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CADOR "Core with Adding DOppleR effect" concept application to sodium fast reactors

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Abstract. Generation-IV sodium fast reactors (SFR) will only become acceptable and accepted if they can safely prevent or accommodate reactivity insertion accidents that could lead to the release of large quantities of mechanical energy, in excess of the reactor containment's capacity. The CADOR approach based on reinforced Doppler reactivity feedback is shown to be an attractive means of effectively preventing such reactivity insertion accidents. The accrued Doppler feedback is achieved by combining two effects: (i) introducing a neutron moderator material in the core so as to soften the neutron spectrum; and (ii) lowering the fuel temperature in nominal conditions so as to increase the margin to fuel melting. This study shows that, by applying this CADOR approach to a Generation-IV oxide-fuelled SFR, the resulting core can be made inherently resistant to reactivity insertion accidents, while also having increased resistance to loss-of-coolant accidents. These preliminary results have to be confirmed and completed to meet multiple safety objectives. In particular, some margin gains have to be found to guarantee against the risk of sodium boiling during unprotected loss of supply power accidents. The main drawback of the CADOR concept is a drastically reduced core power density compared to conventional designs. This has a large impact on core size and other parameters.

1 Introduction

The sustainable development of nuclear energy depends on its capability to make a rational use of natural resources, minimise its waste production, be economically competitive and, above all, guarantee a safety level that is considered acceptable by the general public.

Therefore, the fundamental nuclear safety objective assigned to fourth-generation reactors is to eliminate the risk of radioactive releases, which would require extremely restrictive offsite measures even in the case of a severe accident. For this reason, the Western European Nuclear Regulators Association (WENRA) states in its report [1] that "accidents with core melt which would lead to early or large radioactive releases have to be practically eliminated and, for those that have not been practically eliminated, design provisions have to be taken so that only limited protective measures in area and time are needed for the public and that sufficient time is available to implement these measures". Reaching these objectives means guaranteeing that under no circumstances can there be a release of mechanical energy higher than the reactor's containment capacity.

With this in mind, the fourth-generation reactors have to be designed in line with two key aspects: prevention and mitigation of severe accidents. Prevention involves the implementation of all possible technical means to avoid such severe accidents. As part of the fourth level of defence in depth, mitigation involves the implementation of suitable devices designed to manage core meltdown situations and their consequences.

Core meltdown accidents that result in the release of unacceptable quantities of energy are caused by prompt critical reactivity excursions. In prompt critical conditions, the dynamics of the transient is governed by the time between two successive generations of prompt fission neutrons, which is extremely short, i.e. some microseconds. The resulting rapid power increase can then lead to a violent release of mechanical energy and the destruction of the reactor, as was the case during the Chernobyl accident in 1986 [2].

In the case of sodium-cooled fast reactors (SFR), rapid reactivity insertions can be triggered by different initiators depending on the reactor design and operating conditions. The main reactivity insertion accident initiators are as follows:
– flow of a large gas bubble through the core;
– significant core compaction
– sudden break of the core support structure, leading to the withdrawal of all the control and safety rods from the core.

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The time needed to detect the problem and trigger the automatic shutdown system by gravity drop of the safety rods is too long, for this type of sequences, to be effective, i.e. about 1 s, compared with a tenth of a second for the duration of this type of accident. *As the conventional protective system cannot provide protection, these conditions must be eliminated.*

The "practically eliminated" approach involves demonstrating that the implementation of a sufficient number of effective devices can guarantee that the occurrence of the event becomes highly improbable or physically impossible. The "CADOR" approach is quite different, as it is based on an inherent safety principle. Instead of trying to reduce the occurrence of accidental events, the approach is to rely on a sufficiently large inherent Doppler reactivity feedback effect in order to preclude any excessive power excursion following a prompt critical reactivity insertion.

2 Physical principle of the CADOR concept (reinforced Doppler reactivity feedback)

Any net positive reactivity insertion results in a nuclear power increase and consequently an increase in the temperature of the different core materials. The physical effects associated with the temperature increase are as follows:

- *Variations in the density core materials*: These effects are delayed as the heating of the various materials is slowed down by the time constants of the heat transfer mechanisms from the fuel to the others materials, and by the heat exchanges occurring inside these materials; they are therefore largely ineffective at counterbalancing the reactivity insertions in the accidents under consideration.
- *Doppler effect*: This reacts almost instantaneously to any fuel temperature variation and provides a global negative reactivity feedback, mainly due to the changes in the ^{238}U resonance capture cross section induced by the fuel temperature changes.

For steady-state power changes in oxide fuelled SFRs, reactivity is known to vary almost exactly with the average fuel temperature as

$$\delta\rho_{\text{Doppler}} = K_{\text{Doppler}} \times \text{Log}\frac{\text{final fuel temperature}}{\text{initial fuel temperature}},$$

where K_{Doppler} is a constant.

The amplitude of the Doppler effect, the reactivity variation $\delta\rho_{\text{Doppler}}$, depends mainly on the following:

- ^{238}U inventory and neutron spectrum: The larger the proportion of neutrons in the energy region of the ^{238}U capture resonances, the greater the variation. These effects are represented by the Doppler constant (K_{Doppler}) associated with the core and its constituents,
- Fuel temperature variation between the initial equilibrium state and the final one at the end of the transient, when the full Doppler feedback effect has taken place.

Two pathways for increasing the Doppler effect are therefore possible:

Pathway 1: Softening the neutron spectrum so as to favour the proportion of neutrons in the ^{238}U resonance energy region and thus increase K_{Doppler}. This can be achieved by inserting a light material into the core to slow down the fast neutrons to lower energies.

Many authors have proposed introducing light materials as spectrum softeners in plutonium-fuelled SFR cores, e.g. Merk [3] using different arrangements of a ZrH moderator material to enhance feedback coefficients and the global performance of the core. Other moderator materials have been proposed, such as beryllium, not only for improving feedback effects [4] but also for reducing clad irradiation damage caused by fast neutrons [5].

Figure 1, which has been derived from a parametric study, shows the variation of K_{Doppler} as a function of moderator material type and content in an SFR core fuelled with PuO_2-UO_2.

Hydrogenated moderators such as ZrH_2, YH_2 or CaH_2 are, of course, the most efficient materials to improve K_{Doppler}. Nevertheless, beyond 5% of volume fraction, a saturation effect occurs, due to the very high spectrum softening power of hydrogen, which raises the proportion of thermal neutrons excessively.

The neutron spectra corresponding to the different moderators are compared in Figure 2. With accrued moderation, the positive contribution of the Pu fission cross section to the Doppler effect increases and partially compensates the negative contribution due to ^{238}U, which is more sensitive to epi-thermal neutrons.

We conclude that hydrogenated moderators are not really well adapted to our objective, all the more as they come with a risk of dissociation and release of hydrogen during transients, which are important issues to be addressed. Beryllium appears as a more suitable moderator for our purpose, as it increases the epi-thermal neutron fraction in the range of ^{238}U capture resonances, without slowing down too many neutrons to lower energies.

Pathway 2: Increasing the fuel temperature difference between the initial operating temperature and the final maximum permissible temperature.

For this objective, carbide- and nitride-based fuels would have advantages over other fuels, thanks to their better thermal properties, as shown in Appendix A. Nevertheless, as $(U,Pu)O_2$ oxide is the reference fuel in France and because its cycle is completely mastered from manufacturing to reprocessing, we decided to focus our study on the application of the CADOR concept to oxide-fuelled cores. As the objective is to prevent fuel melting, the maximum permissible temperature corresponds to the fuel melting temperature. More specifically, the maximum temperature limit used to calculate the Doppler effect corresponds to the mean fuel temperature when the fuel in the hottest pin reaches its melting point. Melting points are inherent to the nature of the fuels, i.e. typically 2700 °C for a fresh $(U,Pu)O_2$ mixed oxide fuel. This means that they correspond to physical limits, which cannot be increased. The fuel temperature during nominal operation, on the other hand, can be lowered by core design.

By combining the two pathways, a target design region can be derived for CADOR, as shown in Figure 3. The

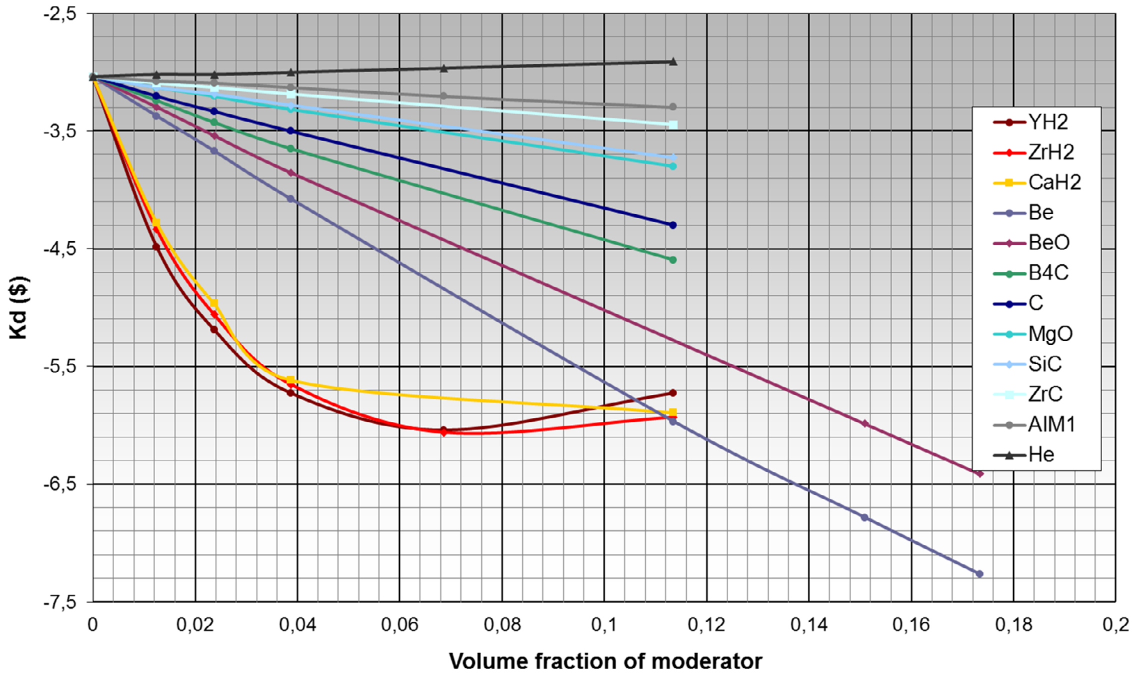

Fig. 1. K_{Doppler} for different types of moderators as a function of their core volume fraction.

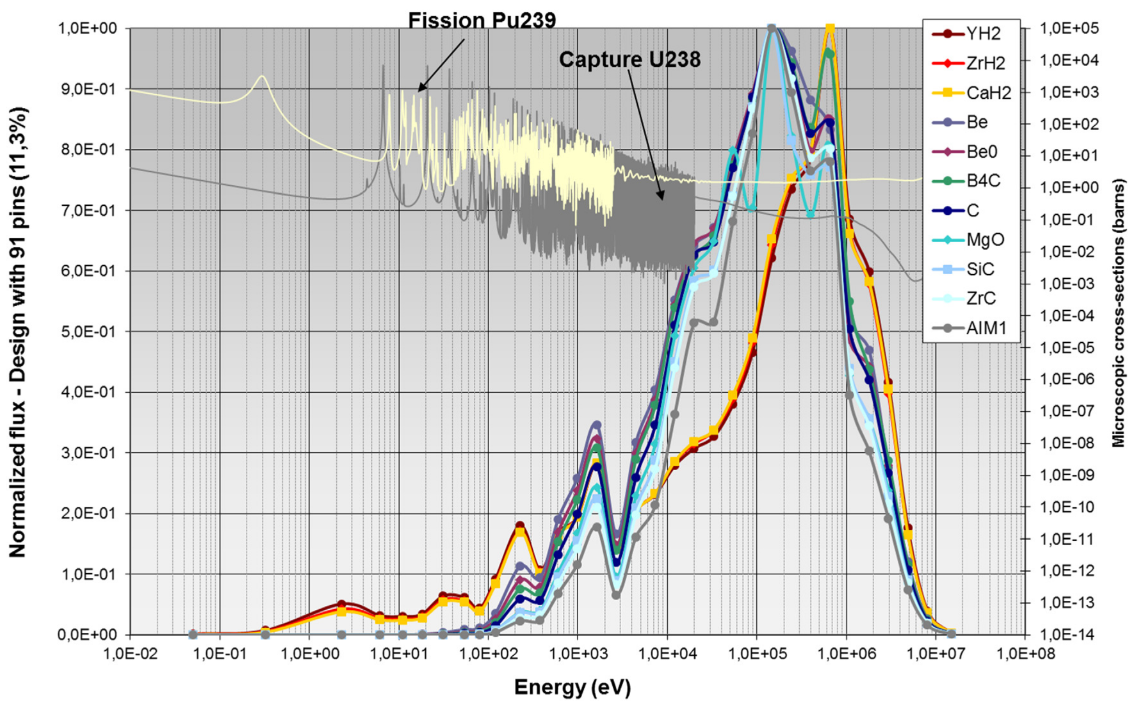

Fig. 2. Neutron spectra for different types of neutron moderator materials in the core (11% in volume fraction) compared with a reference case without moderator (AIM1). ^{238}U capture and ^{239}Pu fission cross sections are also plotted.

corresponding range for conventional SFRs is also shown for comparison purposes.

In conventional SFRs, some postulated accident scenarios can lead to large reactivity insertions, of about 5$. This is the case of a large gas bubble flowing into the core or the relative withdrawal motion of all the control rods following a rupture of the core support structure. As the Doppler integral reactivity difference between the

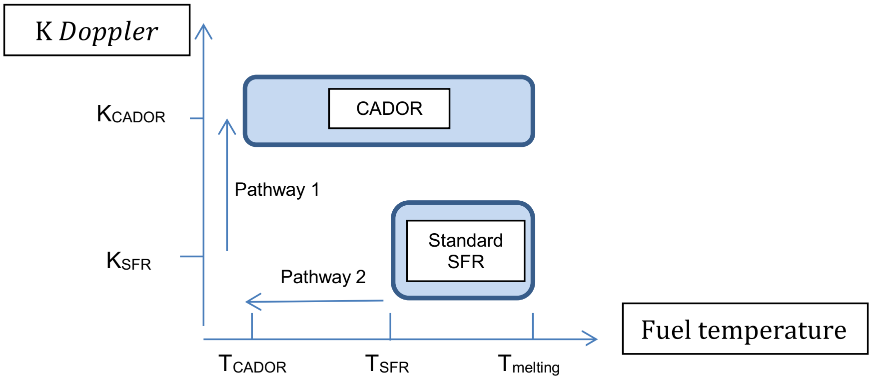

Fig. 3. CADOR operating domain compared to standard SFR.

nominal operating conditions and the conditions where the fuel in the hottest pin reaches its melting point (called the Doppler integral reactivity at melting) is quite low, being around 0.2–0.3$, it is not able to compensate a 5$ reactivity insertion.

In the CADOR concept, we set out to increase the Doppler integral reactivity at fuel melting to reach at least 4$ to avoid any prompt reactivity excursion, i.e. a 15- to 20-fold increase compared to standard cores. To reach this objective, it is necessary to involve both pathway 1 and pathway 2, so as to increase as much as possible K_{Doppler} and simultaneously lower as much as possible the fuel temperature in nominal conditions.

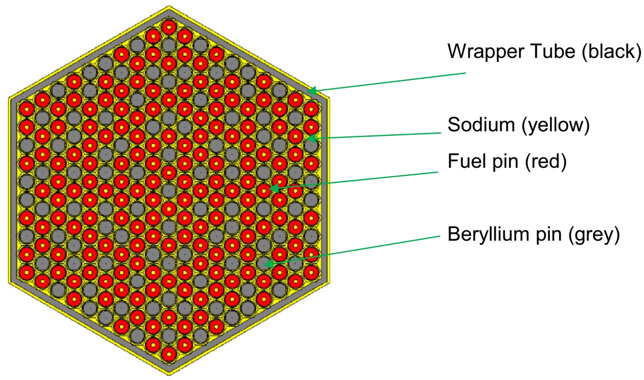

Fig. 4. CADOR fuel assembly (radial cut).

3 Application to generation-IV SFR

3.1 Core design approach

Our reference is a low-void-coefficient core concept, named CFV, which is the basis for the ASTRID 600 MWe design [6]. The specificity of this CFV core is to provide negative reactivity effect if the core is completely voided of its sodium. This performance is achieving by increasing axial neutron leakage in case of sodium voiding by means of a "sodium plenum" placed over the fuel zone (see axial fuel description in Appendix B).

Starting from this reference CFV core-type, we introduce the following modifications to arrive at a CADOR core:

- Reduce the fuel temperature at nominal power by decreasing the mean linear power density by a factor of 3. To reduce the penalty on the core radius (discussed under §3.3), an axially homogeneous subassembly concept is selected (see Appendix B). So, the fissile height is moving from 70 (CFV) to 120 cm (CADOR).
- Insert Beryllium metal pins within fuel subassemblies in place of fuel pins. The selected volume fraction of beryllium in the subassembly is 11%, which represents a compromise between a higher K_{Doppler} value and penalties in terms of neutronic parameters such as breeding gain and reactivity loss during irradiation.

The CADOR fuel subassembly design is shown in Figure 4. The total number of pins is 271, comprising 198 fuel pins (in red) and 73 beryllium pins (in grey).

The main design parameters of the two cores are summarized in Table 1.

The much lower neutron flux level in CADOR leads to a much increased fuel residence time, by a factor of 3. Mean Pu content and burn-up swing, on the other hand, are not very different as the favourable effect of the larger CADOR core is compensated by the unfavourable impact of a softer spectrum on the neutronic balance. The two cores reach the same maximum burn-up rate. Due to a softer spectrum, the clad damage rate is lower for CADOR by about 15%.

The mean fuel temperature in nominal conditions in CADOR is much lower (700 °C) compared with that of the CFV core (1300 °C). As a result, the CADOR K_{Doppler} constant is significantly larger: 6.0$ versus 2.2$.

3.2 Analysis of the safety parameters of the CADOR and CFV cores

The CADOR lower fuel temperature and larger K_{Doppler} translate into a much larger Doppler feedback reactivity at melting (4.3$) than for the CFV reference core (0.2$), by a factor of 20.

Table 2 compares the maximum reactivity contributions for three types of accident. The margins of the

Table 1. Comparison between the CADOR and CFV cores.

600 MWe SFR	Reference low-void-coefficient core (CFV)	CADOR core 11% Be
Unit thermal power (MWth)	1500	1500
Maximum linear power density (W/cm)	460	150
Mean linear power density (W/cm)	337	100
Fissile height (cm)	70	120
Number of fissile subassemblies	288	615
Number of pins per subassembly	217	271
Number of fuel pins per subassembly	217	198
Number of Be pins per subassembly	0	73
Mean Pu content (wt.%)	21.8	20.6
Management: Frequency × fuel cycle length (EFPD)	4 × 360	10 × 450
Residence time (EFPD)	1440	4500
Reactivity loss (pcm/ EFPD)	−3.7	−2.1
Overall breeding gain	−0.01	−0.06
Mean fresh fuel temperature at nominal power (°C)	1300	700
K_{Doppler} ($)	2.2	6.0

Table 2. Safety parameters of CADOR core compared to CFV core.

600 MWe fast reactor core	Reference low-void-coefficient core (CFV)	CADOR core 11% Be
Doppler integral reactivity at melting ($)	0.2	4.3
Effect in terms of maximum reactivity ($):		
Gas bubble in the core	4.5	4.3
Core compaction	2.0	1.2
Rod ejection	3.6	2.2
Margin with respect to melting ($):		
Gas bubble in the core	−3.3	+1.0
Core compaction	−1.8	+3.1
Rod ejection	−3.4	+2.1

CADOR core with respect to severe accident conditions are also compared. The three types of accidents correspond to three different postulated initiators:

– A large gas “bubble” flowing into the core, the size of the bubble corresponding to those core regions having a positive void reactivity effect.
– A compaction of the core corresponding to a reduction of all the gaps between the wrapper tube of subassemblies, assuming collapsing of the interassembly spacer pads.
– A rod ejection corresponding to a withdrawal of all the absorber rods inserted into the core at the beginning of the cycle.

We distinguish the case of the "gas bubble in the core" accident from the two other accidents, as the first one is fleeting, while the other two contribute a permanent change in reactivity. The objective in the first case is to avoid prompt criticality since the excess reactivity dissipates rapidly. The criterion for the other two cases is to compensate for the total inserted reactivity by Doppler effect to reach a stable condition. The margins given do *not* include calculation uncertainties.

The CADOR core meets the criterion of no prompt criticality for all three reactivity accidents. These “theoretical” results based on a direct comparison of the reactivity balance are confirmed by detailed calculations performed with the CATHARE code [7].

The neutronic parameters needed as inputs are obtained from 3D ERANOS [8] calculations, while the thermal fuel evolution during irradiation is calculated by the GERMINAL code [9].

3.2.1 Behaviour of the CADOR core during transient over power

An unprotected transient over power (UTOP) caused by a gas bubble flowing through the core inducing a 5$

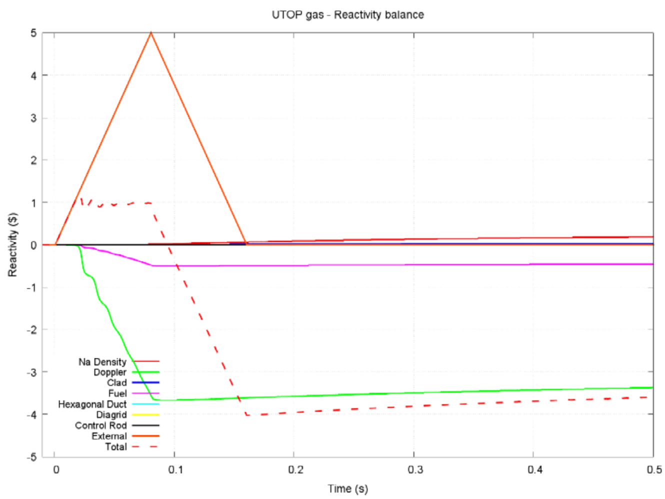

Fig. 5. UTOP reactivity balance.

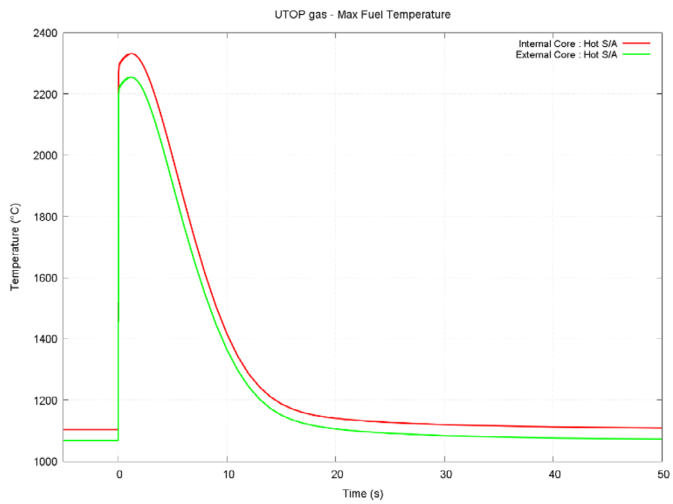

Fig. 6. UTOP maximal fuel temperature.

reactivity insertion is simulated by CATHARE for the CADOR core in an ASTRID reactor type. Figures 5 and 6 show the reactivity balance and the evolution of the fuel temperature during the transient.

The positive reactivity due to sodium voiding rises with time as the gas bubble moves through the core (see orange curve in Fig. 5). A 5$ maximum value is reached after 80 ms. The Doppler effect (green line) compensates for the reactivity insertion. The other feedback effects (as fuel or steel densities) have no significant impact. The net reactivity stays near $1 (red dotted line) until the inserted positive reactivity reaches a peak, then goes down. The total power of the reactor is increased by a factor of 1000. The maximum fuel temperature rises strongly up to 2300 °C but remains below the melting limit for both the inner core (in red) and the outer core (green line), as shown in Figure 6.

3.2.2 Behaviour of the CADOR core during loss-of-coolant accidents

The second type of accidents susceptible of resulting in a widespread core meltdown are those caused by a loss of coolant in the core. The historical reference accident in this category is triggered by primary pump failure, which is itself caused by a total loss of power, combined with failure of the emergency shutdown system. This choice of accident is motivated by the presumed envelope nature of its possible impact, taking into account all the phases which occur in the sequence of events from sodium boiling to melting core compaction, rather than the probability of such a sequence, which is extremely low (10^{-14} per reactor-year). Conventional SPX-type (Super Phenix) [10] or EFR-type (European Fast Reactor) [11] cores have large positive sodium void reactivity effects. Following a pump failure accident without rod drop, in some conditions the sodium temperature may increase and reach its boiling point. The resulting sodium voiding then evolves into a prompt critical excursion. This type of accident has been studied to make sure that the SPX and EFR containment vessels would be able to resist the consequences of a core meltdown accident.

With the goal of improving the inherent nuclear safety of Generation-IV SFRs with respect to this type of accident, two objectives were set:
– The first straightforward objective is to avoid any primary prompt critical excursion.
– The second, more ambitious objective is to prevent sodium boiling during the accident transient.

A primary prompt critical excursion is excluded for the CADOR core since the Doppler effect compensates for the sodium void effect. However, is a CADOR-type core also capable of preventing sodium boiling? To avoid boiling, the reactor power must drop quickly enough so that it "mirrors" the drop in the flow rate, and hence prevents the sodium from heating up excessively. To achieve this, the net reactivity balance of all the feedback effects combined must be as negative as possible. As the initial fuel temperature at nominal power in conventional cores is high, the Doppler reactivity feedback effect provides positive reactivity during the transient, which counters the power drop. In such circumstances, the increased K_{Doppler} could be seen as a disadvantage for the CADOR cores. However, as the initial fuel temperature is low for CADOR cores, it tends to increase during the transient due to the influence of the increasing sodium temperature. In the end, the Doppler effect provides *negative* reactivity feedback and thus helps the reactor power drop faster.

In a similar manner, during loss-of-heat-sink (LOHS) accidents (failure of secondary pumps), the reactor tends to reach conditions of isothermal equilibrium. Compared with conventional cores, the CADOR cores have less "distance" to cover for lowering the fuel temperature from nominal power down to equilibrium conditions at the end of the transient. This is shown in Table 3, which compares the Doppler reactivity feedback contributions needed for the different cores to transition from nominal conditions to isothermal conditions at 650 °C, which is necessary to avoid vessel creep issues.

Table 3. Doppler reactivity effect in a LOHS accident for the CFV and CADOR cores.

	CFV core	CADOR core
Fuel temperature at nominal power (°C)	1300	720
Doppler coefficient ($)	2.2	5.8
Doppler integral reactivity 650 °C ($)	+1.0	+0.4

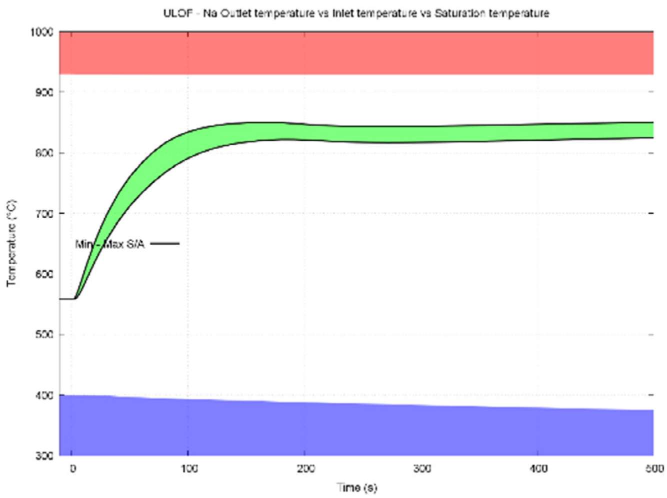

Fig. 7. Na outlet temperature.

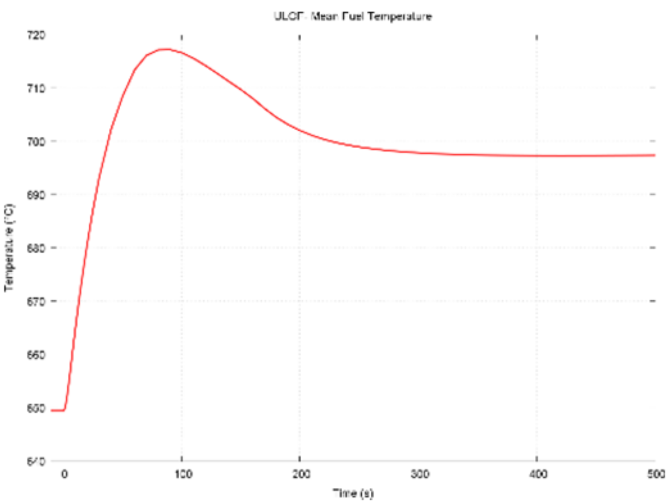

Fig. 8. Mean fuel temperature.

It can be seen that the Doppler integral reactivity of the CADOR core is notably lower. We can therefore expect a better natural behaviour for CADOR core during loss-of-coolant sequences. This has been confirmed by CATHARE calculations performed for the CADOR cores (see later).

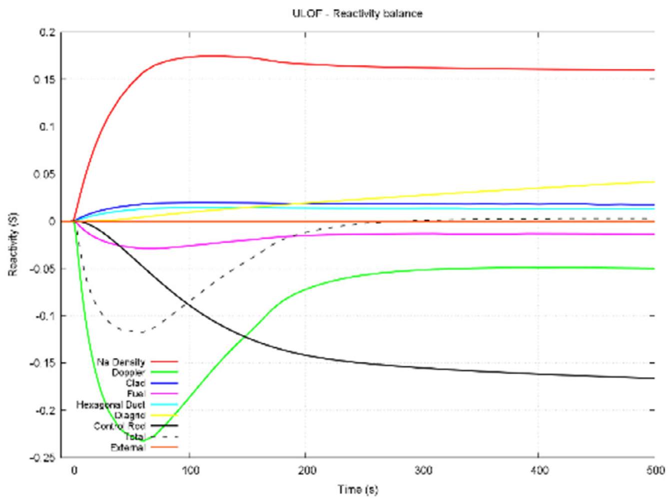

Fig. 9. Reactivity balance.

3.2.2.1 Behaviour of CADOR core during unprotected loss of flow (ULOF)

The behaviour of an ASTRID reactor-type with a CADOR core during an ULOF accident calculated by CATHARE is illustrated in Figures 7–9.

The sodium outlet temperature increases during the transient, reaching 850 °C, with a good margin to avoid any risk of boiling (see green curve in Fig. 7 compared to the saturation temperature limit in red). This very good behaviour is due to the non-standard CADOR Doppler effect. In a standard core, the Doppler feedback has a positive value due to the reduction of the fuel temperature during the transient. In CADOR core, in nominal conditions, a large fraction of the fuel is “cold”, so the mean fuel temperature actually increases (see Fig. 8) and the Doppler feedback is negative (green curve in Fig. 9). This negative Doppler feedback combined with the other negative reactivity coefficients (mainly “control rod” feedback see black line) compensate for the positive sodium density effect (red curve), thus causing a faster reactor power decrease, which limits the sodium temperature rise.

3.2.2.2 Behaviour of CADOR core during unprotected loss of heat sink (ULOHS)

During a loss of heat sink, the reactor power decreases (see Fig. 10) mainly due to core diagrid structure thermal expansion (yellow line in Fig. 11). Compared to standard cores, the Doppler effect in CADOR is less positive, thanks to a low fuel temperature at nominal power. The “equilibrium” temperature of the CADOR reactor ultimately reaches about 650 °C (see Fig. 12), which is near the maximum allowed value to avoid any risk of vessel creep.

3.2.2.3 Behaviour of CADOR core during unprotected loss of supply power (ULOSSP)

For an unprotected loss of supply power accident, the behaviour of the CADOR core is very similar to that of the

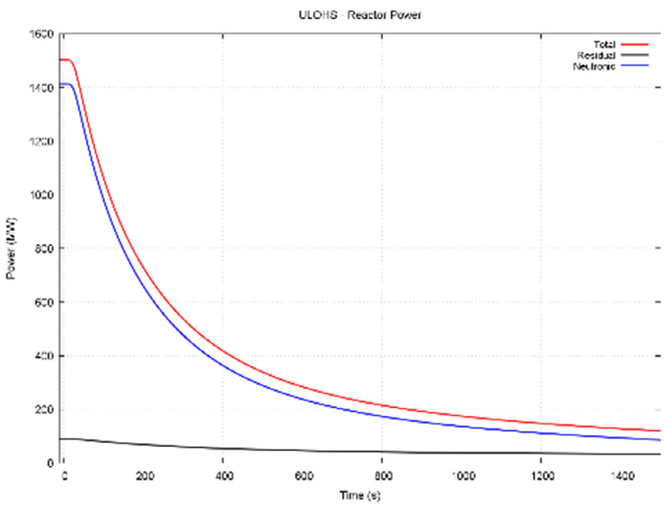

Fig. 10. Reactor power.

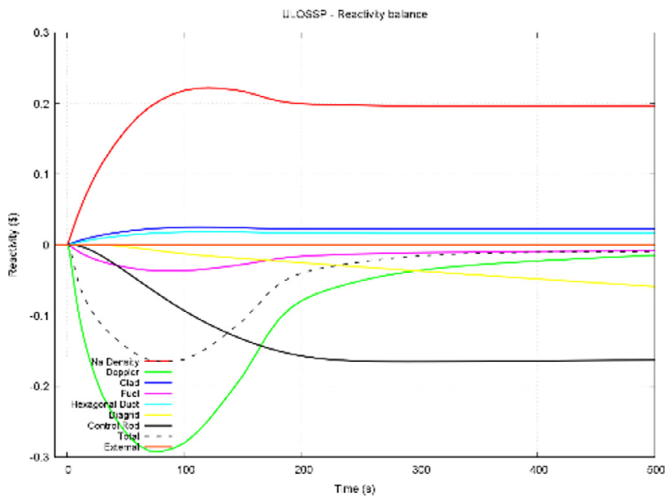

Fig. 13. Reactivity balance.

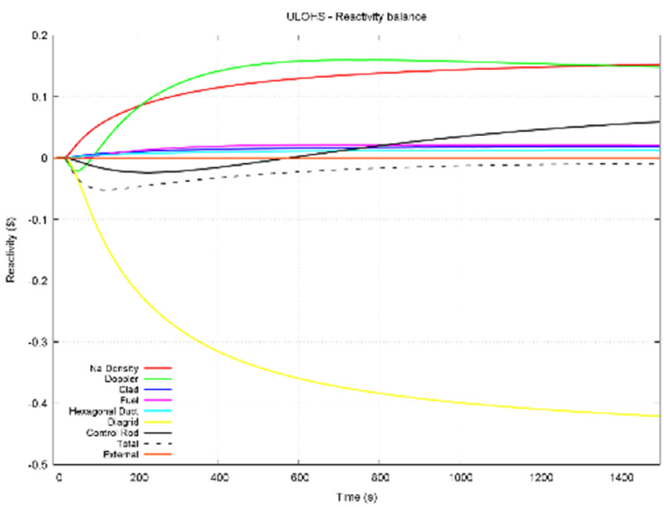

Fig. 11. Reactivity balance.

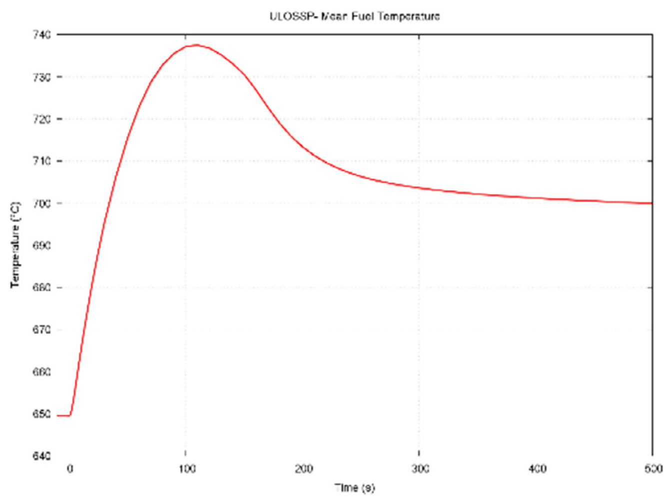

Fig. 14. Mean fuel temperature.

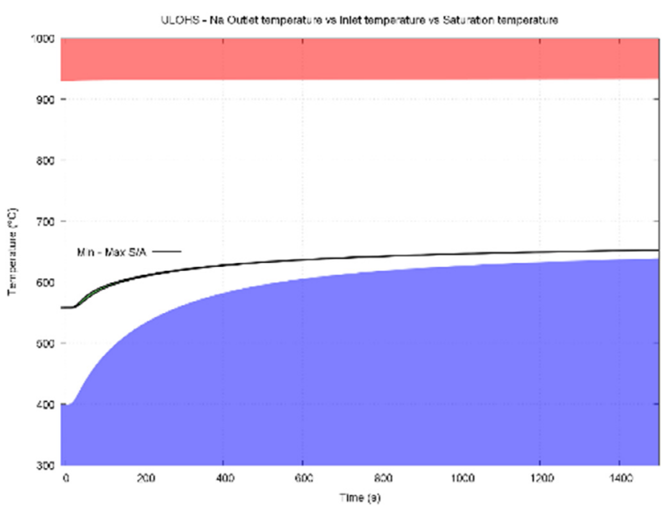

Fig. 12. Core temperature.

ULOF case. But, despite the favourable Doppler feedback (see green line in Fig. 13) due to the mean fuel temperature increasing (Fig. 14), the loss of extracted power by the secondary circuit is penalised due to the reduction of core support structure feedback (see yellow curve in Fig. 13), compared to ULOF case; as a consequence, the sodium temperature reaches a higher value, about 900 °C (see Fig. 15). Considering calculation uncertainties, the margin to Na saturation temperature seems too small to guarantee any risk of sodium boiling.

3.2.3 Safety performances of CADOR core during severe accidents

Table 4 summarises the performance levels of the CADOR core in accidental situations, compared to conventional SPX/ EFR cores.

We conclude that the CADOR core shows better safety performance than standard SFR cores for the various accidental transients considered. For the particular case of "unprotected loss of primary and secondary pumps", the performance may be improved by optimising the reactor design to avoid any risk of sodium boiling.

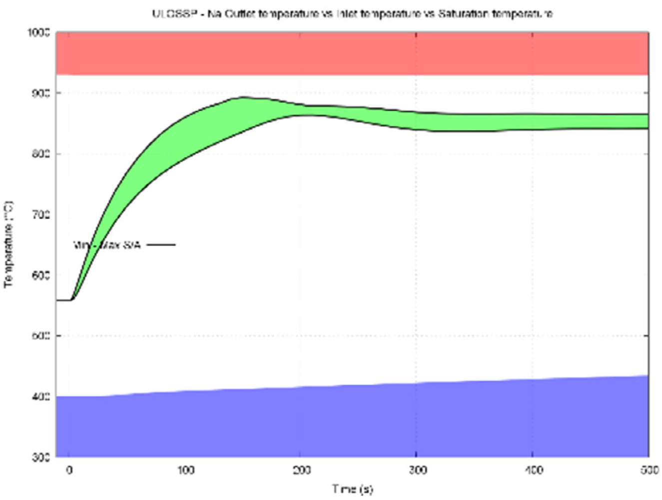

Fig. 15. Na outlet temperature.

3.3 Other advantages and drawbacks of the CADOR concept

Compared to the reference CFV core (see Tab. 5), the main disadvantage of the CADOR core arises from its lower power density, which has a direct impact on core size:

- The fuel core radius increases by 60%. The main consequence is that the radii of the above-core structures are equally increased. However, when considering the core as a whole (fuel + reflector + shielding regions), this drawback is mitigated since it becomes possible to eliminate at least one row of reflector subassemblies, thanks to the reduced neutron flux in the CADOR cores. In the end, the overall core radius is increased by only 15%.
- From an axial perspective, a preliminary design study shows that the total height of the subassembly increases by about 7% compared to the reference CFV core (see Appendix B).

At the same time, the Pu inventory in the CADOR core is significantly larger, by a factor of 3, compared to the reference CFV core. However, by considering the total Pu inventory (reactor inventory + cycle inventory) and a duration of 7 years to carry out the cycle operations (5 years before reprocessing and 2 years for re-manufacturing), the increase is closer to a factor of 2 (23 t compared to 12 t).

Table 4. Global performance comparison between the different types of cores.

	Standard oxide fuel cores as SPX, EFR types	CADOR oxide fuel Core
Transient over power		
Large gas bubble through the core	Prompt reactivity excursion/fuel melting	No fuel melting
Full core compacting	Prompt reactivity excursion/fuel melting	No fuel melting
All control rods withdrawal due to core support structure breaking	Prompt reactivity excursion/fuel melting	No fuel melting
Unprotected loss of coolants		
Loss of primary pumps	Na boiling	No Na boiling
Loss of heat sink	Equilibrium temperature = 800 °C	Equilibrium temperature = 650 °C
Loss of primary and secondary pumps	Na boiling	Na boiling

Table 5. Comparison of the CADOR and CFV core parameters.

600 MWe SFR	Reference low-void-coefficient core (CFV)	CADOR core 11% Be
Fuel core radius (cm)	159	255
Total core radius (cm)	346	400
Total Pu mass in core (t)	4.8	15
Number of fuel subassemblies discharged by year	80	48
Mean burn-up rate (MWd/t)	80	92
Maximum burn-up rate (MWd/t)	126	127
Maximum clad damage rate (dpa)	115	101

Furthermore, a key point is that the number of subassemblies to be loaded and unloaded every year is reduced in the case of the CADOR cores. This is due to the increased fissile height; at identical burn-ups, the greater the mass of fuel loaded per subassembly, the longer the irradiation time. The reduction, by about a factor of two, is a serious advantage as it translates in reduced handling times during refuelling outages. On the other hand, increased fuel subassembly height has some drawbacks for handling and transport operations. The real impact on the availability factor of the reactor would have to be assessed by taking into account more precisely all the other tasks performed during outages.

The "damage rate"/"burn-up rate" ratio is smaller since the neutron flux in the CADOR cores and the mean energy of the neutrons are lower. Higher burn-up rates are therefore accessible with CADOR cores for the same damage limit as the reference cores (imposed by the selected cladding material).

3.4 Technological maturity of the CADOR core

The CADOR core subassemblies are made of axially homogeneous fuel pins based on the conventional design that has been the historical choice for SFRs. It therefore benefits from the operating experience collected from the Phenix and Super-Phenix plants.

One specificity of the CADOR core is that the oxide fuel operates in non-standard linear power density and fuel temperature conditions. The CADOR fuel operates at a low linear power density, typically around 100 W/cm for the mean value and 150 W/cm for the maximum. Operating experience from PHENIX [12] shows that irradiation of an SFR fuel element at such a low linear power density poses no particular difficulties, neither during normal operating conditions nor when subject to normal power variation transients.

However, the thermomechanical behaviour of such fuel pins in control rod ejection type accidental transients can be a problem. Gas retention within the fuel is significantly higher than at high power and a "cold" mixed oxide fuel is less likely to creep. These two factors can combine to cause a high intensity fuel-cladding mechanical interaction after a rapid power increase, generating stress in the cladding, which could exceed the elastic limit of the irradiated material and potentially ultimately destroy the pin.

In CADOR conditions, the linear power density is so low that there is very little fuel restructuring, which means that the initial pellet-cladding gap remains open throughout irradiation, thus mitigating the risk of fuel-cladding mechanical interaction after a rapid power increase.

At this stage of study, we have concluded that these operating conditions are acceptable for the CADOR cores.

Another specificity of the CADOR core is the insertion of beryllium metal pins into the fuel subassemblies. This material benefits from considerable feedback collected from irradiation experiments performed in reactors. Based on the current state of knowledge, there seems to be no showstopper. The main issue relates to its high swelling rate and how to define the gap between clad and beryllium pin to accommodate it.

By performing an irradiation test on a beryllium rod at the expected temperature, neutron spectrum and neutron fluence conditions expected in CADOR, it would be possible to specify the swelling law to be applied and to validate our preliminary design.

At some point, the impact of beryllium on the neutronic parameters of the core (particularly the Doppler coefficient on which the CADOR concept is based) should be validated experimentally through a specific programme to be performed in a critical mock-up.

4 Conclusion

Generation-IV SFRs will become acceptable and accepted only if they are designed so as to prevent the repetition of large-scale accidents such as Fukushima or Chernobyl. This means ensuring the efficient prevention of reactivity insertion accidents that could lead to the release of large quantities of mechanical energy exceeding the reactor containment's capacity.

The CADOR approach based on reinforced Doppler reactivity feedback appears to be an effective means of preventing such reactivity insertion accidents. This study shows that it is possible to design such CADOR cores so that they meet the goals of fourth-generation SFRs. The accrued Doppler feedback is achieved by combining two effects: (i) Introducing a fraction (10% in volume) of some light material such as beryllium in the core, so as to soften the neutron spectrum and (ii) simultaneously reducing strongly the linear power rating (by a factor of three), in order to lower the fuel temperature. The resulting CADOR core can withstand a reactivity injection of up to 5$ without damage. In addition to its inherent resistance to reactivity insertion accidents, the CADOR core also shows very favourable properties with respect to unprotected loss-of-coolant accidents.

These preliminary results have to be confirmed and completed to meet all safety objectives. In particular, to guarantee against the risk of sodium boiling during unprotected loss of supply power, some margin gains have to be found. A very promising way, currently under study, is to consider the CADOR core concept in the context of a small and modular reactor (SMR).

Author contribution statement

Alain Zaetta and Robert Jacqmin provided global definition of the concept and evaluated its performances. Bruno Fontaine and Pierre Sciora were in charge of neutronic studies of moderated subassemblies and application to core design. Vincent Pascal contributed to the neutronic core design of the CADOR by performing study on the moderator material choice to improve Doppler effect. Romain Lavastre was in charge of modelling the CADOR core with the CATHARE code and then performing the CATHARE calculations in order to assess the behaviour of the CADOR core during safety transients. Michel Pelletier

and Gérard Mignot were in charge of evaluating behaviour under irradiation of CADOR fuel subassemblies. Aurélien Jankowiak was in charge of comparing and establishing characteristics of the different beryllium-based materials.

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Appendix A: Characteristics of different SFR fuel types

	Metal	Carbide	Oxide	Oxide
Type of fuel	(U,Pu)$Zr_{10\%}$	(U,Pu)C	(U,Pu)O_2	(U,Pu)O_2
Melting point (°C)	1160	2325	2740	2740
Thermal conductivity (W/(mK)	22	12	2	2
Linear power rating (W/cm)	450	450	450	220
Maximal fuel temperature at above linear power rating (°C)	~900	~1000	~2500	~1600
Linear power rating at fuel melting point (W/cm)	~950	~2100	~500	~500

The previous table compares the main characteristics of the different SFR fuels, i.e. metal, carbide and oxide.

At identical linear power densities (≈450 W/cm), the metal fuel is the "coldest" (≈900 °C), followed closely by the carbide fuel (≈1000 °C), owing to the high thermal conductivity. The oxide fuels can reach a significantly higher centreline temperature, by about +1500 °C, due to their very low thermal conductivity.

The margin between the maximum fuel temperature in nominal conditions and the fuel melting temperature is largely in favour of the carbide fuel. The metal fuel is penalised by its low melting point (≈1200 °C), while the oxide fuels have the highest melting point (≈2700 °C) but their maximum temperature at nominal operation proves to be penalising. The best compromise is with the carbide fuel, which combines a low nominal operating temperature (≈1000 °C) and a high melting point (2300 °C).

Nitride fuels have similar characteristics to those of carbides but are limited by the need to use N^{15} enrichment to offset the excess neutron captures by N^{14}, which cripples the neutron balance.

Based on these considerations alone, the carbide fuel seems to be the most appropriate fuel for the CADOR concept.

Appendix B: Axial description of the CADOR fuel subassembly compared with the low-void-coefficient core (CFV) fuel subassembly [13]

- The CADOR fuel pin is homogeneous with a 1.2 m central fissile part sandwiched between two 20 cm axial fertile blankets.
- The axial gas plena (expansion tanks) are comparatively longer compared to low-void-coefficient core (CFV) fuel subassembly in order to take into account the greater fuel mass in the pins, with the same maximum pressure criterion on the cladding.
- Removing the sodium plenum and lowering the neutron flux allow for a thinner neutron shield in the CADOR fuel subassembly.

The overall height of the subassembly is 4.80 m, which is only 7% taller than the CFV subassembly.

This very preliminary design needs further investigation to take account of the lower gas release rates for fission products in the CADOR fuel, which impacts the height of the fission gas plena with a possible additional reduction in total length of the fuel subassembly.