Importance of the Doppler Constant and of the fuel temperature evaluation for the design of a 'CADOR' core

P. Sciora, J.-B. Droin, B. Fontaine, Alain Zaetta

▶ **To cite this version:**

P. Sciora, J.-B. Droin, B. Fontaine, Alain Zaetta. Importance of the Doppler Constant and of the fuel temperature evaluation for the design of a 'CADOR' core. ICAPP 2019 - International Congress on Advances in Nuclear Power Plants, May 2019, Juan-Les-Pins, France. cea-02394084v1

HAL Id: cea-02394084

https://cea.hal.science/cea-02394084v1

Submitted on 24 Feb 2020 (v1), last revised 6 Mar 2020 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

000393 - Importance of the Doppler Constant and of the fuel temperature evaluation for the design of a 'CADOR' core

P. Sciora[1*], JB. Droin[1], B. Fontaine[1], A. Zaetta[1]

[1] CEA Nuclear Energy Division Cadarache Center, 13108 Saint Paul Lez Durance, France
[*] Corresponding Author, E-mail: pierre.sciora@cea.fr

The sustainable development of nuclear energy depends in particular on its capacity to demonstrate important improvements in terms of safety and acceptance by the general public. In the case of Sodium Fast Reactors (SFR), some Fast Transients Over Power (FTOP) can be responsible of core melting. To make them acceptable, the safety approach generally relies on the demonstration that their occurrence can be "practically eliminated". The "CADOR" (Core with Adding DOppleR effect) approach is quite different and proposes to preclude any excessive power excursion by designing a core with a large inherent Doppler reactivity feedback.

The design of such a core is based on a physical analysis (1D Model) of main moderators available and of interest in maximizing the Doppler Effect. Calculations are also made with a full core and a 3D model to validate the first conclusions and the influence of the main parameters on the value of the Doppler Effect.

To design the CADOR core, it is also necessary to minimize the fuel temperature in order to maximize the integral of the Doppler feedback coefficient between the nominal and the fuel melting conditions. The design of the core and the verification of its associated safety criteria are also depending on the precision of the Doppler Constant and of the fuel temperature evaluations. To estimate the importance of the fine prediction of these two parameters, three main transients are studied: FTOP caused by bubble gas, FTOP caused by a break of the core support structure and an ULOF. Sensitivity studies present the consequences on the core or system design in order to keep the same safety objectives.

KEYWORDS: Sodium-cooled fast reactor, conceptual design, CADOR, enhanced safety, Doppler sensitivity, transients study

Introduction – Context of the study: the CADOR core

The development of low carbon energies will be based on sustainable energies, such as renewable ones: solar, wind, biomass … One of the main sources is the nuclear energy thanks to its very compressive way of operating (very low impact on the ground. This last part is mainly based on the use of the Generation IV reactors which permits the use of recycled Uranium and Plutonium.

In France, the technology of the sodium-cooled fast reactors is well known (Phénix, Superphénix), the uranium and plutonium recycling process is well mastered and the amount of uranium and plutonium is enough important to start many reactors with MOX fuel. However, such kind of reactors will not be retained if they are not able to demonstrate important improvements in terms of safety issues and acceptance by the general public.

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. The fourth generation of reactor has also to be designed by taking into account two main aspects of severe accidents: the prevention and the mitigation. Prevention involves the implementation of technical means to avoid such severe accidents. Mitigation involves the implementation of suitable devices to manage core meltdown situations and their consequences.

Some accidents resulting in prompt critical excursions are governed by very fast dynamic transient and can lead to violent release of mechanical energy and also unacceptable consequences. For the sodium cooled fast reactor, hypothetical initiators could be a flow of a gas bubble through the core, a core compaction or a break of the core support structure [1]. The CADOR approach involves demonstrating that no excessive power excursion can follow a prompt critical reactivity insertion caused by such initiators, without assuming that their occurrence could be “practically eliminated” due to their very low probability.

This demonstration mainly relies on a core design with a large inherent Doppler reactivity feedback. The Doppler Effect can be enhanced by adding moderators in the core. The efficiency and the different ways to insert moderators are presented in a first part.

To increase the Doppler feedback between nominal and start-of-melting conditions, the average temperature in operating conditions is also reduced by minimizing the linear power on fuel pins. Considering these options, different transients are evaluated with a proposed CADOR core of 1500 MWth and sensitivity studies are presented to evaluate the interest in reducing the uncertainties of the Doppler constant and the fuel temperature evaluation.

Design of a CADOR core

Starting from a reference core designed for 1500 MWth SFR (V2B core [2]), homogeneous fractions of different kinds of moderators (Z2, Be, C, MgO) are progressively inserted in the sub-assemblies, replacing fuel volume. Core radius is increased to keep a linear power constant and Pu content is adjusted to maintain core criticality.

The Doppler constant (KD) is evaluated between the operating fuel temperature and the melting one using the classical logarithm formula. Neutronic calculations are done with the ERANOS system [3].

$$K_D = \frac{\Delta\rho(T_{operating} \rightarrow T_{melting})}{\ln(\frac{T_{operating}}{T_{melting}})}$$

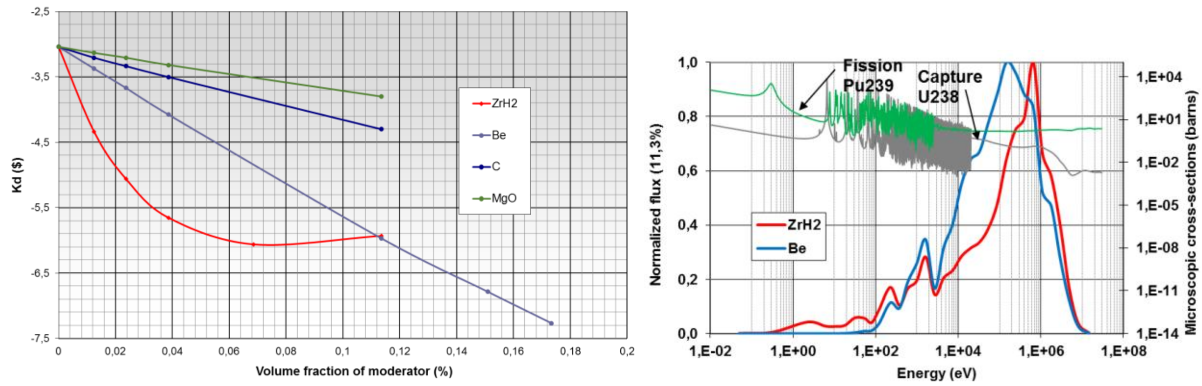

Figure 1 : Doppler constant depending on volume fraction of 4 different moderators inserted (left) - Flux spectrum (ZrH_2, Be) and microscopic cross sections of fission (^{239}Pu) and capture (^{238}U) (right)

The hydrogen material (ZrH2) is the most efficient. However, its contribution is limited to few percentages of insertion because of the too important slowing term and also of the appearance of the contribution of the fission resonances of the Pu isotopes (Figure 1). A second point not in favor of the hydrogen material is that the neighboring fuel pins are impacted by the much moderated flux and can present high gradient of power. Besides, the beryllium can be as effective as the ZrH2 or even more effective if more than 11% is inserted, but of course, the neutronic penalties will be more important (reactivity loss, Pu content needed). C and MgO are less effective and will not be further studied in this paper. For all these reasons, the beryllium is kept as the best candidate as moderator in this study.

Considering the way of insertion of the beryllium in the fuel sub-assemblies, it can not be done by mixing beryllium and MOX powder which is an alpha-ray emitter. The important reaction rate (α, n) on the beryllium will considerably penalize handling of the fresh fuel subassemblies.

Nevertheless, to obtain an efficient moderation, the beryllium has to be placed in the core by the most homogeneous way. Considering Be/MOX successive interfaces, the moderation effect of the beryllium is the most effective in the first centimeters of the fuel layer. The Table 1 presents the decomposition of the Doppler Effect in a 1D linear model (Figure 2). The thickness of the beryllium layers is changed between 1cm (~1 pin) and 36 cm (~2 subassemblies).

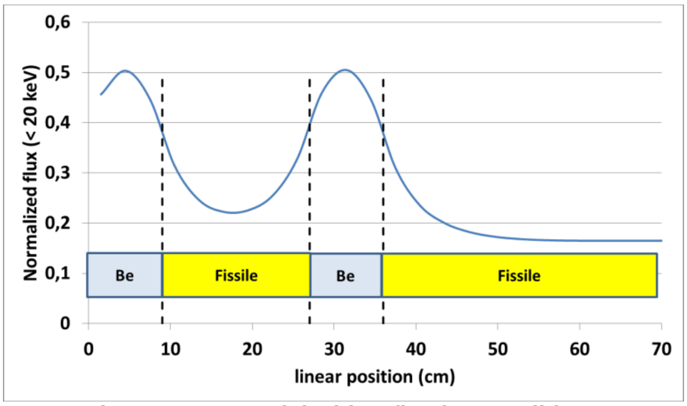

Figure 2 : 1D model with reflective conditions

Be	1cm Be	3cm Be	5cm Be	7cm Be	9cm Be	12cm Be	15cm Be	18cm Be	36cm Be
U238 Capture	-103	-130	-146	**-151**	-147	-147	-129	-116	-110
Pu239 Fission	5	12	20	**27**	29	35	27	20	15
Pu239 Capture	-6	-12	-19	**-24**	-26	-30	-23	-18	-14
Total	**-104**	**-130**	**-145**	**-148**	**-143**	**-143**	**-125**	**-114**	**-109**

Table 1 : decomposition of the Doppler Effect (between operating and melting temperatures) depending on a 1D model, with variation of the beryllium thickness (pcm)

For thin layers of Be, the gain in moderation increases with the increase of the beryllium layer thickness to a maximum of 7 cm. Consequently, the use of the beryllium in dedicated sub-assemblies separated from MOX sub-assemblies implies to design a core with a reduce lattice pitch (~7 cm) not compatible with a large 1500 MWth core.

Considering that, the choice has been done to place the beryllium in dedicated pins among the fuel pin bundle in the same subassembly.

The fuel sub-assembly is described on the Figure 3. The beryllium pins are in grey on the left figure of subassembly. The core is also presented on the right. Fuel assemblies are yellow (inner core) and green (outer core), control and diverse absorbing rods are printed in blue and black; diluents and reflectors are in grey.

The maximum linear power is fixed at a value of 150 W/cm (a factor of three compared to the maximum V2b value) in order to reduce significantly the fuel temperature at nominal condition.

The main performances of CADOR core are given in the Table 2. With cycles around one year and a half, the variation of reactivity along the cycle is about -2.8$. The relatively low power density impacts the total sodium void worth, however the moderator limits this value about 4.6$. The maximal positive value of sodium void worth, which corresponds to a very large gas bubble centered in the middle of the core is not so different (4.8$) because of the few neutron leakages at the periphery of the core.

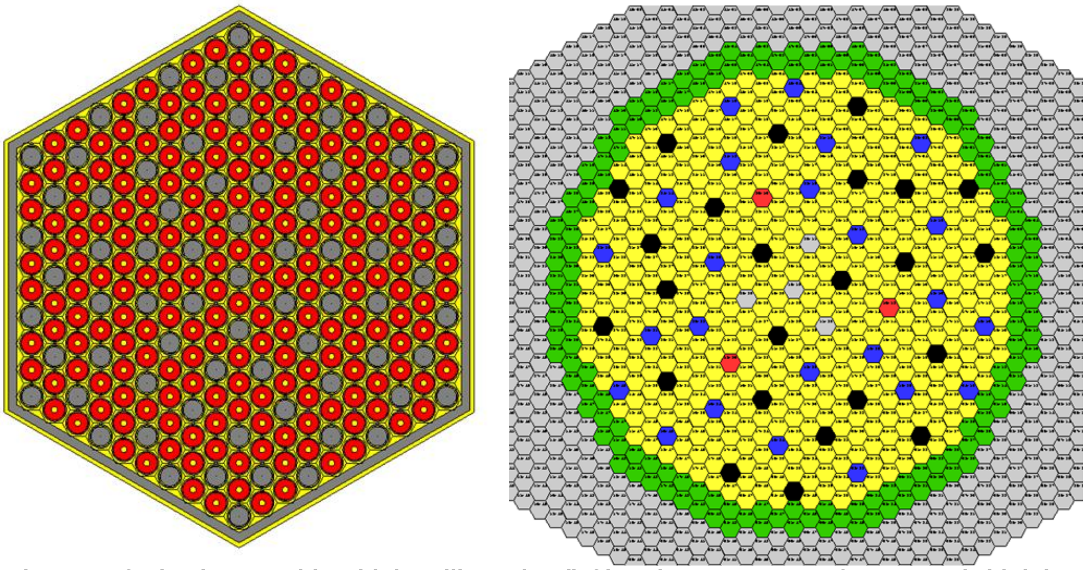

Figure 3 : fuel sub-assembly with beryllium pins (left) and CADOR core of 1500 MWth (right)

Power density (W/cm3)	65
Max linear power (W/cm)	150
Reactivity loss (pcm/efpd)	-2,1
Reactivity loss per cycle (pcm)	-960
Breeding ratio	-0,06
Average burn-up GWd/t (inner core/outer core)	103 | 71
Effective delayed neutron fraction (pcm)	347
K_D fissile Doppler constant (pcm)	-1942
Sodium void ($)	4,6
Maximum positive sodium void value ($)	4,8

Table 2 : main performances of the CADOR core

Studied transients

Different transients have been studied, especially unprotected transients with the code MACARENa [4]. This is a fast-running tool aiming at simulating the primary phase of the accidental transients occurring in the primary circuit of a SFR, with mostly zero or low dimensional physical modellings. Concerning the neutronics, the tool handles a 0D neutron kinetic formulation with 8 groups of delayed neutron precursors. Concerning the thermal-hydraulics, a one-dimensional representation of the sodium flow is considered in each representative sub-assembly. Variables (such as temperatures in the fuel, the cladding or the sodium) are space-averaged over each axial mesh.

Some of the studied transients are the classical ULOx, (Unprotected Loss Of Flow), which corresponds to the loss of the primary and / or secondary pumps without scram operating. The other transients, UTOP (Unprotected Transient OverPower), for which the CADOR core has been designed have also been studied. For this sensitivity study, two UTOP have been considered:

- The flow of a large bubble gas through the core,
- The break of the core support structure.

One ULOF is also presented: the loss of all the primary pumps.

UTOP – Flow of a large bubble gas

The large bubble gas is defined as the most available positive value on the core by voiding some zones of the core geometry. It corresponds in fact to a very large bubble which does not include the periphery of the core which is mainly negative (dominated by the leakage term). The kinetic of this transient is directly given by the velocity flow of the sodium through the core in nominal conditions.

For this core, the transient is defined by the step of reactivity presented on the next Figure 4.

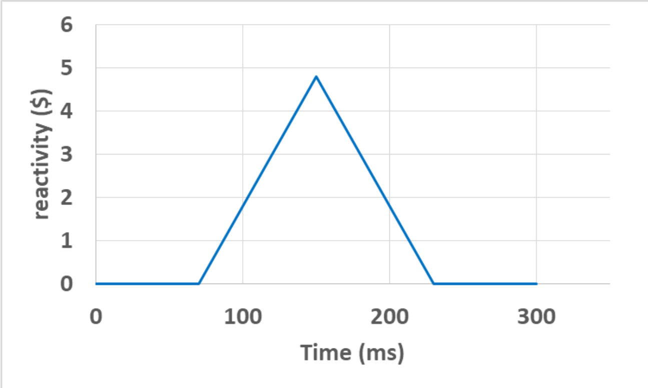

Figure 4 : kinetic of reactivity insertion due to a large bubble gas flow

The reactivity insertion increases very quickly in around 80ms, and decreases immediately with the same kinetic. The maximum value corresponds to the maximal sodium void: 4.8$.

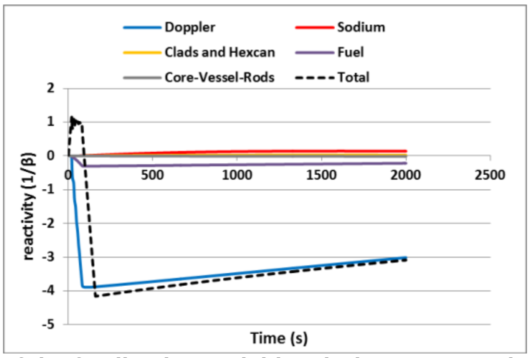

Figure 5 : evolution of the feedback reactivities during an UTOP (Bubble gas) transient

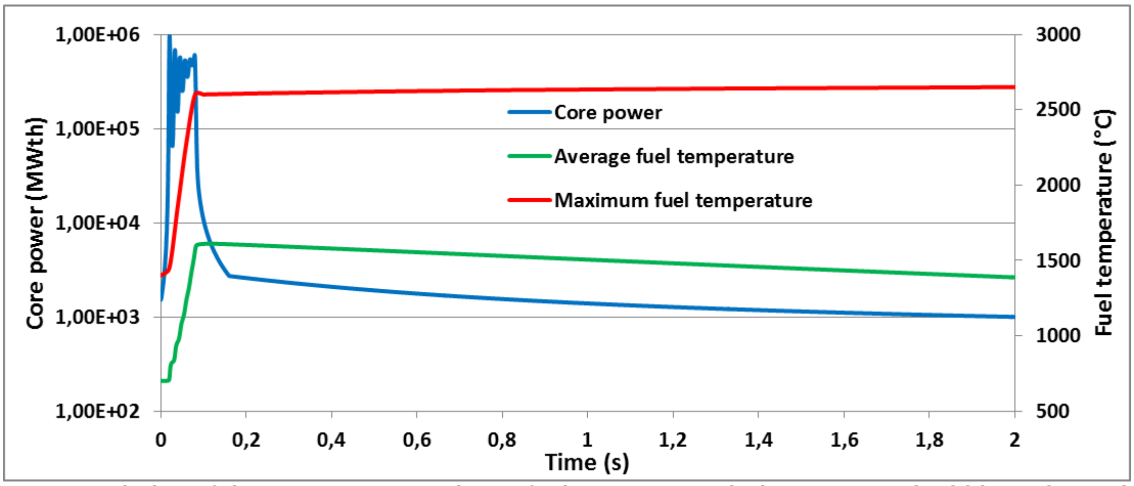

Figure 6 : evolution of the core power, maximum fuel temperature during an UTOP (Bubble gas) transient

The fuel Doppler Effect is the only feedback which is able to react in time and amplitude to this reactivity insertion. The Doppler effect due to iron (included in the clad and hexagonal can feedback coefficient) and the other ones are negligible. In this case, thanks to the increased Doppler Constant and to the enlarged margin to the fuel melting, the fuel fusion point (~2800°C) is not reached. During the reactivity insertion, the maximum and average fuel temperatures kinetic are similar (+1000°C in 0.1s) due to the quasi-adiabatic fuel pins heating-up for such a short transient duration. However, after the reactivity insertion, the maximum fuel temperature still increases for a few seconds whereas the average temperature decreases. This is linked to the radial conductive characteristic time in the pellets (~2s) which explains that the temperature at the fuel periphery decreases faster than on its inner face.

We have to remark that this study is done with a value of the Doppler Constant evaluated in nominal conditions, without uncertainties on the value and taking into account the whole core full of liquid sodium. In fact, the core is during this transient partially voided, and even quite fully voided of sodium during a very short time. The voiding of the core impacts directly the value of the Doppler Constant by hardening the neutron spectrum (Figure 7). The Doppler Constant is also reduced about 12% in the worsted case for a CADOR core. For a casual fast reactor core with MOX-fuel, the penalty is about 30%.

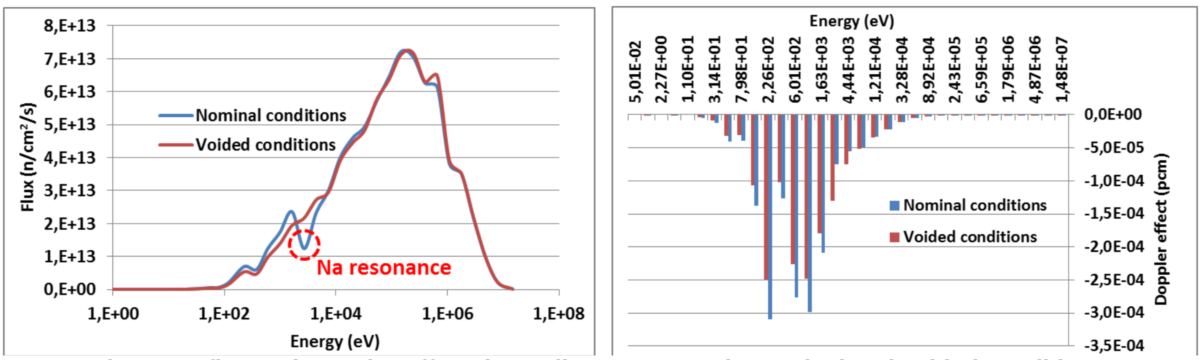

Figure 7 : flux and Doppler Effect depending on energy in nominal and voided conditions

As it is not easy to make the real transient with an evaluation of the Doppler Constant at each calculation time step, a sensitivity study has been done by varying the value of the Doppler Constant. It permits to evaluate the available margin on this transient due to uncertainty or bias on the Doppler Constant. The Figure 8 presents the fuel melting instant (infinity if no boiling is seen during the 250s of the evaluated transient) depending on the value of the Doppler Constant. The 'x' axis is presented as the percentage of the nominal value calculated.

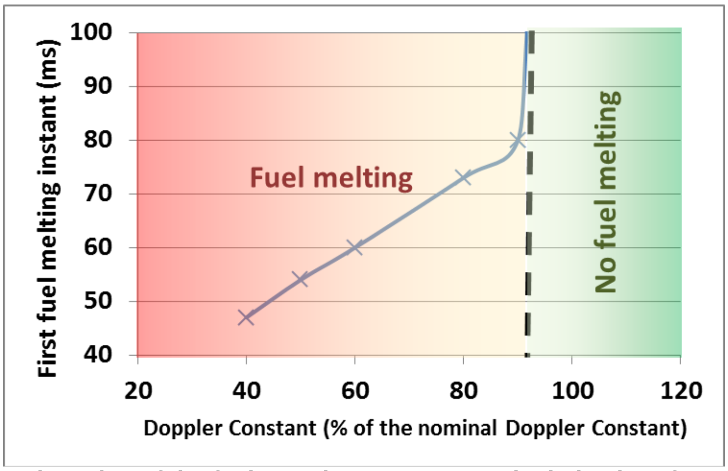

Figure 8 : sensitivity to the value of the fuel Doppler Constant on the behavior of a CADOR core during an UTOP (Bubble gas) transient

This study has also been done with sensitivities to the average fuel temperature and the results are equivalent. A variation of the best-estimate value about 10% leads to an important change in the behavior of the core.

UTOP – Core support break

The core support break is defined as a downfall of the whole core. As the rods are supported by the reactor plug, they stay at their initial position. The conservative accident is defined by the total excursion of all the rods, which corresponds at the beginning of cycle to the whole reactivity loss. For this core, the transient is defined by a step of reactivity presented on the Figure 9 and 10.

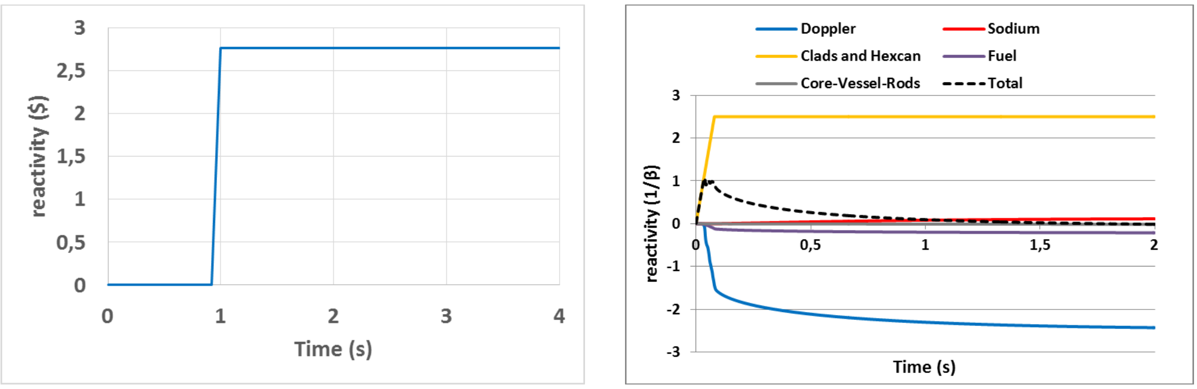

Figure 9 : kinetic of reactivity insertion due to a core support break (left) and evolution of the feedback reactivities during an UTOP (Core support break) transient (right)

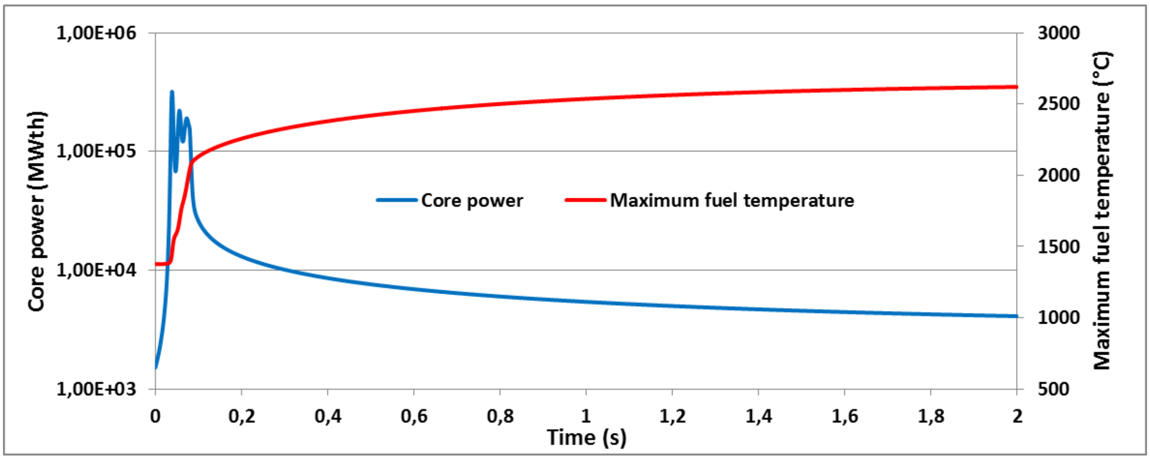

Figure 10 : evolution of the core power, maximum fuel temperature during an UTOP (Core support break) transient

Contrary to the flow of the bubble gas, the inserted reactivity is maintained until the end of the evaluation of the transient. However, the amplitude of the inserted reactivity is reduced by a factor of two. The maximum fuel temperature is obtained with a new equilibrium a few seconds after the reactivity insertion. The fuel melting is avoided with a margin about 100°C. The Figure 11 presents the sensitivity of the behavior of the core depending on the value of the Doppler Constant.

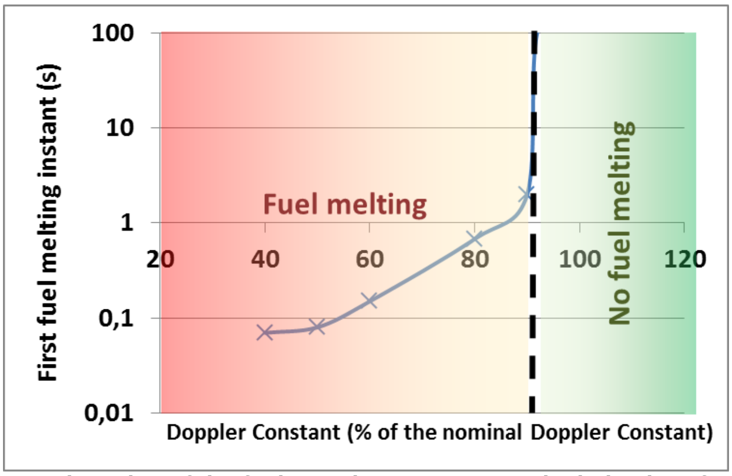

Figure 11 : sensitivity to the value of the fuel Doppler Constant on the behavior of a CADOR core during an UTOP (Core support break) transient

A margin of about 10% of the Doppler Constant is available with this transient to avoid the fuel melting. A poor estimation of the Doppler Effect leads to fuel melting: first with a few pellets, then with some important parts of the core. Concerning the time appearance, if the melting is occurring, it's always in a very short time (<10 s). On these both UTOP transients, the value of the Doppler Constant, or even more the integral of the Doppler Effect between nominal temperature and fuel melting is of first order importance for the good behavior of the core.

ULOF

The ULOF is characterized by a decrease of the sodium mass flow rate in the core (Figure 12).

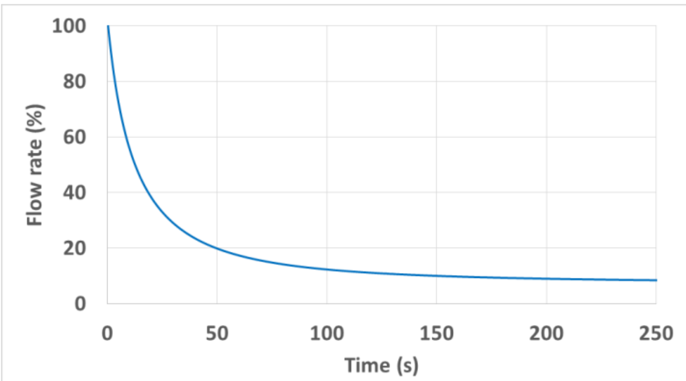

Figure 12 : evolution of the core sodium flow rate during an ULOF

Contrary to the Fast Transient Over Power, the whole feedbacks are impacted and the answer of the system is depending of a lot of parameters. In the particular case of the CADOR core, the fuel is at a very low temperature. As soon as the sodium starts to increase, the average fuel temperature increases even if the core power is decreasing. The Doppler is also negative and helps to manage the good behavior of the core during this transient: the sodium stays under its boiling limit (~920°C) as it can be seen on the Figure 13.

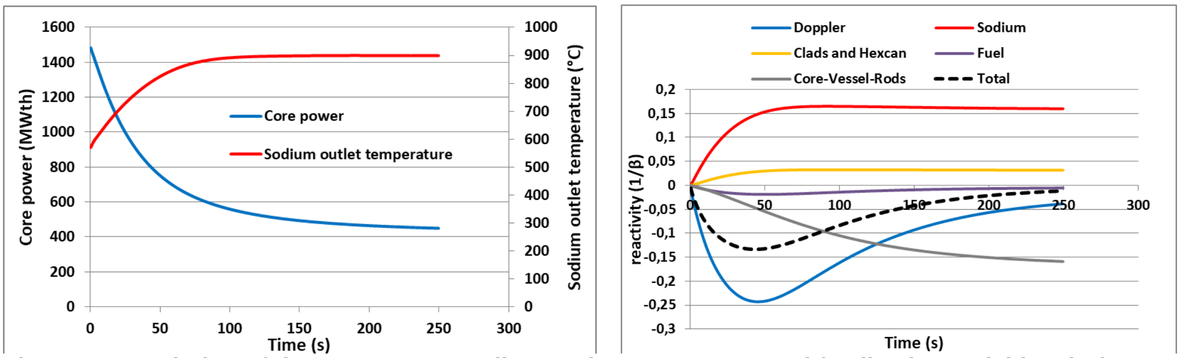

Figure 13 : evolution of the core power, sodium outlet temperature and feedback reactivities during an ULOF transient

However, the margins are not important and uncertainties on the feedback coefficients may be responsible of the change on this conclusion. The exercise has been done with the Doppler Constant and with the fuel average temperature. Results are presented on the Figure 14.

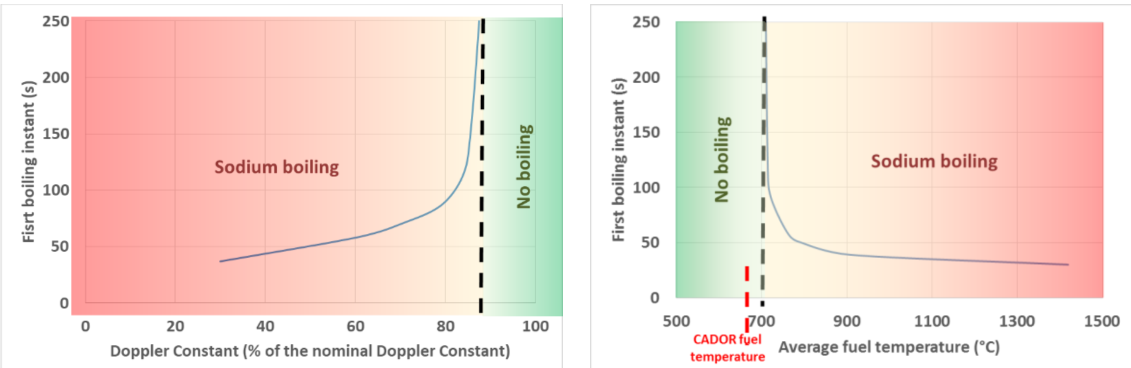

Figure 14 : sensitivity to the value of the Doppler Constant and the of the average fuel temperature on the behavior of a CADOR core during an ULOF transient

About 15% of reduction of the Doppler Constant seems to be acceptable with the good behavior of the core during the ULOF transient. For the fuel temperature, a bad estimation of about 20°C is also acceptable.

These two sensitivity studies have in fact to be placed in a more complex study: for example, a probabilistic study based on multi-parameters variations, taking into account at least the whole feedback coefficients. Indeed, on the contrary to the FTOP transients, the whole feedbacks are playing a role during this transient and they tend all together to stabilize themselves and the core for the same reason. It is then difficult to estimate the real impact of the variations on the core by making them vary one by one.

Conclusion

The CADOR concept is based on the objective to eliminate the whole accidents able to lead to the violent mechanical energy release, in particular the ones which operates very quickly. These transients were “practically eliminated” in the current and standard safety approach by reducing their occurrence probability. With the CADOR design, they do not lead to problematic issues: no sodium boiling or no melting fuel. The excursions of power are limited and the consequences are acceptable. These transients are the Fast Unprotected Transients Over Power (large bubble gas, core support beak, core compaction).

However the demonstration of the safety of such a core is mainly based on the Doppler feedback. The whole uncertainties on the evaluation of the Doppler Constant and on the estimation of the average and maximum fuel temperature will be directly traduced in design margins. The more precise the evaluation of the Doppler Integral will be, the more economic it will be to design the core.

The impact on the core design would be an increase of the moderation fraction and a more intensive reduction of the volume power. In the both case, the impact on the core volume and also on the main performances of the core will not be negligible.

Some hypotheses to ease the calculations have now been done and will be reduced in the future. Work is also being done to estimate more precisely the behavior of the fuel at a relatively low temperature compared to standard fuels of liquid metal cooled fast reactors. The precision on the evaluation of the Doppler Effect in a "moderated-fast" spectrum is also being investigated [5].

Acknowledgment

The authors wish to thank FRAMATOME and EDF for their financial support to these studies.

References

1) A. Zaetta et al., "CADOR 'Core with Adding DOppleR effect' concept – Application to Sodium Fast Reactors", EPJN (2019)
2) P. Sciora et al., "A break even oxide fuel core for an innovative French sodium-cooled fast reactor: neutronic studies results", GLOBAL 2009, Paper 9528, Paris, France
3) G. Rimpault et al., "The ERANOS Code and Data System for Fast Reactor Neutronic Analyses", International Conference on the New Frontiers of Nuclear Technology : Reactor Physics, Safety and High-Performance Computing, PHYSOR'02, October 7-10, 2002, Seoul, Korea.
4) JB. Droin et al., "Physical tool for Unprotected Loss Of Flow transient simulations in a Sodium Fast Reactor", Annals of Nuclear Energy 106 (2017) 195–210
5) M. Zajaczkowski et al., "Performance analysis of APPOLO3 applied to moderated SFR fuel assembly", ICAPP 2019, Juan-Les-Pins, France.