Comparative review on different fuels for Gen IV Sodium Fast Reactors: merits and drawbacks

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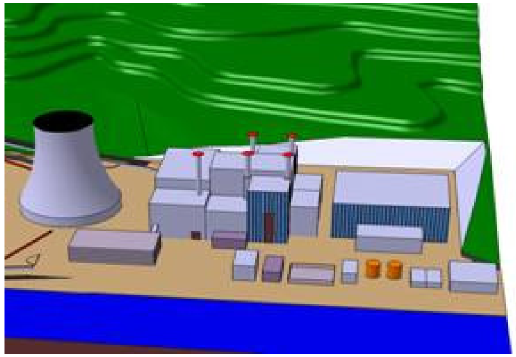
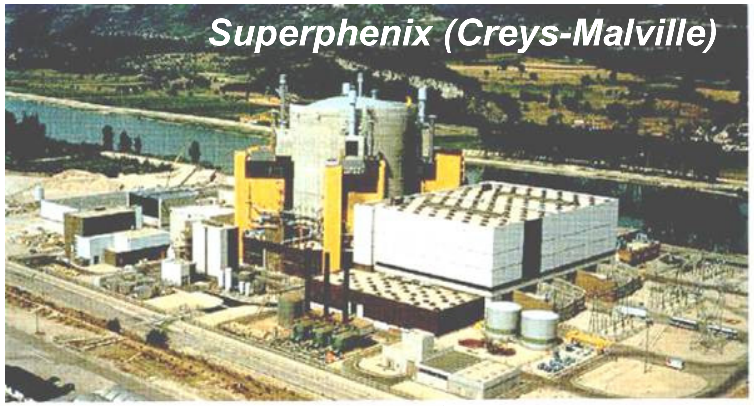
Introduction (1/2)




Superphenix (Creys-Malville)

- Sodium cooled Fast Reactor (SFR) is in France the candidate for a prototype of GEN IV system to be built as early as 2020. Due to the important and satisfactory feedback experience built upon oxide fuels and its industrial maturity on the one hand, and to its full characterization in normal and accidental conditions on the other hand, mixed oxide fuel (U,Pu)O2 is considered as the reference fuel for the core of the ASTRID (French prototype).

- The objectives followed for the next generation SFR in terms of safety are achievable with an oxide fuel in a large power core (3600 MWth) while implementing adequate designs features.

Introduction (2/2)

Nevertheless, innovative studies performed at CEA show that the use of a dense and cold ceramic fuel such as carbide might even improve the core performances.

Focused on some other key design parameters (such as high breeding capability, safety, expected performances of the fuel cycle based on pyrometallurgical processes), several countries are considering the metal fuel for the SFR either as a long term reference or as a challenger to oxide fuel.

The COCONS approach was used to evaluate the core behavior during conventional unprotected transient conditions for each type of fuel. This method appears to be a useful tool in terms of assessing new SFR core options.

Objectives

The core design of French advanced sodium cooled fast reactors is mainly driven by the enhancement of performances in terms of safety, competitiveness and flexibility margins compared to previous SFR projects. Performance objectives are :

- Improvement of safety features based on minimization of the burn-up reactivity loss (to limit consequences of control rod withdrawal transients), a significant reduction of the sodium void effect and a high resistance to core compaction, All these points have the objective to improve natural core behavior during transients and to exclude important mechanical energy release in case of severe core damages accidents.
- Flexible management of Plutonium (optimization of Uranium resources) and transmutation of minor actinides (environmental burden decrease).
- High burn-up rate, high operating availability.
- Proliferation resistance enhancement with integrated fuel cycle.

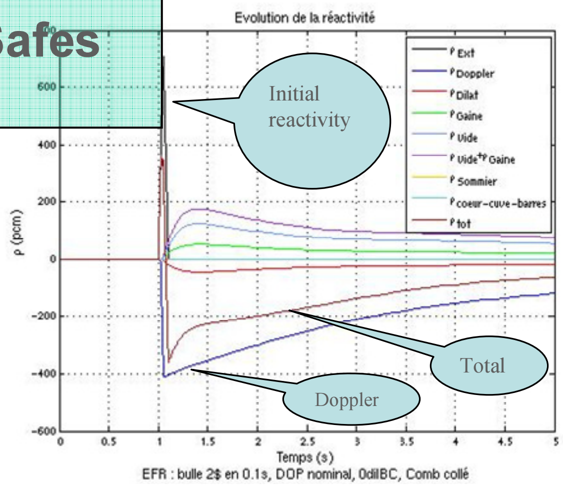
Core design methodology: COCONS Approach

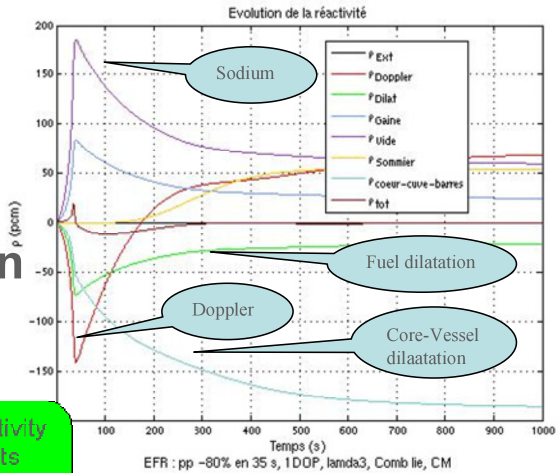
COCONS: COnception of COres Naturally Safes approach is based on 3 main steps:

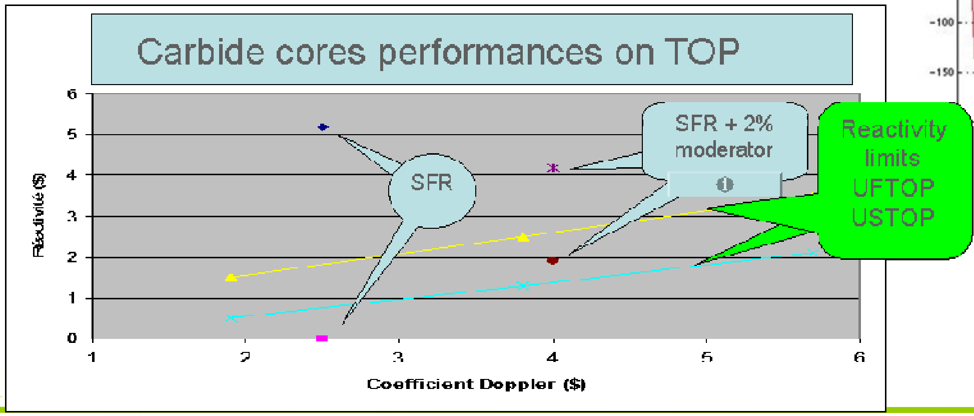
- **determine impact of reactivity coefficients on passive core behaviour during accidental transients types:**
  - **Unprotected Transient over Power (UTOP)**
  - **Unprotected Loss of Flow (ULOF)**

define reactivity coefficients domains to avoid any severe damage on the core

propose some trends for innovative fuel core design





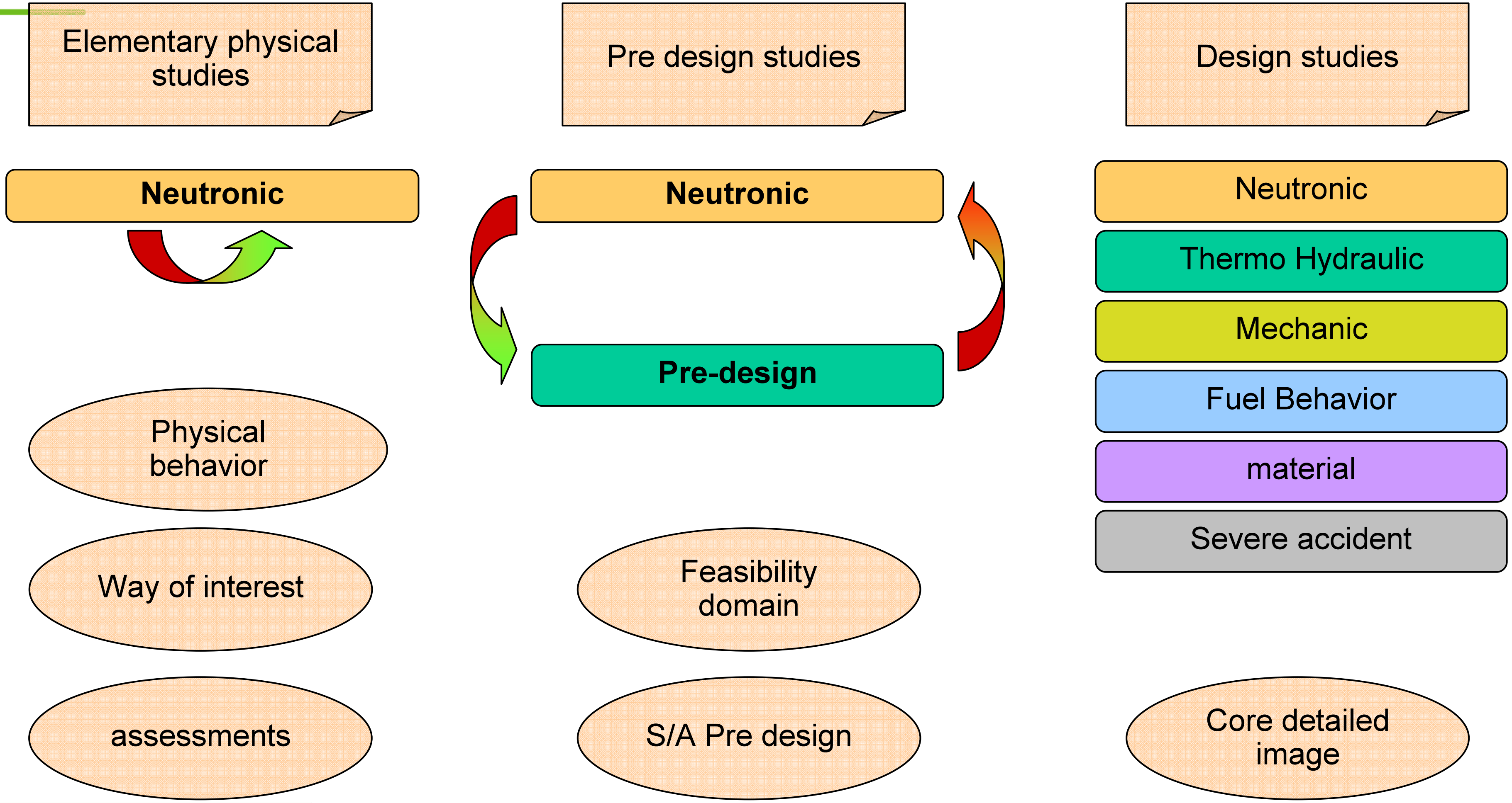


Core design methodology: parametric study trends

Ways to improve the breeding gain	Ways to improve the Void/Doppler ratio
Geometry modifications	
Increase of the fuel volume fraction	Decrease of the sodium volume fraction
Increase of the height / diameter ratio (0<H/D<1)	Decrease of the core volume
Increase of the core volume	Decrease of the height / diameter ratio (0<H/D<1)
Increase of the sodium volume fraction	Increase of the fuel volume fraction
Increase of the core radius	Modification of the core radius
« options » addition	
Minor actinides addition	Sodium plenum addition
Sodium plenum addition	Addition of CaH_2 moderator
Annular core	Addition of B_4C moderator
Addition of B_4C moderator	Addition of an internal fertile axial blanket
Addition of an internal fertile axial blanket	Annular core
Addition of CaH_2 moderator	Minor actinides addition
Fuel type	
	Carbide
Carbide	Oxide
Metallic	
Oxide	Metallic

Large deterioration — No Effect — Large improvement

Core design methodology: general approach



Fuel candidates for Fast Neutron Reactors

	(U,Pu)O2	UPu-Zr10	(U,Pu)C
Melting point (°C)	2740	1160	2325
Theoretical Density (g/cm3)	11.0	15.8	13.6
Smeared density	~ 85 %	~ 75 %	~ 75 %
Thermal conductivity (W/m/K) at 1000°C	2.0	22.0	12.8
Swelling	Low	High	High
Chemical characteristics	Poor compatibility with Sodium	Eutectic fuel-steel at 725°C	Poor compatibility with air and water

The main theoretical advantages of these alternative fuels (carbide and metallic) are to have a higher density and better thermal conductivity (6 to 14 times that of the oxide as displayed in table 2). However, the increase of the theoretical density should be balanced by a significant decrease in the smeared density for both fuels to accommodate their swelling under irradiation, which is much higher than for the oxide fuel.

Cores design comparison

Parameters	Oxide	Carbide	Metal core
Core power (MWth)	3600	3600	3600
Number of fuel assemblies	453	493	424
Number of control rods	36	33	33
Fuel vol. fraction (%)	43.7	33.16	40.83
Sodium vol. fraction (%)	27.6	31.22	27.08
Structures vol. fraction (%)	20	22.19	18.48
Void vol. fraction (%)	8.7	13.43	13.61
Fissile height (m)	1.0	0.97	1.0
Sub-assemblies pitch (mm)	210.8	208.5	203.9
Core average Pu content (%vol.)	15.8	15.2	8.3
Inner/Outer core Pu content (%vol.)	14.5/17.5	13.8/17.3	7.4/9.2
Max. linear power (W/cm)	420	252	520
Loading frequency	5	3	5

Cores performance comparison

Performances	Oxide	Carbide	Metal core
Plutonium inventory (t)	12.5	11.9	7.5
Core power density (W/cm3)	206	200	260
Fuel residence time (EPFD)	2050	1350	2578
Average fuel burn-up (GWd/t)	98	63	101
Maxi. Fuel burn-up (GWd/t)	148	100	164
Internal breeding gain	0	0.05	0.22
Doppler coefficient ($)	-1.3	-2.6	-0.59
Sodium void reactivity ($)	5	6.5	6.22
Core pressure drop (bar)	3.8	2.7	3.2
Maximal fuel temperature in nominal conditions (°C)	2400	980	950

Front End trends

Oxide is the only type of fuel whose fabrication process has reached an industrial stage. Its irradiation behavior is understood and the core designer is enabled to optimize the fuel pin to meet ambitious objectives taking into account both nominal and transients fuel performance.

This optimization will be more difficult to perform employing alternative fuels because of the limited experience available and of their high swelling rate, which leads to much higher design uncertainties.

This seems especially true for carbide fuel, which behavior appears to be less forgiving in terms of clad failure risk, compared to a more ductile metal fuel.

For Carbide and metal fuel, there is only a limited database in terms of safety (incidental and accidental behavior) experiments and in terms of minor actinide bearing fuel fabrication and irradiation demonstration.

Back End trends

Carbide fuel reprocessing is feasible and consists into the PUREX process adaptation to take into account carbide fuel specificities. However, the choice of this fuel for a SFR fleet will require a lot of R&D to be done before reaching an industrial stage.

For Metal fuel, the PUREX process could be employed after major R&D for its adaptation. However pyroprocessing seems appealing although its actinides separation performance are still foreseen to be less good than the industrial process already developed for oxide fuel.

Compared to Carbide and Metal, Oxide fuel cycle is the only one that has been closed up to an industrial stage. This was a decisive reason for the choice of Oxide fuel as the reference fuel for the ASTRID prototype.

ASTRID prototype reactor will provide valuable information about SFR MOX fuel reprocessing that will help to come up with an industrial treatment process that can meet economics, proliferation, waste minimization and safety GEN IV objectives.

Conclusions

- Oxide fuel has the main advantage that, from the front end to the back end, its fuel cycle is mastered up to the industrial scale. In addition, oxide fuel irradiation behavior is well understood for both nominal and accidental conditions.

- Preliminary studies have demonstrated the interest of Carbide fuel to enhance core design safety performance according to the COCONS approach. However, various issues concerning both the front end and the back end need to be addressed to demonstrate the feasibility of a carbide industrial scale closed fuel cycle.

- The use of metal fuel in a SFR can enhance economic performance as it was demonstrated in this preliminary study. However, future studies will have to show that such fuel can be used in a reactor with at least, comparable safety performance with the reference Oxide fueled SFR design. Its fuel cycle will have to be demonstrated to be suited with French reactor fleet objectives, especially in terms of minor actinides multi-recycling for waste transmutation.

- For these reasons, ASTRID prototype reactor, which is planned to be built in the early 2020, will employ oxide as the reference fuel. This will provide valuable information to demonstrate the feasibility of developing, within the next decades, an oxide fueled SFR fleet with a closed fuel cycle, meeting GEN IV safety, economics, waste management and proliferation resistance requirements.