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CHALLENGES ASSOCIATED TO THE MITIGATION OF ULOF IN SODIUM-COOLED FAST REACTOR CORES

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Abstract

The reactivity effects associated to the mitigation of the Unprotected Loss Of Flow (ULOF) in Sodium Fast Reactors are being studied for finding means to reduce the potential release of mechanical energy.
The studies performed with ERANOS illustrate the importance of the cladding removal as well as the radial leakage changes during the core slump-down. Possible arrangements and dispositions to be taken to avoid re-criticality and hence the possibility to go into severe power excursions are then envisioned.
Challenges to be faced by safety studies to ascertain no cliff edge effects are occurring are then listed.

Introduction

Safety studies are classified in different categories depending on their probability of occurrence and on the consequences they might have [1] [2]. Focus, here, has been given on severe accidents, which are the types of accidents which have a very low probability of occurrence but which can have severe consequences, such as the melting of the core. The prevention of these core melting accidents is ensured by:

- Measures of prevention of the initiators which could lead to the core damage.
    - The control of reactivity.
    - The heat removal.
    - The confinement of radioactive materials.
- The studies on the analysis of safety are mainly deterministic; the probabilistic studies are used to justify that some scenarios can be "practically eliminated". However, it should be demonstrated that some scenarios are representative of the most severe conditions so that the overall safety assessment can be accepted.

The ULOF is an accident where the primary flow rate is lost while no SCRAM[1] is occurring and no safeguards are operating. When the coolant circulation is lost in a SFR, the reactivity increases due to coolant expansion, so do the temperatures, the sodium can hence boil causing a primary power excursion (if the core design induces a significant voiding effect), the materials in

[1] SCRAM is an acronym which stands for Safety Control Rod Axe Man, this is the system which triggers the emergency rods.

the core can melt, and the accident can lead to a re-criticality and to a secondary power excursion.

Particular attention is being given to that ULOF accident among other severe ones because it leads to a fast transient when the pump rundown is fast and hence manual interventions in case of equipment failures are not possible. Furthermore, for past designs, this could lead to a quite severe power excursion and was considered as a representative case being used for calculating the integrity of the reactor vessel (chapter 1: ULOF standard scenario).
The approach for the current plant design aims at reducing the mechanical energy release since it allows the possibility of decreasing the reactor vessel size. This, as a consequence, implies to practically eliminate any risk for important reactivity insertion.

Understanding how the accident occurs, is the first step before looking at ways to prevent the re-criticality. Mastering the consequences in case of complete core melting is the last step in these studies.
Re-criticality is analyzed in order to understand how it appears and to find features or specific arrangements to avoid it. Studies presented in chapter 2 are performed in static, so as to understand at first (§ 2.1) the main phenomena inducing the reactivity insertion during the ULOF accident. Solutions to avoid re-criticality, such as adding absorber materials which are miscible with fuel in the molten pool, or ejecting fuel from the core are also presented in that chapter (§ 2.2).
ULOF scenario studies are then in chapter 3. The chapter is sub-divided according to the different phases of the scenario (§ 3.1 primary phase; § 3.2 transition phase; § 3.3 secondary phase). For that last phase, a semi-static semi-transient study is performed so as to identify possible solutions to act during that phase. This is done using an energetic scenario hypothesis for the primary phase of the ULOF accident, the state of the reactor at the end of the primary phase is calculated thanks to the ERANOS code. The following of the accident is calculated with SIMMER for different upper configurations of a given core.
In chapter 4, various solutions are being used to calculate the entire scenario using the SAS code plus the SIMMER code or the SIMMER code only. This illustrates what kind of uncertainty the different routes have and in the same time how the cores can behave under those accidents when no specific measures are taken.
Also chapter 4 lists what solutions could be envisaged to design the core and perform the safety studies and the related necessary code assessments.
Chapter 5 concludes the study and lists the routes which could be followed to design a core with limited mechanical energy release.

1. ULOF standard scenario

The different possible sequences of the scenario were analyzed thanks to calculation codes specific to severe accidents and their associated damaged conditions.
This accident can be divided into several phases:

- The accidental transient.
- The primary phase of the accident.
- The transition phase of the accident.
- The secondary phase of the accident.

1.1 The accidental transient

When the accident begins, the sodium flow rate is highly reduced (to a back-up flow rate) and the core temperature increases. This increase in the temperature creates feedback effects having positive or negative effects on the reactivity. Consequently, the sodium expansion and the structure materials expansion (cladding and hexagonal can) have usually a positive effect on the reactivity, while fuel expansion, grid expansion and core-vessel-rod differential expansion have a negative effect on the reactivity. Another very important effect when temperature increases is the Doppler effect, which is highly negative. Below is an example of reactivity feedback effects during an ULOF.

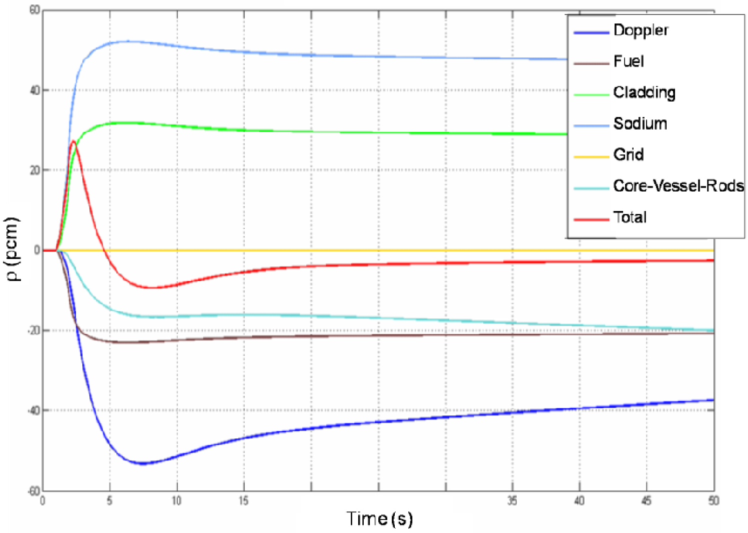

Figure 1 Feedback effects in case of ULOF for the ESFR core

If the feedback effects are favourable enough it is likely that no sodium boiling will occur. It is however possible to reach the sodium boiling point if the core and the plant have not been chosen adequately or if calculation conditions are taken in a very unfavourable way (by assuming that the feedback effects are reduced due to the lack of understanding of the various phenomena or due to computational uncertainties).

1.2 The primary phase of the accident

The sodium boiling can stabilize: when considering SPX, the voiding of the superior axial blankets has a negative reactivity effect. If the boiling is not stabilized, it can lead to general sodium boiling of the core. When the sodium voiding occurs, temperature of the cladding increases and reaches the melting temperature (1300K, but the claddings lose their mechanical properties at 1100K), the fuel expands and fission products apply pressure on the cladding, it breaks and expanding fuel fills all the voided zones (sodium channels). The coolant voiding as well as the cladding removal creates a positive reactivity insertion. The fuel expansion makes it decrease but it does not prevent the primary power excursion.
The rest of the scenario depends highly on the magnitude of the primary excursion:

- If the primary excursion is very weak, the fuel axial expansion could make the core under-critical, there would consequently be no melting of the hexagonal cans and no core slump-down, which means no secondary power excursion.
- If it is moderately energetic, a part of the fuel is ejected outside the core (in the upper parts) but not enough to avoid a power secondary excursion during the core slump-down (hexagonal cans which are collapsing induce the fall of the upper part of the core in the fissile zone).
- If the primary excursion is very energetic, enough fuel is ejected outside the core to avoid any other re-criticality risk.

At the end of the primary power excursion, if this one was sufficiently energetic, part of the fuel has been ejected in the upper part of the core where it becomes solid.

1.3 The transition and the secondary phases

From this point on, the fuel was partly scattered and different scenarios can be considered.
Three different paths can be studied, depending on whether or not there is an important blockage in the subassemblies.

- If there is no blockage:
    - There can be a strong interaction sodium-molten fuel, followed by strong fuel dispersion, thus stopping the accident.
    - There can be a direct dispersion by volume expansion of a vapour bubble, otherwise, the dispersion phenomena are not sufficient enough to stop the accident and it may create blockages in the subassemblies, which would lead to the next phase.
- Or if there is an important blockage: the accident enters a transition phase, then there is the hexagonal can going into melting, the zone above the fissile zone collapses and leads to a core slump-down and a secondary power excursion. The accident ends by a vapour bubble expansion which disperses the fuel.

2. ULOF static studies

In order to understand ways to reduce re-criticality phenomena and possible strategies of mitigation, studies have been performed in static with the ERANOS neutronic code system [3]. These studies only aim at understanding the phenomena occurring during the accident. Indeed, because they are calculated in static, the numerical values which are given are only orders of magnitude and more precise calculations (in transient) must be performed to obtain more accurate values.

2.1 Analysis of re-criticality phenomena

The accidents are divided into several steps and the reactivity insertions at each step are being analyzed. The scenario was divided into 4 schematic static images (Figure 2).

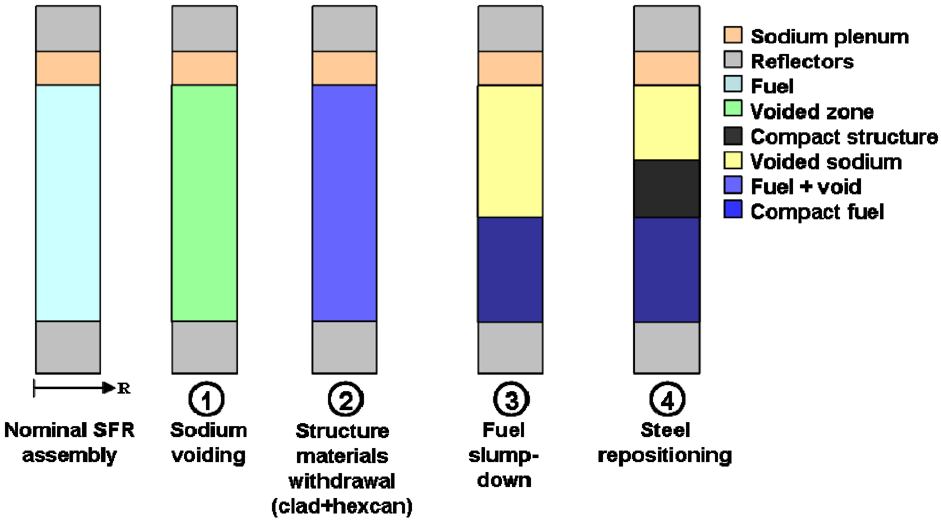

Figure 2: Modelled phases for the slump-down of a CP-ESFR core

Reactivity effects were calculated for each image in 2D (RZ) for the CP-ESFR core [4] [5] [6] with the reference code for fast neutron reactor ECCO/ERANOS [3] (Table 1).

Table 1: Reactivity insertion (in pcm) caused by each step of the scenario for the CP-ESFR core

	CP-ESFR
Sodium voiding (1)	1660
Structure removal (2)	6831
Fuel slump-down (3)	2246
Structure repositioning (4)	1115

The study demonstrated that different phases have a positive effect on reactivity which were understood by analysing the neutron balance:

- Sodium voiding: sodium removal leads to an energetic spectrum hardness ⇒ neutrons are left at a higher importance.
- Structure removal: reduction in neutron absorption ⇒ increase in fission.
- Fuel slump down: reactivity addition due to a decrease of radial leakage. If the core had an infinite radius (no radial leakage), there would be no reactivity addition during slump down.

This study illustrates the importance of the cladding removal – a reduction of neutron absorption - as well as the radial leakage changes during the core slump-down.
Each step can be associated to a solution which enables to limit the reactivity insertion:

- Sodium voiding: decreasing the sodium volume fraction (reducing the volume power), reducing the core height or/and adding a sodium plenum.
- Structure removal: decreasing the structure volume fraction.
- Fuel slump-down: increasing the fuel volume fraction, limiting the radial leakage in the nominal state (by decreasing the height of the core for instance).
- Structure repositioning: decreasing the leakage in nominal or choosing a material for structure miscible with the fuel.

2.2 Analysis of possible mitigations

The amounts of fuel to eject or of absorber to inject in this accident are being investigated.
The fuel mass to eject and the quantities to add to avoid re-criticality were calculated for different molten cores with the code ECCO/ERANOS in 2D-RZ. Cores have one enrichment zone, with a 2.2 meter radius.
Figure 3 presents critical height if fuel and structure remain melted homogeneously, with dependence on the core enrichment.

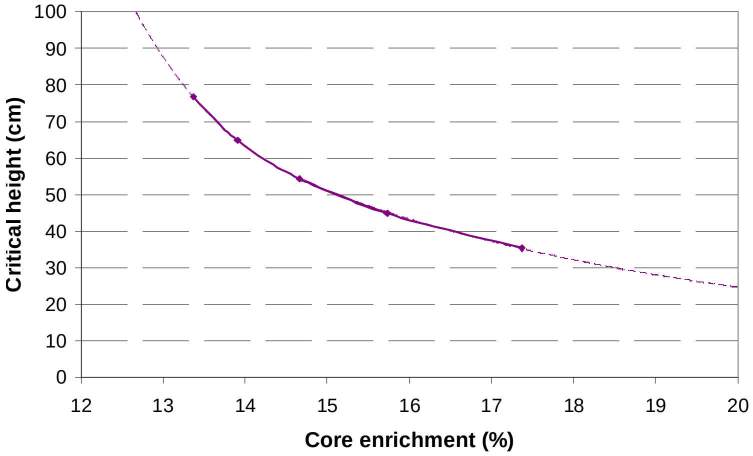

Figure 3: CP-ESFR Fuel Ejection

Figure 4 gives the amount of absorber or diluting material to add homogeneously to the mixture of fuel and structure, with dependence on the core enrichment. Eu_2O_3 and UO_2 have been selected for that purpose as being miscible with the fuel.

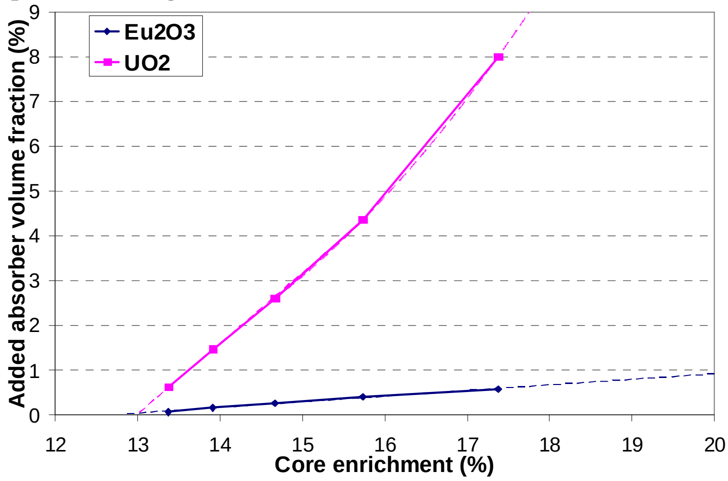

Figure 4: Absorber Addition in CP-ESFR.

Figure 5 gives the mass to eject in combination to the addition of mass absorber when fuel and structure stay melted homogeneously.

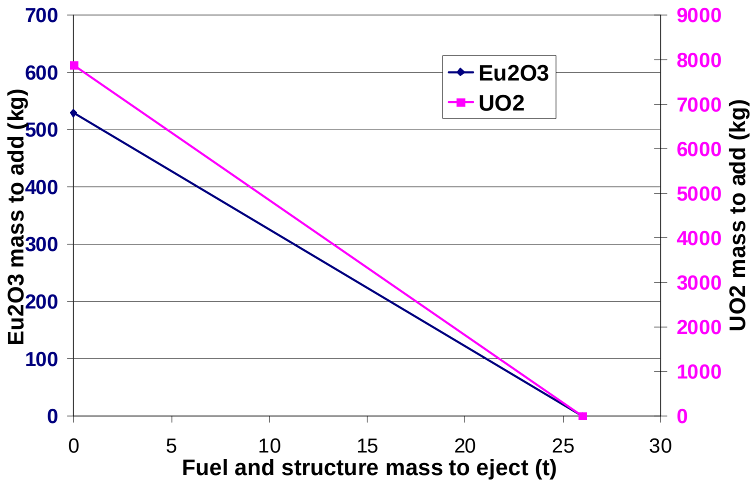

Figure 5: CP-ESFR Fuel Ejection and Absorber Addition.

The amount of fuel to eject or of absorber to add to avoid re-criticality during an ULOF has been estimated in static conditions:

- 29% fuel to eject (or 26tons or 3.2m^3)
- 4.3% UO_2 to add (or 0.75m^3 or 7.9tons)
- or 0.4% Eu_2O_3 to add (or 0.07m^3 or 0.5tons)

It appears that the amount of fuel to eject or absorber to add remains significant and mitigation has to be done at the various phases with a combination of these 2 solutions.

2.3 Analysis of re-criticality phenomena

These values give tracks to possible arrangements and dispositions to be taken to avoid re-criticality and hence the possibility of going into severe power excursions.
This study illustrates the importance of the cladding removal – a reduction of neutron absorption - as well as the radial leakage changes during the core slump-down. The amounts of fuel to eject or of absorber to inject in this accident have been found to be rather huge and that, in order for these solutions to be efficient, the possible arrangements and dispositions to be taken to avoid re-criticality must be available as soon as possible before the slump-down of the pool but also during the different phases of the accident.

3. ULOF scenario studies

Tracks to possible arrangements and dispositions to be taken to avoid re-criticality are being reviewed in the following and hence the possibility to avoid going into severe power excursions.

3.1 Primary phase

The reactivity insertion during the primary phase is a combination of different feedback effects. For the CP-ESFR core, the sodium void effect is positive and is occurring just after the Doppler effect and the axial thermal expansion effect. Reducing the void effect changes the behaviour of the core during an ULOF as it is illustrated in the following study where the void effect is set to zero without any other change in the core characteristics (Figure 6).

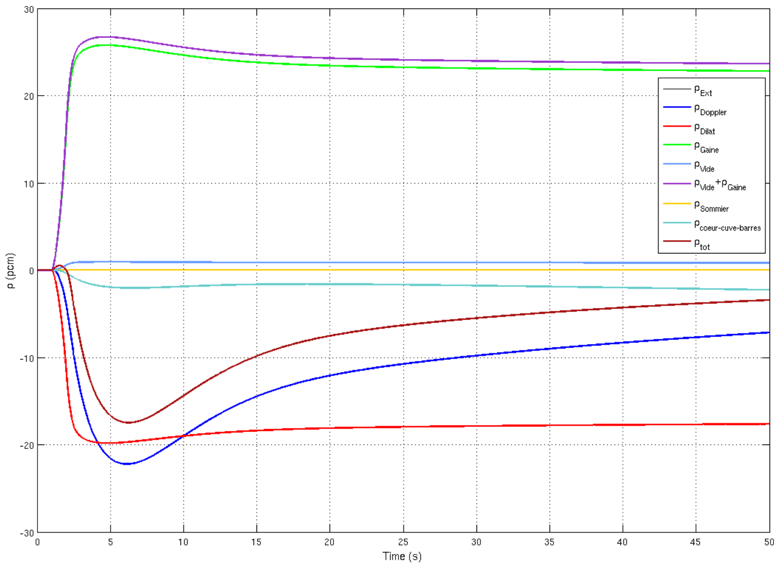

Figure 6: Feedback effects in case of ULOF with zero sodium void

The sum of all reactivity effects remains null during all the accident in opposition to what is achieved in CP-ESFR (Figure 7).

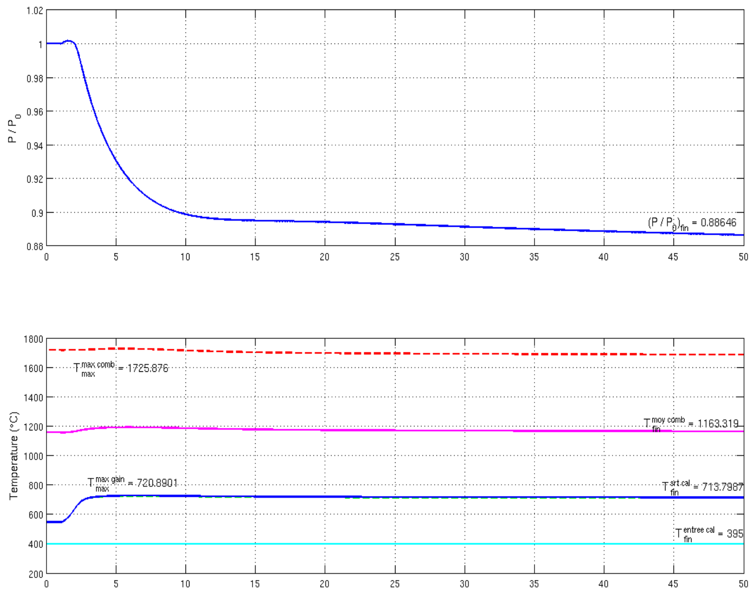

Figure 7: Power and Temperatures during ULOF when sodium void is set to zero

The transient here (performed with MAT4DYN, a simplified tool simulating one representative pin) shows that cancelling the voiding effect changes entirely the transient: the sodium does not boil, the claddings do not melt, and the fuel remains intact.

However, reducing the void effect to such low values remains a challenge. It requires reducing the power density in order to decrease the sodium void fraction, to reduce the height to increase axial leakage, to introduce a sodium plenum to enhance neutron leakage in case of sodium voiding and possibly add some heterogeneity in order to further enhance neutron leakage. All these features require adequate neutronic tools with in particular transport methods able to treat void regions. Benchmarks on the BN1800 cores have showed the limits of current modules and highlight the need to conduct void experiments in the critical facilities like MASURCA or BFS.

At the very edge of such concepts, core designs that can achieve sodium stabilized boiling above the core are also studied. The chimney effect created by void above the core gives some delays in stopping the reactor.
Also, absorbers can be introduced in a passive mode during that phase. The passive systems need to be reliable in order to make a robust demonstration. The system envisaged at that phase of the accident is the SAC (Système d'Arrêt Complémentaire) [7]. This system is based on magnets which lose their properties once temperature is reaching an elevated temperature. The shut down system dropped automatically in the core by a Curie device which cancels the magnetic fields of the gripper as soon as Na temperature reaches some high values. This type of arrangement has been used in Phenix and Super-Phenix where no mechanical failure of electromagnets has been encountered. The same system envisaged for that phase of the accident at JAEA is the SASS (Self Actuated Shut-down System). This type of arrangement is undergoing validation with both in out-of-pile situations or in reactor conditions so as to make a robust demonstration [8] [9].
An alternative to this diversified device is the SEPIA system (SEntinel for Passive Insertion of Antireactivity) being studied in France [10]. For instance, this could be achieved by inserting B_4C pebbles inside a limited number of fuel pins within subassemblies. Their release would be actuated when sodium temperature in the fissile region exceed operating values. Calculations performed confirm the potential efficiency of such SEPIA systems to cope with unprotected loss of flow. Again, reliability studies have to be conducted.

3.2 Transition phase

In this phase, a first fuel melting occurs and hence the reactivity can either increase if there is a fuel slump-down or decrease if the fuel is dispersed. In that phase, the driving force is mainly coming from the fuel-sodium interaction but the release of fission products plays a role too. The thermal conductivity of sodium at atmospheric pressure is very high (140W/m.K) while its boiling temperature at atmospheric pressure is of 1150K. Sodium boiling dries the claddings and make them melt ($T_{steel\ melting\ point}$ =1500K). But, when the molten fuel is released from the pin, it is at such a high temperature ($T_{fuel\ melting\ point}$ =3100K) that it reaches the sodium at its triple point temperature: 2500K. Temperature exchanges are very quick because of the sodium high conductivity. For this moment on, an enormous pressure (~5000bars) exists in the core. The accident is driven by a diphasic fuel-sodium vapour bubble expansion.
Consequently, during that transition phase, solutions are studied so as to master the fuel ejection using either a natural phenomena within the pin: the squirting effect or constructive solutions such as the FAIDUS (Fuel subassembly with Inner DUct Structure) [11] [12].
The FAIDUS subassembly is a JSFR subassembly where 17 pins are removed to make a guide tube of sufficiently large size for the fuel to be ejected from the core in case of CDA. The high vapour pressure in the core acts as a driving force for fuel discharge and fuel is ejected in the upper part of the core.

Calculations were performed at JAEA to study the FAIDUS subassembly using SAS4A [13] [14] and SIMMER [15] [16] [17]: SAS calculations are performed with and without FAIDUS subassemblies and then SIMMER calculations are performed using a power map calculated with SAS. These calculations show that 20% of the molten fuel could be ejected from the core thanks to the FAIDUS subassemblies. This, however, is not sufficient to avoid re-criticality and hence, other mitigating systems are required.

3.3 Secondary phase

Part of the fuel in the previous phase is ejected in the lower or/and upper part of the core, by both the squirting effect and by fuel-sodium interaction. This ejected fuel cools and forms plugs. As temperature increases, claddings and wrappers melt and consequently, the upper part of the core is no longer supported and collapses.
There is then fuel slump-down and a second power excursion occurs.
To study that phase, a method used in the past for defining the maximum energy release during the accident and for verifying that the vessel can withstand it, has been followed. A specific study has been done on Super-Phenix so as to demonstrate that such calculation can be repeated. A parametric study based on that type of approach was performed so as to get an in-depth understanding of the impact of the upper core arrangement on the secondary phase sequence of the accident: the one following the transition phase. The beginning of the accident, the so-called primary phase, which is assumed to release energy, was not calculated in transient but the configuration at the end of this phase was defined thanks to some assumptions. The assumptions are very much based on the fact that the movement of materials stops whenever once the core is back to criticality (after the ejections of materials due to the energy release of the primary power excursion). Given these hypotheses, the configuration was looked for in static with ERANOS, while the following of the accident (the so called secondary phase) was calculated with SIMMER.
Different upper configurations of the core and with different physical phenomena were compared: “with upper fertile blankets”, “with reflectors and without expansion chamber”, “with reflectors and with a 11cm upper expansion chamber where squirting effect is possible”, “with a sodium plenum and a 11cm upper expansion chamber where squirting effect is possible”, “with a high upper expansion chamber where squirting effect is possible”, “with a high upper expansion chamber where squirting effect is not possible”. For each upper core configurations, three calculations were performed: “with only fuel ejected in the upper part of the core”, “with fuel and half of the claddings ejected in the upper part of the core”, and “with fuel only ejected in the lower and in the upper part of the core”.
The static results showed that if fuel is ejected far from the core, it has less effect on the reactivity, and consequently, less fuel has to be ejected from the core to be critical again.
When looking at the transient results, the following of the accident, the amplitude of the power excursion, were very different but on the whole, all the transients happened to behave the same way: the fuel slump-down made the reactivity increase, most of the time leading to the power excursion; sometimes, steel falls in the pool, delaying the reactivity peak. After the power peak, fuel and steel are ejected from the pool, creating a voided zone in the core.
Two points are however important to notice: all the transients led to a power excursion, the addition of absorber above the plenum did not enable to prevent it because the transient is much too fast; the secondary phase of the accident lasts at maximum 0.4 seconds, it is very fast and thus, it is difficult to prevent it: the accident must be stopped sooner, during the primary phase.

Hence it can be concluded that without specific measures, the molten fuel is sent back to the core and may cause another criticality event.

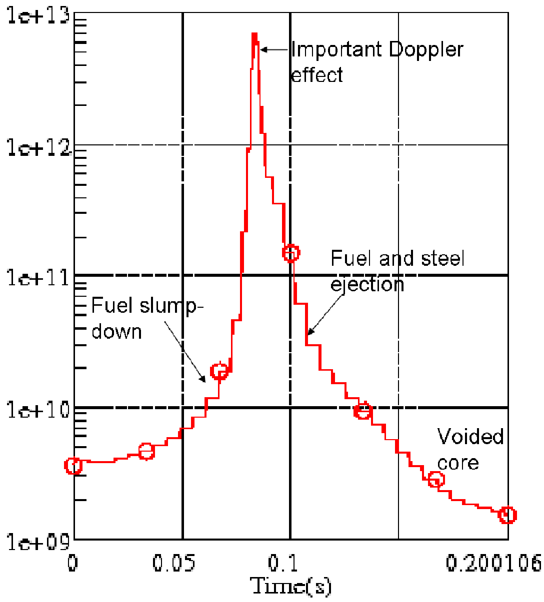

Figure 8: Power excursion during the secondary phase of the ULOF for a configuration with blankets

The CRGT (Control Rod Guide Tube [18] concept is a subassembly dedicated to fuel discharge (for example a guide tube of control rods) aiming at preventing another criticality event. This system needs specific features to operate: the CRGT has to be connected to the lower plenum which is at high pressure, but it is necessary to have a system decreasing the pressure for the fuel to be ejected. The molten fuel will thus be ejected in the lower part of the guide tube.
As far as the CRGT is concerned, the study of the design is done so as to avoid re-criticality when the molten fuel is moving from the top of the core to the core catcher located below.

4. Analysis of the ULOF studies

An important point associated to these studies is the reliability of the calculations so as to ensure a robust demonstration. Uncertainties are very difficult to assess in such ULOF accident but without taking them into account makes it difficult to conclude on the conservatism of the accident.
The code should enable to suppress the favourable effects to see the impact on the calculations. In the Monju safety report for instance [18], the voiding effect of the core was increased by 30% due to uncertainty and the axial expansion feedback effect which has beneficial effects was suppressed to bring some conservatism to the calculation. A better knowledge of these uncertainties together with a better modelling of the axial expansion feedback effect would lead to reduce the magnitude of the conservative energy release.
Also, in a recent study revisiting past calculations, event sequences were analyzed again to assess the effect of the mechanical energy release during ULOF. A significant advance has been made in the safety analysis codes reflecting the knowledge obtained through extensive safety research programs in the last decades, notably the CABRI in-pile experiments [18] [19]. The present results with the advanced analysis codes showed that the mechanical energy release in the

current Monju core was reduced although the changed neutronic characteristics of the core have led to an increased value.

A quite large uncertainty associated to the movement of materials within the core exists during the transition phase. The assumptions, used for Super Phenix, are based on the fact that the movement of materials stops whenever once the core is back to criticality (after the ejections of materials due to the energy release of the primary power excursion). This was verified by a full SIMMER calculation and results compared. The full SIMMER calculation did really show that criticality was achieved at the end of the transition phase but the distribution of materials were not really well represented as can be seen on Figure 9.

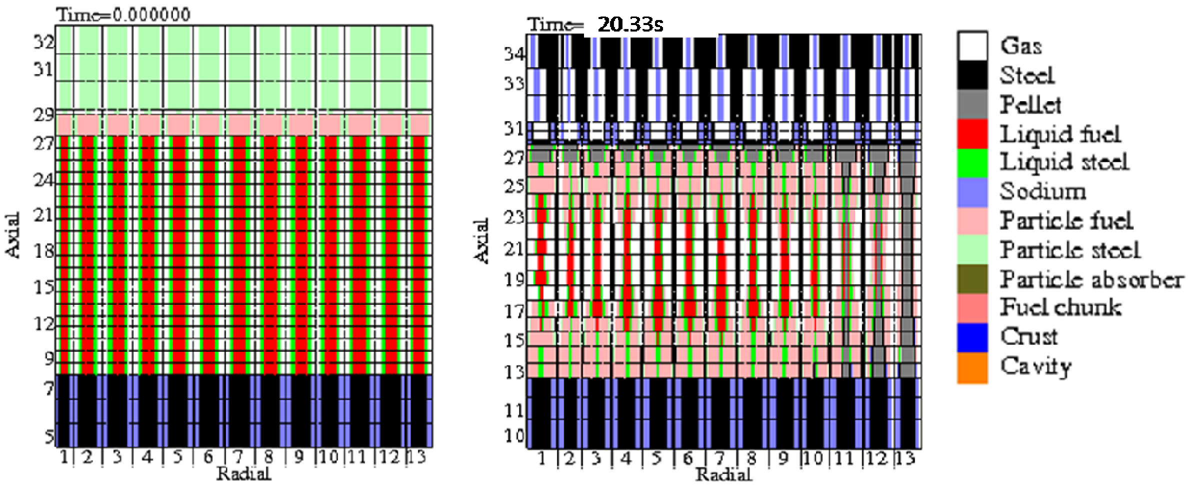

Figure 9: Material distribution at the end of the transition phase of the ULOF for simplified and full calculations

The two calculations were compared for the second power excursion and showed a much larger power excursion with the method used for Super-Phenix and a very light one with the new method of calculation. In this case, the study performed with a lot of hypotheses leads to much more severe situations. But, this simplified approach to tackle the problem illustrate the fact that the large uncertainties associated to the movement of materials in the transition phase are somehow limited in magnitude by the fact that the core is back to criticality at the end of that phase.

But full transient calculations are necessary in order to get more precise safe arrangements. In order to quantify somehow the uncertainties associated to these calculations, a comparison has been performed with 2 calculation routes:

- Use of SAS4A for the primary phase of the accident, and then SIMMER-III for the secondary phase,
- Use of SIMMER-III to calculate both the primary and the secondary phases.

The comparison between the usual route SAS4A/SIMMER-III and SIMMER-III showed important discrepancies on the times and on the amplitudes of the power peaks (Figure 10).

Indeed, SIMMER delays and over-estimates the first power excursion. The fact that the first power excursion is much more energetic in the whole SIMMER calculation makes the reactivity decrease more after the first peak and then, the secondary power excursion does not exist; in the SAS/SIMMER calculation, there is a slight secondary power excursion.

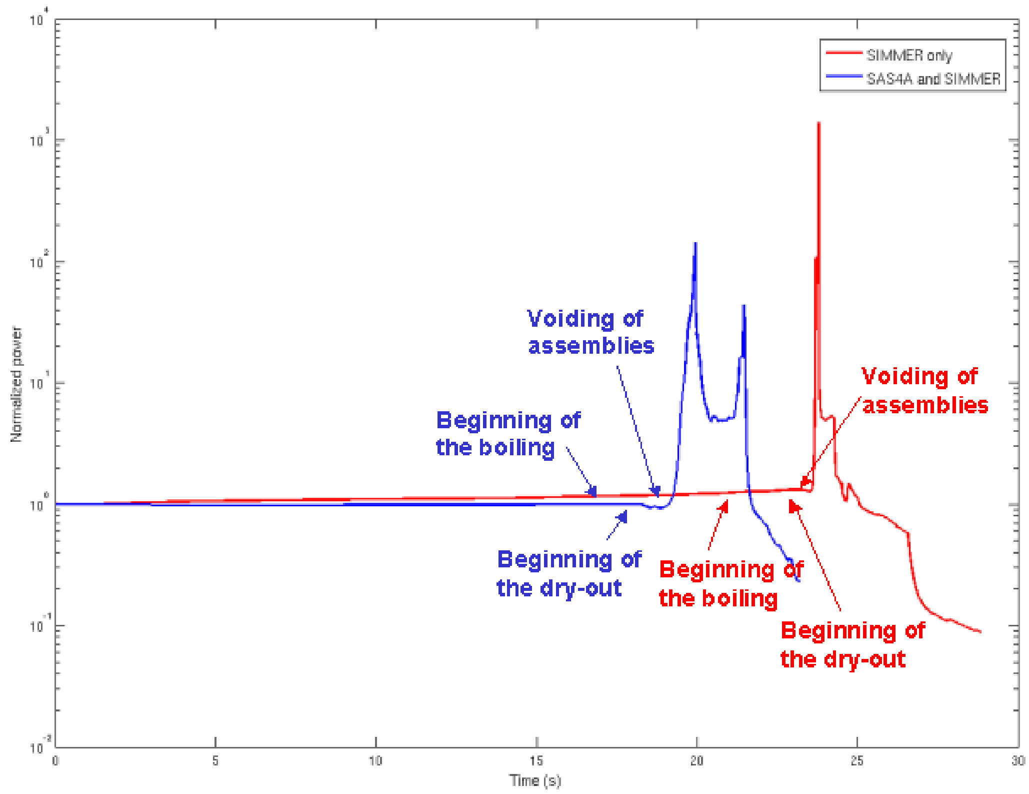

Figure 10: Power change during ULOF for two different calculation routes

The discrepancies come from different points:

- The model of the calculation:
  - The "Power/Flow rate" ratios were bigger in SAS than in SIMMER (but that is due to the 2D model of SIMMER).
  - The use of the SPIN model in SIMMER does not describe the temperature gradient in the pin (but the more accurate DPIN model [20] takes too much calculation time to be used).
- The models in the codes:
  - The expansion effects of materials are not modeled yet in SIMMER and they are of major importance when calculating the primary phase of the accident. A model of material expansion with feedback effects is being implemented in SIMMER at KIT.
  - Coherent parameters for the 1D model of the subassembly must also be given.
  - A pre-irradiation model should be added to SIMMER (for instance by coupling GERMINAL [21] with SIMMER).

But despite the improvements required in the code, the ULOF scenario for the CP-ESFR core is ascertained. There is an important primary power excursion due to the sodium voiding, the subassemblies then begin to melt and there is a slight re-criticality. Calculations need to be validated on critical experiments [22] but also on material relocation experiments (CABRI [14] [18] [24], SCARABEE [25], others [26] [27]), rather than by performing comparisons. But this comparison illustrates the significant changes a rather weak validation might lead.
Moreover, if solutions to prevent the re-criticality from the primary phase such as ejection of fuel and addition of absorber are being studied, tools to perform the transients need to be improved. However, this study illustrates that a design of a reactor which will practically eliminate the scenarios leading to whole core melting will require a very robust demonstration. Furthermore, even with current approach, the study shows that there are no simple solutions to achieve such a goal and that many devices need to be introduced each of them requiring their own validation.

5. Conclusion

Among all the types of accidents to be considered for the safety licensing of a plant, some have a very low probability of occurrence but might have very important consequences: the severe accidents or Hypothetical Core Disruptive Accidents (HCDA).
The reactivity effects associated to the mitigation of the Unprotected Loss Of Flow (ULOF) have been studied in a simplified manner with the objectives to understand what could possibly make the reactivity increase during this accident and what could be the means to reduce the energetic release of the scenario (ULOF).
For that purpose, the accidents were studied in static with the ERANOS neutronic code system. The accidents were divided into several steps and the reactivity insertions at each step have been analyzed. This study illustrates the importance of the cladding removal – a reduction of neutron absorption - as well as the radial leakage changes during the core slump-down. The amounts of fuel to eject or of absorber to inject in this accident give tracks to possible arrangements and dispositions to be taken to avoid re-criticality and hence the possibility to go into severe power excursions.
The possible solutions to maintain the energetic release of the ULOF within acceptable limits is so as to act as soon as possible with the introduction of absorbing materials, introduction triggered by self-actuated systems located within the fuel sub-assemblies and operating independently from the control rods. Since, it has been found that the amount of absorbing materials required is rather large once the cladding is starting to melt, the possibility of having clad materials with higher melting point such as Vanadium based materials should be envisaged. Also the height of the core should remain as low as possible since reduction in core height is another source of reactivity insertion, one should try to contain. The possibility of having strong reactivity feedbacks has also been illustrated with the void effect being set to zero. Designing a core with limited void effect should then be highly favorable for the accident.
Since, it is very difficult to contain the melted fuel with the driving force of the fuel coolant mechanical interaction; one has to use either FAIDUS or CRGT type of arrangement to channel the fuel towards the core catcher where it could be cooled in stable conditions.
The transients are currently being studied with the SAS and the SIMMER codes coupling mechanics, thermo-hydraulics and neutronics. This way to address the topic is being reviewed since safety dossiers require a robust demonstration with the assurance of being away from cliff edges. Some alternatives calculation routes are being investigated – in particular for the primary

phase with ERANOS or SIMMER replacing SAS - with the objective of better understanding the possible sources of uncertainties and on the long run of reducing them. SIMMER is always used to calculate the secondary phase of the ULOF.

Numerous studies corresponding to various assumptions and plant designs have to be conducted, the challenges lying in the validation process on experiments, in particular when using passive mitigating systems such as absorbers and channels to eject the melted fuel.

6. References

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