydraulics (TH)
  - “Thermohydraulics of core and fuel assemblies” will be addressed in PS2 “Reactor design and thermohydraulics” (for normal operation?)
  - “Core monitoring” is addressed in PS5 “Safety and instrumentation”
- Core thermal mechanics (TM)
  - Mechanical behaviour is addressed in PS3 “Materials and coolant technology” but not from viewpoint of impact on reactivity
- Structural materials behaviour (SM)
  - Addressed in PS3 “Materials and coolant technology”
- Fuel behaviour (FB)

NS	NK	TH	TM	SM	FB	SFR	LFR	GFR	Norm	DBA	DEC	Exp.	Code
X	X	X	X		X	X	?	?	X	X		X	X

Task: Validation of codes by re-analysing fast reactor experiments: static and unprotected transients

Subtasks:

- List of data available
- Core specifications: Phenix, SPX, EBR-II, FFTF, BFS, MASURCA, …
  - Validation of static codes – data and code to code
- MOX base irradiation
- Transients: Phenix-EOL-NC, SPX start up, EBR-II ULOF, ...
  - Validation of transient codes

NS	NK	TH	TM	SM	FB	SFR	LFR	GFR	Norm	DBA	DEC	Exp.	Code
X	X	X	X	X	X	X	X	X	X	X	?	X	X

Task: Thermal-mechanical reactivity feedbacks in fast reactors

Subtasks:

- Modeling of deformations of reactor structures (fuels, clads, rod bundles, grids, wrappers, SAs, core restraint structures, diagrid, strongback, vessel, CR drivelines, …) coupled to thermal hydraulics (to predict temperatures and thermal expansions) and neutron kinetics (especially impacted by fuel/coolant/clad/absorber differential expansions).
- Validation versus available experiments (Phenix, SPX, …)

NS	NK	TH	TM	SM	FB	SFR	LFR	GFR	Norm	DBA	DEC	Exp.	Code
	X	X	X		X	X				X		X	X

Task: SFR core behaviour in ULOF before the core degradation

Subtasks:

- Modeling of sodium boiling in rod bundle and open plenum
- Modeling of neutronics for high coolant density gradients
- Modeling of thermal mechanical reactivity feedbacks
- Modeling of fuel behaviour
- Validation needed
- Development of new models/codes needed
- New experiments needed: ?

NS	NK	TH	TM	SM	FB	SFR	LFR	GFR	Norm	DBA	DEC	Exp.	Code
	X	X		X		X	X	X		X		X	X

Task: Third independent passive shutdown system

Subtasks:

- Comparative study of different solutions
  - Hydraulic rods
  - Two-fluid systems
- Development of new models/codes needed
- New experiments needed

NS	NK	TH	TM	SM	FB	SFR	LFR	GFR	Norm	DBA	DEC	Exp.	Code
X		X	?		?	X	X	X	X			?	X

Task: High-fidelity modeling of fast spectrum cores

Subtasks:

- Coupling of Computational Fluid Dynamics and Monte Carlo neutron transport
- Core thermal mechanics ?
- Fuel behaviour ?
- Validation

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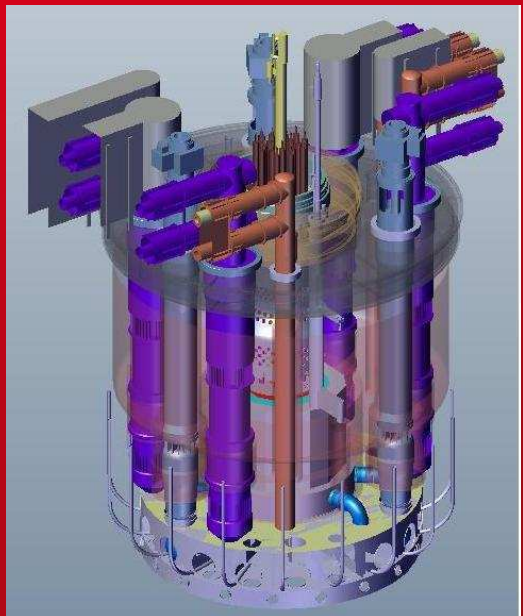

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DEN/CAD/DER/CPA

ESNII
European Sustainable Nuclear Industrial Initiative

SFR R&D Needs:

Topic 1: Core and Fuel

BRUSSELS, MARCH 18th, 2015

Main priorities for ASTRID Topic 1

1. Validation of the simulation tools for the core :
   - Neutronics
   - Fuel behavior
   - Core mechanics
   - Thermal-hydraulics
   - Severe accidents

2. Measurement techniques :
   - Irradiated fuels
   - Irradiated materials

3. Irradiation (analytical type) in MTR and post-irradiation examination
   - Fuel (U, Pu)O_2
   - Innovative absorbent materials
   - Protection materials

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Simulation tools for the core

- Neutronics to design the core, to check the linear power criteria, the safety criteria, to determine the feedback coefficients …
- Fuel behavior to design the fuel element and the fuel sub-assemblies
- Core mechanics to design fuel sub-assemblies, to check the RAMSES criteria, to assess the core compactness
- Thermal-hydraulics to design the core ie. to optimize the flow distribution, to check the clad temperature criteria, to determine the hex-can temperature
- Severe accidents to simulate the core degradation scenarios, primary and secondary phases and corium relocation phenomena

➔ Needs concern the validation of the tools :
- Benchmarks
- Comparison with reference tools
- Comparison with experimental measurements

Fuels and Materials

- Development of measurements techniques to obtain some measures on the properties of materials already irradiated “Trésor Phénix”:

  - Irradiated spent fuel: thermal and mechanical properties,

  - Irradiated B_4C : thermal properties and release/retention (helium, tritium).

Fuels and Materials

- Separate effect irradiations in MTR followed by post-irradiation examinations, in support of the simulation

    - Representative annular fuel (U, Pu)O_2, at the very beginning of irradiation, that could be manufactured in a European laboratory,

        - In support of the validation of the model of gap closure | fracturing, relocation of the fuel at the beginning of irradiation,

        - With reduced pellet-clad gap to support the validation of the simulation of the PCMI (Pellet Clad Mechanical Interaction) phenomenon

Fuels and Materials

- Separate effect irradiations in MTR followed by post-irradiation examinations, in support of the simulation

  - Innovative absorbent materials to acquire, in particular, thermal properties at the irradiated state (HfB_2, TiB_2... compared to the B_4C in reference),

  - Shielding materials (boron steel), in order to know its evolution under irradiation, as well as those of its properties,

  - Behavior under irradiation of the constituents of the Electro-Magnet; measurement of magnetic properties on different materials of interest :
    - effect of temperature and Φ*t,
    - measurement on irradiated materials.

LFR R&D needs

Topic 1: Core and fuel

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ESNII biannual conference

Brusselles, 17-19 March 2014

LFR: Need 1

NS	NK	TH	TM	SM	FB
	X	*X*	*X*		

Norm	DBA	DEC
	X	

Exp.	Code
X	*(V)*

Task: Prediction of temperatures distribution and hot spots localization during Unprotected Loss Of Flow situations

Subtasks:

- Assessment of power distribution and hot spots localization (partly in preparation)
- Assessment of reactivity coefficients
- Assessment of cladding temperature distribution and hot spots localization (ongoing)

- Validation of existing models/codes needed/ongoing
- Nuclear experiments in temperature needed

LFR: Need 2

NS	NK	TH	TM	SM	FB
	X	*X*	*X*		*X*

Norm	DBA	DEC
	X	

Exp.	Code
X	*X*

Task: Prediction of temperatures distribution and hot spots localization during Unprotected Transient Of Power situations

Subtasks:

- Assessment of power distribution and hot spots localization (partly in preparation)
- Assessment of reactivity coefficients
- Assessment of fuel temperature distribution and hot spots localization

- Validation of existing models/codes needed
- Nuclear experiments in temperature needed

LFR: Need 3

NS	NK	TH	TM	SM	FB
	X	X	X	X	

Norm	DBA	DEC
	X	

Exp.	Code
X	X

Task: Prediction of temperatures distribution and hot spots localization during Unprotected Loss Of Heat Sink situations

Subtasks:

- Assessment of reactivity coefficients and validation of neutronic codes
- Assessment of vessel temperature distribution (ongoing)
- Assessment of passive DHR systems performances

- Development and Validation of existing models/codes needed (ongoing)
- Nuclear experiments in temperature needed
- Qualification experiments of DHR systems needed (planned)

LFR: Need 4

NS	NK	TH	TM	SM	FB
		X	*X*		

Norm	DBA	DEC
	X	

Exp.	Code
X	*X*

Task: Anticipation of cladding degradation during Flow Blockage situations

Subtasks:

- Assessment of flow blockage development
- Assessment of detectability of flow blockage (planned)
- Assessment of cladding temperatures evolution

- Development and validation of models/codes needed (ongoing)
- Experiments in representative conditions needed

LFR: Need 5

NS	NK	TH	TM	SM	FB
		X		X	

Norm	DBA	DEC
	X	

Exp.	Code
X	X

Task: Prediction of sloshing effect on core compaction during earthquake

Subtasks:

- Assessment of lead sloshing dynamics
- Assessment of deformations under combined earthquake and sloshing actions

- Development and validation of models/codes needed
- Representative experiments needed

LFR: Need 6

NS	NK	TH	TM	SM	FB
X	*X*		*X*		*X*

Norm	DBA	DEC
X	*X*	*?*

Exp.	Code
X	*X*

Task: Assessment of closed fuel cycle option for LFR systems (perspective)

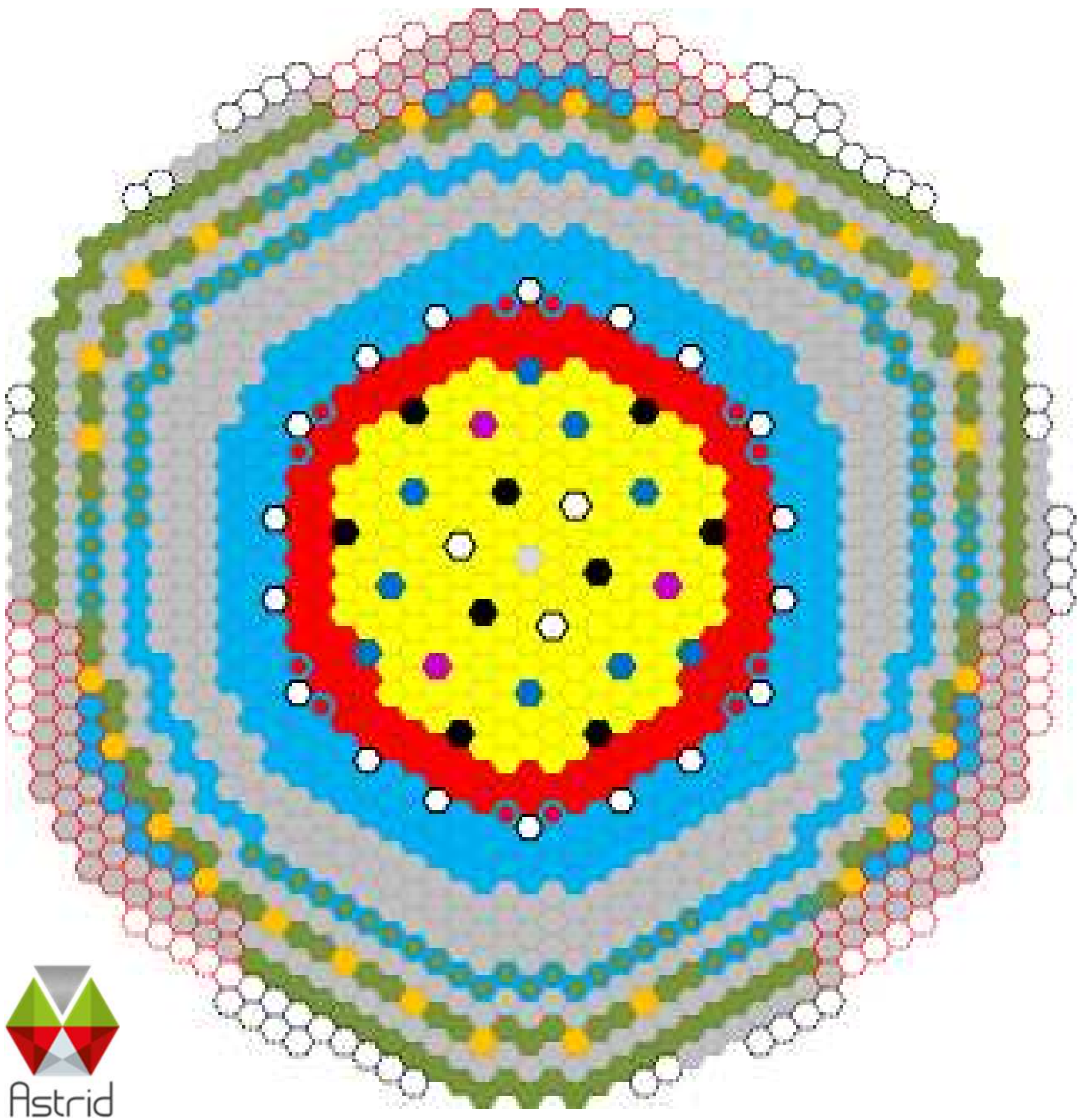
Subtasks:

- Qualification of MA-bearing (equilibrium concentration) fuels
- Assessment of thermomechanics of innovative fuel pins (targeting higher BU)
- Demonstration of «adiabatic» operation of LFR
- (Development and qualification of homogeneous reprocessing techniques)

- Development and validation of models for MA-bearing fuel behavior needed
- Experiments for characterization and qualification of innovative pins/cores needed
- (industrialization of homogeneous reprocessing methods)

Backup slides

The core CFV



- 1 Dummy S/A
- 180 Inner core fuel S/As
- 108 Outer core fuel S/As
- 9 RBC S/As
- 9 RBD S/As
- 344 MgO S/As
- 12 positions for fuel S/As
- 72 positions for internal storage

- 550 B_4C S/As
- 3 DCS-P-H S/As
- 21 DCS-M-TT S/As
- 144 Internal storage
- 28 Debugging positions
- 74 available positions
- positions without sodium flow

Fuel Sub-Assemblies (S/A)

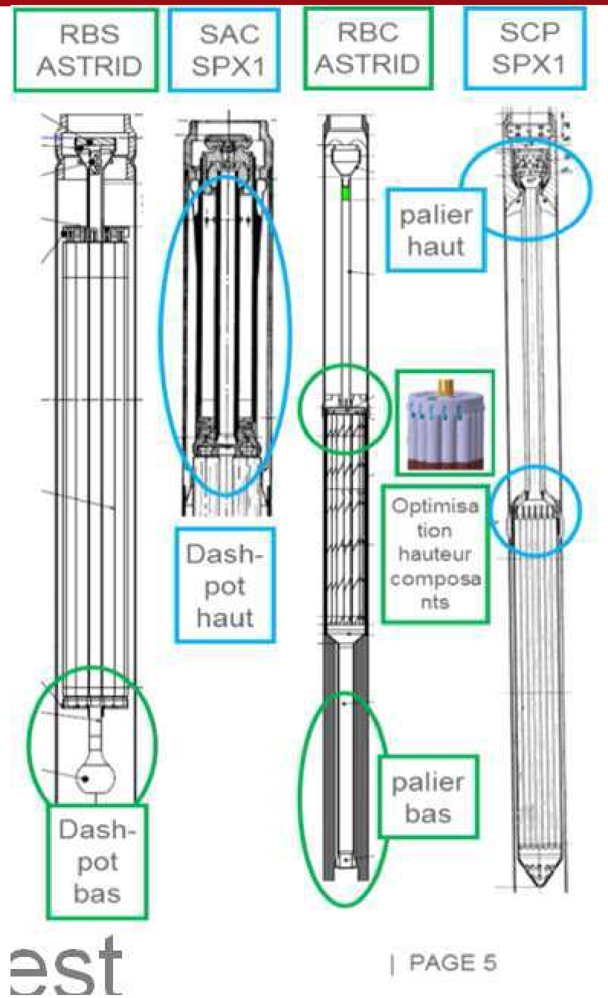
UPuO2 fuel, AIM1 cladding, EM10 hex-can
Specificities : inner fertile blanket bundle geometry, sodium plenum, upper neutron shielding, ..
Need for Experimental Qualification
Exams of Phénix irradiated pins (Pavix-8)
New irradiation of a prototype fuel S/A
->feasibility of tests in BN600 + Joyo/Monju

Main/Diversified Control Rod S/As

B4C absorber + shroud, sodium bonded,
Exp. Qualification: hydraulic mock-up (water test)
+ performance enhancement,
Exams of Phénix irradiated absorber rods
New irradiation of a prototype absorber rod

Complementary/Passive Shutdown S/A

Hydraulic activation, mock-up of the working zone, water test

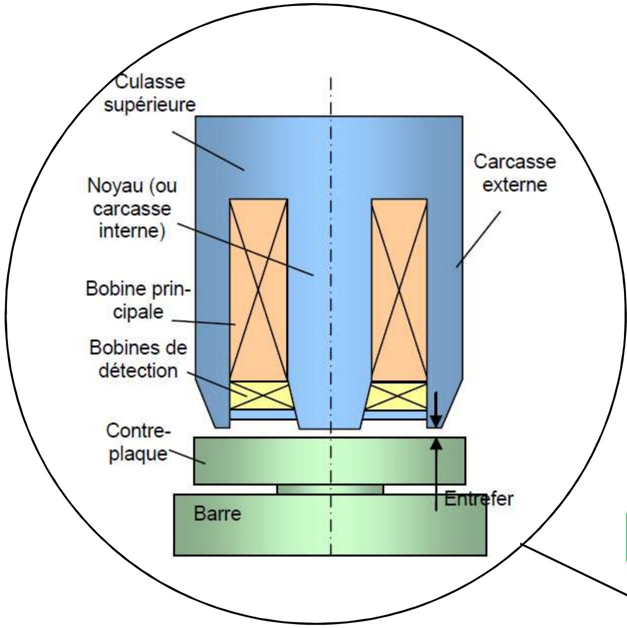


Electro-Magnet, key component of the diversified control rod

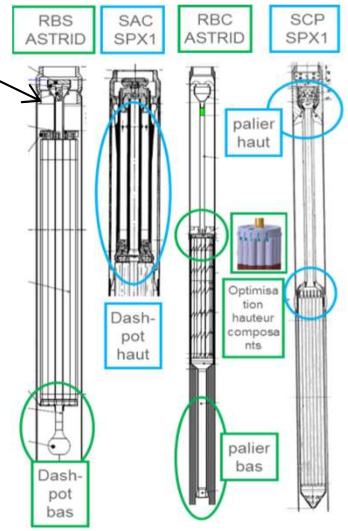
ASTRID need

- Analytical program on mechanical and magnetic properties of EM materials and components (iron, austenitic, …) and their evolution in reactor (effect of ageing, low irradiation, magnetic field)
  - Out of Pile test
  - Sample irradiation in MTR
  - Out of Pile test on irradiated materials

- Realization of a prototype, test in a sodium loop then in prototypic conditions (ie in a sodium cooled FR)

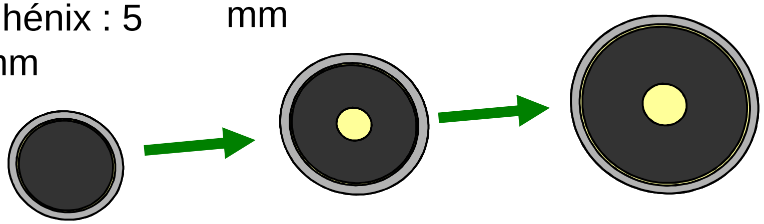


EM is a key component of the diversified control rod system = connection between the absorber rod (in core) and the mechanism (upper structure)



Core design options for ASTRID

Phénix : 5 mm | Super Phénix : 7 mm | Astrid : 9 mm



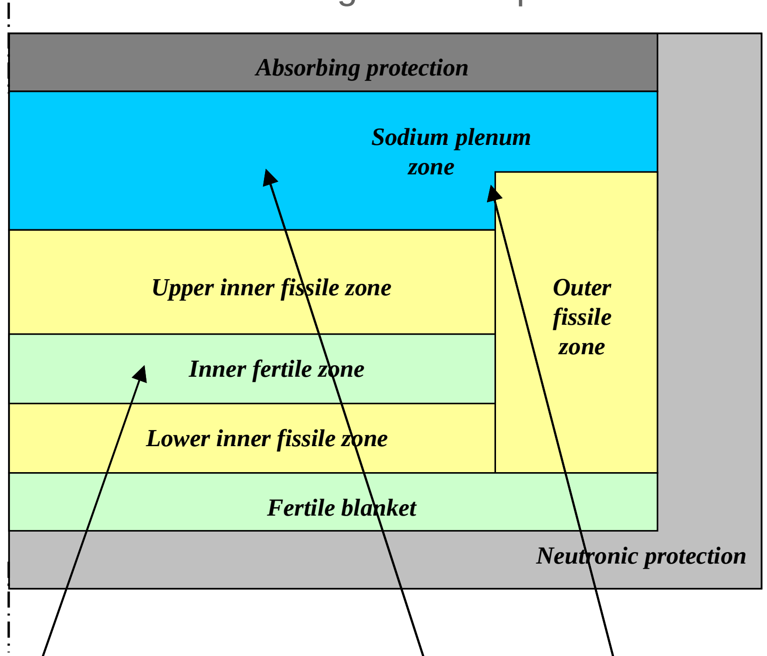
Larger pin :

- Increase of the fuel fraction
- Low reactivity loss during cycle
- ↘ of the Na fraction ⇒ lower Na voiding effect

➔Improvement on control rod withdrawal

Axis of core

Heterogeneities options



CFV Core
(Coeur Faible Vidange): Sodium void worth strongly reduced
➔ Na void effect < 0

Internal fertile zone :
(heterogeneous fuel subassemblies) + asymmetric core geometry + reduced core height

➔ Increase of neutron leakages

Sodium plenum :
Neutron reflector in normal conditions
➔ Reduction of neutron reflection capability if Na temperature increases
➔ Increase of neutron leakage when Na boiling

(Patent CEA EDF AREVA)