COOLANT VOID EFFECT INVESTIGATION - CASE OF A NA-COOLED FAST REACTOR

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ABSTRACT

In the frame of the last EURATOM-FP7 Program, a large sized Sodium-cooled FR (SFR) has been studied. Mixed carbides fuel (U, Pu)C has been adopted for the backup core solution and important work has been also performed in order to obtain an "optimised" backup configuration "close" to the reference one, which is fueled by mixed oxides fuel (U, Pu)Ox. The peculiarity of both core designs (the reference configuration and the optimised backup configuration) is the adoption of a 60 cm Plenum zone in the upper part of each fuel assembly (FA), that is filled by coolant, in order to mitigate (when emptied) the core positive coolant void effect. This paper presents some results of a detailed study of the coolant void effect for the above SFR with mixed carbides core. Many aspects, like geometric heterogeneity, the burnup state, the operating conditions, etc., have been taken into consideration in order to obtain information about the "propagation" and the behaviour of the coolant void effect itself. The performed study investigates also the coolant void effect consequences on some reactivity coefficients, which are important for a safe behaviour of the reactor. The investigation consisted in the steady state simulations of the reactor on different operating conditions in Monte Carlo approach.

Key words: Core Design, Reactivity Coefficients, Coolant Void Effect, Nuclear Data, Monte Carlo.

Background

Fast reactors neutron economy, good heat transfer characteristics and a boiling point higher than the normal operating temperature of the reactor - which allows the avoidance of a high pressure primary system - make the liquid metals attractive coolant materials. Of course, the coolant boiling somewhere in the core, leading to the creation of voids, cannot be excluded from an accident scenario. Independently from the mechanism which causes the coolant boiling, or the loss of the coolant, normally a large positive reactivity contribution could be introduced. In other words, from safety point of view the coolant void effect is a very important neutron parameter and the consequences on the performances and on the behaviour of the reactor are of primary importance. The coolant void effect depends on many factors, like: fuel type, enrichment, core geometry, operating conditions, coolant void scenarios, etc. Moreover, any optimisation process regarding power distribution, burn-up swing, conversion ratio, as well as pins lattice pitch P/D, core H/R ratio, etc., impacts tightly on the coolant void effect behaviour and its study becomes a really complex issue.

Introduction

For the understanding of the phenomenon and its consequences, it would be useful to highlight from the beginning that the coolant void (coolant loss) reactivity effect is exceedingly space-dependent. The reason of this assertion becomes evident from the physical effects associated with the coolant voiding (coolant loss):

spectral hardening: caused by a reduced moderation of the neutrons -due to the lack of coolant - leading to an increase of the neutrons average energy, having as consequence the increase of the neutrons importance, and as a result a positive reactivity contribution;

self-shielding variation: caused by the coolant absence leading to a small reactivity contribution;

coolant capture effect: coolant captures elimination caused also by the coolant absence, introduces a small positive reactivity contribution;

increased leakage: deriving again from the lack of coolant, which reactivity contribution (especially near the core edge) can counterbalance~~s~~ the reactivity effect of the spectral hardening.

Figure 1 [1] shows the behaviour of the total elastic and inelastic scattering cross-sections for ^{23}Na and Pb isotopes, the most attractive liquid metals coolants; below about 0.5 MeV the slowing down is practically due to elastic scattering events, while for higher energy values the inelastic scattering events become competitive with those of elastic scattering.

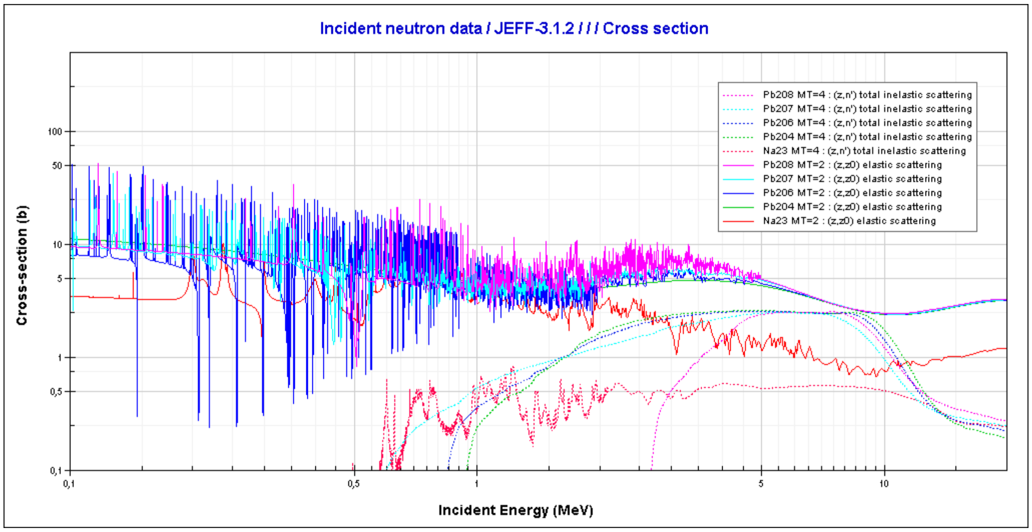

Figure 1 *Total elastic and inelastic scattering cross-sections for ^{23}Na and Pb isotopes*

Based on the transport theory formalism, the perturbation theory allows the evaluation of the reactivity contribution of each physical event, determining the coolant void reactivity effect. Unless a normalization constant, it follows that [2]:

spectral hardening contribution:

$$\rho \propto \int \sum_{g} \Phi_{g}^{*}(\vec{r}) \left[\sum_{g'<g} \delta\Sigma_{g'\to g}(\vec{r})\Phi_{g'}(\vec{r}) - [\delta\Sigma_{erg}(\vec{r}) + \delta\Sigma_{irg}(\vec{r})]\Phi_{g}(\vec{r}) \right] d\vec{r} \qquad (1)$$

self-shielding contribution:

$$\rho \propto \int \sum_{g} \Phi_{g}^{*}(\vec{r}) \left[\chi_{g} \sum_{g'} \delta(\nu\Sigma_{f}(\vec{r}))_{g'} \Phi_{g'}(\vec{r}) - \delta\Sigma_{ag}(\vec{r})\Phi_{g}(\vec{r}) \right] d\vec{r} \qquad (2)$$

coolant capture contribution:

$$\rho \propto \int \sum_{g} \Phi_{g}^{*}(\vec{r}) \delta\Sigma_{Na,cg}(\vec{r})\Phi_{g}(\vec{r}) d\vec{r} \qquad (3)$$

leakage contribution:

$$\rho \propto \int \sum_{g} \nabla\Phi_{g}^{*}(\vec{r}) \delta D_{g}(\vec{r}) \nabla\Phi_{g}(\vec{r}) d\vec{r} \qquad (4)$$

In terms of neutrons balance equation, i.e.: total loss = total gain in the steady state configuration, where:

$$total\ loss = captures\_rate + fissions\_rate + loss(n,xn)\_rate + leakage \qquad (5.1)$$

$$total\ gain = \nu * fissions\_rate / k_{eff} + gain(n,xn)\_rate \qquad (5.2)$$

$$gain(n,xn)\_rate = 1*(n,1n) + 2*(n,2n) + 3*(n,3n) + ... = \sum_{\mathrm{x}} \mathrm{x} * (n,\mathrm{x}n) \qquad (5.3)$$

the reactivity variation of the whole system, between normal and voided states, becomes:

$$\delta k_{eff}/k_{eff} = \sum_{j} C_{j}\delta\xi_{j}/\xi_{j}\ ;\ C_{j} = \left(\delta k_{eff}/k_{eff}\right)/\left(\delta\xi_{j}/\xi_{j}\right)\ \xi_{j} \in [\nu, fiss\_rate, capt\_rate, ...] \qquad (6)$$

Based on the set of equations (5) the following analytical forms, for the coefficients C$_j$, would be obtained:

$$\begin{aligned}
&C_{\nu} = 1, \qquad C_{fiss\_rate} = 1 - k_{eff}/\nu \\
&C_{capt\_rate} = -k_{eff}(capt\_rate/\nu * fiss\_rate), \\
&C_{loss(n,xn)} = -k_{eff}(loss(n,xn)\_rate/\nu * fiss\_rate), \qquad (7) \\
&C_{gain(n,xn)} = -k_{eff}(gain(n,xn)\_rate/\nu * fiss\_rate) \\
&C_{leakage} = -k_{eff}(leakage\_rate/\nu * fiss\_rate).
\end{aligned}$$

This paper deals with the behaviour of the coolant void effect, the investigation of some of its dependencies and the consequences on some other neutron parameters which are important for a safe behaviour of the reactor. The numerical results are referring to a large-sized Na-cooled core (SFR) [3], fuelled by mixed mono-carbides (UC, PuC), in an optimised configuration as it has been defined and characterised within the FP7-EURATOM program CP-ESFR [4].

SFR core description and assumptions

The optimised (U, Pu)C core configuration consists of two enrichment zones, of 225 and 228 FAs, respectively, having 271 fuel pins/FA, with fresh fuel Pu content of: 14.05% and 18.35%, respectively.

The (Pu + Am) vector is constituted by ^{241}Am, in the ratio of: ^{241}Am / (Pu + ^{241}Am) = 0.0077, with:

^{238}Pu: 3.5977%; ^{239}Pu: 47.7577%; ^{240}Pu: 29.8902%; ^{241}Pu: 8.2939%; ^{242}Pu: 10.4605%,

while the complementary material is depleted Uranium (0.25% of ^{235}U).

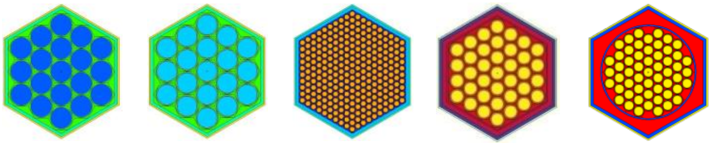

Figure 2 *Sections of: Reflector, Absorber, Fuel & Control Rods (CSD, DSD) assemblies.*

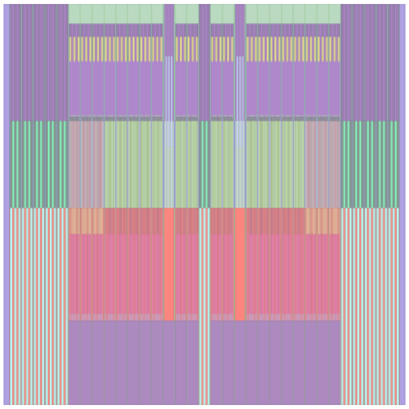

Figure 3 *Core layout: xy and yz plane sections.*

Figures 2 and **3** show the single-assembly geometry and the core configurations used for a full heterogeneous description in the simulations performed during this investigation. Detailed input data for core configurations can be found in [3, 4]. Since the contribution of “loss” of coolant in the Plenum zone works to mitigate the positive contribution, in case of “loss” of coolant in the active core, due to the increased neutron leakage, for understanding the phenomenon, such a contribution is without a particularly physical meaning. So, for this kind of study, it was decided to investigate the reactivity variation in case of “loss” of coolant in the whole active core, but not in combination with the voided Plenum zone.

The steady state neutron studies have been performed in stochastic approach using MCNP5 (version 1.6) & Serpent_1 (version 1.18) Monte Carlo codes [6, 7], with continuous energy single-nuclide cross-section libraries taken from JEFF 3.1.2 and/or ENDF/B-VII evaluated data files [1,8], using NJOY99_upd364 [9], and/or MCNP/MAKXS [10], codes.

The investigated configurations are based on the following operative conditions:

- BoL: Start up (fresh fuel isothermal state at 395°C), corresponding to T_{cool} inlet temperature;
- BoL: Hot state, or: full power state characterised by:
    - T_{cool}: Inlet=395 °C, Outlet=545 °C,

  - $T_{absorber}$: B4C=627 °C, and
  - T_{fuel}: (U, Pu)C=887 °C, while
  - cladding temperature has been assumed to be equal to the axial average T_{cool};
- BoEC and EoEC: Beginning / End of Equilibrium Cycle configurations, characterised by a burnup reactivity swing (1 year cycle length between BoEC and EoEC) of:

$$\Delta k_{BU} = -\ 0.00370 \pm 0.00049$$

or, at 3σ confidence interval,

$$-\ 0.00517 \leq \Delta k_{BU} \leq -\ 0.00223$$

while the EoEC core cofiguration is characterised by the criticality levels of:

$$k_{eff} = 0.98585 \pm 0.00032 \qquad \text{and} \qquad k_{eff} = 1.00718 \pm 0.00035$$

at inserted and withdrawn CRs states, respectively. Other “hybrid” configurations have been adopted in order to explain the coolant void effect behaviour. Important remark: when comparisons are envisaged, they are performed between results coming from coherent data / codes.

SFR core coolant void effect investigation

Table 1 collects results regarding coolant void reactivity worth for the configurations taken into consideration. By hardening the neutrons spectrum a progressive increase of the reactivity worth has been observed. Within the equilibrium cycle, the results obtained show the impact of the burnup, i.e the consumption of fissile material and the build up of fission products, leading to a further spectrum hardening. With regard to the Pu content impact, at EoEC it has been found that:

- Inner Active Core: $(\Delta k_{eff}/k_{eff})$Inn-Act.Core = + 0.01240 ± 0.00047,
- Outer Active Core: $(\Delta k_{eff}/k_{eff})$Out-Act.Core = + 0.00503 ± 0.00048

Table 1 *Coolant void reactivity worth and variations of average neutrons energy and of reaction rates.*

	BoL Startup State	BoL Full Power	Equilibrium BoEC & EoEC
$(\Delta k/k)_{eff}$	+ 0.00859 ± 0.00028	+ 0.00980 ± 0.00029	+ 0.01490 ± 0.00038 + 0.01715 ± 0.00029
δ <E_n>	+3.49%;	+3.56%	+ 3.27% (*)
^{238}U δ(cpt)	– 0.85%,	– 1.11%,	– 1.09%, (*)
^{238}U δ(fis)	+ 3.98%,	+ 4.00%;	+ 4.24% (*)
^{239}Pu δ(cpt)	–7.75%	–7.36%,	– 6.28% (*)
^{239}Pu δ(fis)	–0.07%,	+0.13%.	+ 0.69%. (*)

(*) at BoEC

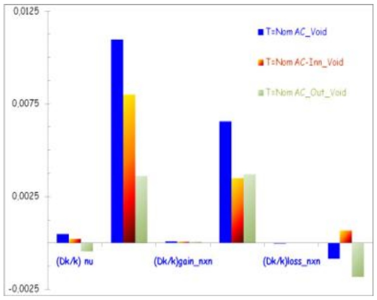

Figure 4 *Coolant void effect spectral decomposition*

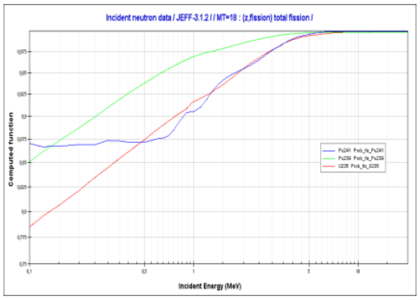

Figure 5a *Odd nuclei fission probability vs. neutron incident energy*

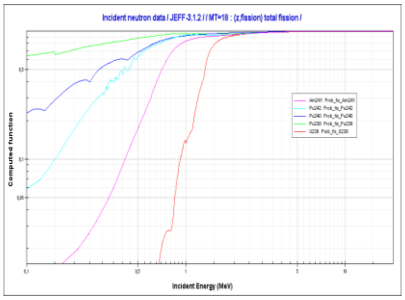

Figure 5b *Even nuclei fission probability vs. neutron incident energy*

Figure 4 show the neutron balance spectral decomposition between normal and voided states. The role played by the fissions is dominant, while a not negligible contribution to the positive reactivity is due to the captures rate reduction. The following values have been obtained:

for fissions: + 1.74%, for captures: -1.05% and for leakage: + 7.91%.

Moreover, a consequence of the "loss" of coolant is an increase of the neutrons (causing fissions) average energy which leads to a reduction of the captures and to a simultaneous increase of the fissions. While the relative reduction of the ^{239}Pu captures is six times higher than the relative reduction of the ^{238}U captures, the relative increment of the ^{239}Pu fissions is about 7 times lower than the relative increment of the ^{238}U fissions. This type of behaviour has been observed in the other cases investigated. Such a behaviour is common among even and odd nuclei; the **Figures 5a** and **5b**, which present the fission probability behaviour vs. incident neutrons energy show also the physical reason of the major contribution of the even nuclei to the positive reactivity in case of loss of coolant: the gradient of their fission probability is more accentuated with respect to the odd nuclei, that is typical for the nuclei characterised by a fission threshold energy. Of course among even nuclei the major role, in terms of reaction rates, is played by ^{238}U due to its high content in the fuel. So, the largest contributor to the positive reactivity worth, in case of loss of coolant, is ^{238}U followed by other even nuclei.

Other important aspect regards the spatial distribution of the reactivity worth; Figures 6a and 6b show the total and average per ring coolant void reactivity effect, characterised by a wavy behaviour.

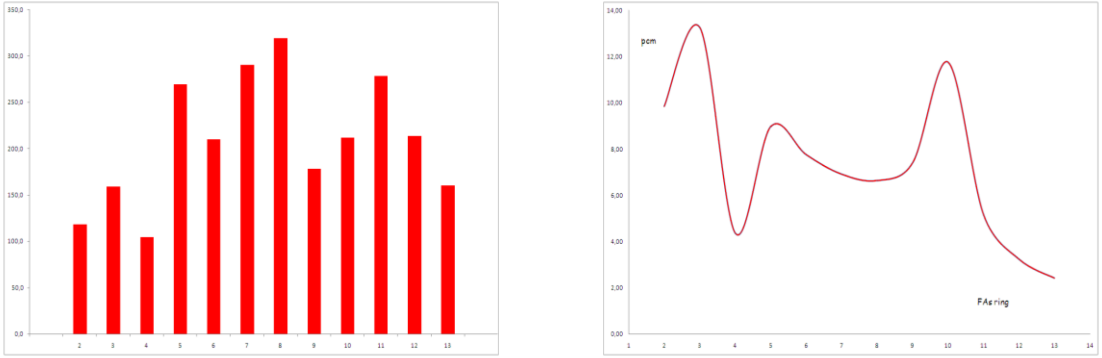

Figure 6 *Coolant void effect, total and average, ring by ring distribution*

Of course such behavior which is very far from the classical radial "monotone" one (typical for fresh fuel configurations) is tightly depending on a strong spatial heterogeneity of the core, **Figure 3**, as well as on the different enrichment zones created during the irradiation cycles. The above results highlight the strong space dependency of the coolant void (or coolant loss) effect, emphasizing the need of a particular attention on the modeling of the phenomenon and on the evaluation tools and approaches.

SFR core coolant void impact on the safety parameters

There is no doubt on the importance of the coolant void (or coolant loss) for the safe behaviour of the reactor. The concerns of the core designer should be the reduction, as much as possible but inside an optimisation context, of the coolant void effect, and in addition, the identification of the "paths" to mitigate its conseguences. Both require deep knowledge of the phenomenon. The simultaneous events of captures rate reduction and of fissions rate increase of the even nuclei, especially for the ^{238}U, when neutron spectrum hardens, are followed by the competion among phenomena that are important from safety point of view:

- an increasing (in absolute value) of the Doppler coefficient,
- an increasing of effective delayed neutrons fraction,
- a reduction of the neutrons generation time (faster kinetics).

All these are directly connected to both captures rate reduction and fissions rate increase in ^{238}U , while minor contributions come from the others even nuclei having similar behavior, as well as from the fission rate increase of the odd nuclei.
Concerning the Doppler coefficient for the EoEC configuration and for a temperature transient of:
T_{fuel}: (1160 -1500) K, it has been found:

- Nominal state: $\Delta k_{eff}/k_{eff} = -0.00141 \pm 0.00050$ □ $\Delta k_{eff}/\Delta T = -0.418\ (1 \pm 0.3536)$ pcm/K;
- Voided state: $\Delta k_{eff}/k_{eff} = -0.00173 \pm 0.00049$ □ $\Delta k_{eff}/\Delta T = -0.521\ (1 \pm 0.2807)$ pcm/K;

Detailed results regarding delayed neutrons fraction and generation time are collected in **Table 2**, where the percent variations are also included. Consistent differences have been found, especially for the neutrons fraction, with favorable impact on the transient evolution involving the coolant void effect.

Table 2 *Coolant void (coolant loss) impact on the Kinetics parameters*

	Nominal State	Voided State	Δ (%)
β_{eff} BoLStartup	0.00336 ± 0.00026	+ 0.00390 ± 0.00027	+16.07
Λ_{gen} (1E-7 sec)	$3.9749(1 \pm 0.0167)$	$3.7223(1 \pm 0.0154)$	- 06.35
β_{eff} BoL Power	0.00358 ± 0.00027	0.00385 ± 0.00027	+07.54
Λ_{gen} (1E-7 sec)	$3.8198(1 \pm 0.0145)$	$3.6551(1 \pm 0.0164)$	- 04.31
β_{eff} BoEC	0.00347 ± 0.00030	0.00425 ± 0.00030	+22.48
Λ_{gen} (1E-7 sec)	$3.8368(1 \pm 0.0189)$	$3.6938(1 \pm 0.0189)$	- 03.73
β_{eff} EoEC	0.00315 ± 0.00023	0.00399 ± 0.00031	+26.67
Λ_{gen} (1E-7 sec)	$3.7216(1 \pm 0.0146)$	$3.5627(1 \pm 0.0178)$	- 04.27

Remarks

Coolant void effects of a large sized Na-cooled FR fueled by mixed mono-carbides have been investigated. The aim of investigation has been the demonstration of the importance of the ^{238}U in the fuel which influences the behaviour and the values of many neutron parameters. (U, Pu)C fuel generally behaves in some different way with respect the (U, Pu)Ox. General trends have been confirmed, while the discrepancies depend on the different behaviour of graphite with respect to the oxygen during the neutrons slowing down process. Burnup and space dependencies of the reactivity worth have been also confirmed. Generally, the coolant void effect involves complex and interdependent phenomena, with dependencies on materials, fuel assembly geometry (i.e. P/D), core size and neutron performances. Important aspects, like the influence of the coolant void effect on many reactivity coefficients, that is important for the safe behaviour of the reactor, have been also confirmed. The fuel composition, conditioning the fissions to captures ratio, is the main factor causing the behaviour and of the consequences of the coolant void (loss) effect. Competition (and compensation) effects are running following the spectrum hardening. Also, the reactivity balance and the reactivity worth for (U-Pu) fuels are strongly dependent on the fuel composition due to the importance of the ^{238}U. Improvement of the effects of the coolant void can be achieved by an optimisation process, taking into consideration the impact on the global behaviour and neutron performances of the core. From safety point of view, the dynamic behaviour is conditioned by the combined effects of the positive reactivity insertion, the favourable prompt feedback from the Doppler effect, the increased delayed neutrons fraction and by a faster kinetics. Beyond the minimization of coolant void effect and the identification of mitigation paths of the effects, the concern of the core designer must be the correct evaluation of the set of the neutron data that should be provided for a correct safety analysis.

Acknowledgements

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