# OSCARD coupling software for Main Steam Line Break fault analysis
# Assessment of the mixing phenomena in the vessel

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## ABSTRACT

The main steam line break (MSLB) is an overcooling accident, which may lead the core to criticality and to a return-to-power, despite the reactor trip. The asymmetrical cooling between the steam generators and the limiting assumption of a RCCA bank stuck out of the core induce a strong radial distortion of the neutronic flux (“small core” effect).

The physical understanding of the mixing phenomena in both the lower and upper plenums of the vessel is a significant issue regarding the MSLB transient simulations. The neutronic and thermal hydraulic behavior of the core is influenced by the core inlet temperature distribution, induced by the mixing phenomena in the lower plenum. The flow and the heat exchanges in the primary loops can be affected by the mixing phenomena in the upper plenum. When the reactor coolant pump (RCP) trip is considered, the mixing assumptions can have a significant impact on the natural circulation which gradually becomes predominant.

EDF developed the software OSCARD which is devoted to simulating the MSLB transients, as part of EDF's PWR safety demonstration. OSCARD couples the CATHARE2, COCCINELLE and THYC qualified codes. CATHARE2 simulates the nuclear steam supply system (NSSS) behavior, including the safeguard systems, while the three-dimensional neutronic and thermal hydraulic phenomena in the core are accurately predicted by COCCINELLE and THYC.

In order to enhance the mixing effects in the vessel, some models have been developed to take into consideration these phenomena for both the upper and lower plenums. These models, which are inserted at the coupling interfaces, use mixing maps and coefficients as input parameters. Furthermore, an improved representation of the whole vessel inside CATHARE2 has been set up to be consistent with these mixing models.

Several sensitivity studies and a detailed physical analysis have then been performed to assess both the consistency and the relevance of these models inside OSCARD. This work focused on the assessment of the combined effects of all mixing phenomena in the vessel. Transients with and without RCP trip were considered. OSCARD has thus been improved to model the relevant physical phenomena during the MSLB transients. The validation of a limiting set of mixing parameters for these models is the next issue to be investigated. This work has already started, and will rely on both experimental results and CFD simulations.

**KEYWORDS**
MSLB, thermal hydraulics, neutronics, code coupling, vessel mixing phenomena

# 1. ABBREVIATIONS

| | |
|---|---|
| MSL | MAIN STEAM LINE |
| MSLB | MAIN STEAM LINE BREAK |
| PWR | PRESSURIZED WATER REACTOR |
| RCCA | ROD CONTROL CLUSTER ASSEMBLY |
| NSSS | NUCLEAR STEAM SUPPLY SYSTEM |
| ECCS | EMERGENCY CORE COOLANT SYSTEM |
| RCP | REACTOR COOLANT PUMP |
| CFD | COMPUTATIONAL FLUID DYNAMICS |
| SG | STEAM GENERATOR |
| RCS | REACTOR COOLANT SYSTEM |
| MSIV | MAIN STEAM ISOLATION VALVE |
| MFWS | MAIN FEED WATER SYSTEM |
| EFWS | EMERGENCY FEED WATER SYSTEM |
| MTC3D | 3D FULLY COUPLED METHODOLOGY |
| DNBR | DEPARTURE FROM NUCLEATE BOILING RATIO |
| MLPD | MAXIMUM LINEAR POWER DENSITY |
| SB-SLB | SMALL BREAK - STEAM LINE BREAK |
| 2A-SLB | DOUBLE-ENDED GUILLOTINE STEAM LINE BREAK |

# 2. INTRODUCTION

The Main Steam Line Break (MSLB) fault is a design basis accident of EDF’s PWR reactors. The MSLB fault is required to be investigated and the safety requirements have to be demonstrated. For these purposes, EDF have developed the software OSCARD [1] to perform accurate MSLB transient simulations. OSCARD couples together several codes:

- COCCINELLE: simulation of the spatial distribution and the evolution of the nuclear power [3],
- THYC-COEUR (THYC): simulation of the thermal hydraulic phenomena in the core [5],
- CATHARE2: simulation of the thermal hydraulic behavior of the NSSS and the safeguard system actuation [7].

Over the past few years, EDF have been upgrading the OSCARD software to improve the depiction of the physical phenomena during a MSLB transient. This paper presents most of the improvements which have been achieved in OSCARD. In particular, efforts have been made to model the vessel mixing phenomena, in both the lower and the upper plenum. The vessel mixing phenomena issues have recently been questioned by the French safety regulator, and have thus been investigated to great length.

This paper aims at assessing the ability of the OSCARD software to consistently predict all vessel mixing phenomena during MSLB transients, regarding both the vessel modeling and the mixing models which have been chosen.

This paper mainly focuses on the EPR$^{TM}$ reactor. Some points are therefore EPR specific.

# 3. MAIN ISSUES OF MSLB TRANSIENTS

## 3.1. MSLB transient description

The Main Steam Line Break (MSLB) is an overcooling accident, which may lead the core to criticality and to a return-to-power, despite the reactor trip. This accident is considered within the design basis. Thus, it has to be considered in the safety demonstration.

The accident is initiated by a break on a main steam line, downstream of the steam generators (SG). Once the break occurs, the escaping steam results in a fast depressurization of all SGs. The vaporization of the SG water induces a global overcooling of the RCS.

The MSIVs are rapidly closed, which h prevents the depressurization of all SGs. If the break is located upstream the MSIV, the affected SG cannot be isolated from the break, and thus keeps on depressurizing. From that time, only the affected SG continues on cooling the RCS. As a consequence, the RCS cooling becomes asymmetrical (see *Figure 1*).

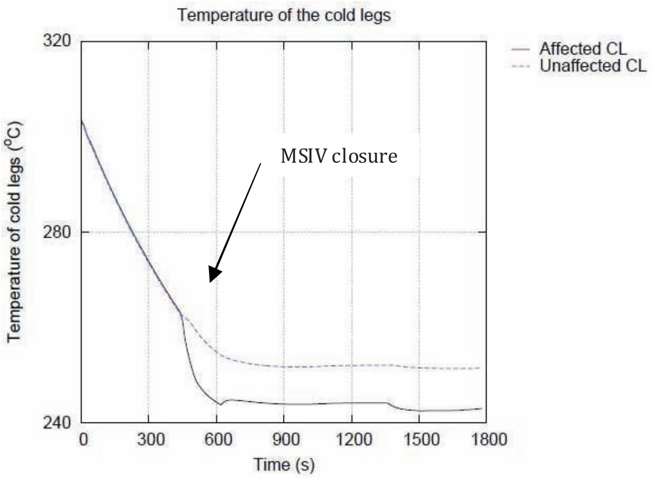


**Figure 1 – Evolution of the temperature in cold legs (example from SB-SLB transient)**

The accident study is penalized by assuming that one RCCA bank entirely remains stuck out of the core (single failure assumption). This assumption decreases the shutdown margin due to the reactor trip, but also induces a strong radial distortion of the neutronic flux (“small core” effect). The local linear power density could become excessive, and lead to boiling crisis occurring around the hot fuel assembly channel (see *Figure 2*).

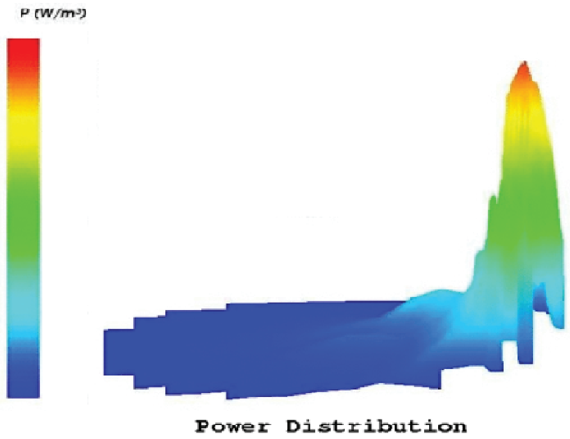


**Figure 2 – Illustration of the neutronic « small core » effect during a MSLB transient**

The neutronic and thermal hydraulic behavior of the core is influenced by the core inlet flow rate and temperature distribution. The asymmetrical cooling between the loops directly affects this, but the mixing phenomena in the lower plenum must also be taken into consideration.

The flow and the heat exchanges in the primary loops can be affected by the temperature distribution in the hot legs. The hot leg temperature distribution is influenced by all the mixing phenomena in the vessel, including those which occur in the lower plenum, in the core and also in the upper plenum.

In the case of MSLB transients, the cladding integrity is required to be demonstrated. Thus, two safety criteria are introduced: the fuel maximum linear power density (MLPD), and the minimum departure-from-nucleate boiling ratio (DNBR).

### 3.2. Main emergency core cooling systems

In order to mitigate the MSLB transient, several protection systems are automatically actuated. The main ones are described below.

- Reactor trip
- Closure of all MSIV
- Isolation of the MFWS
- Safety injection
- RCP trip
- EFWS start-up

Some of the protection systems can induce negative effects in the specific case of the MSLB fault. As an example, the automatic start-up of the EFWS increases the cooling of the RCS. Nevertheless, this system has to be taken into account. The closure of all MSIVs, as well as the isolation of the MFWS, can be actuated on a low SG pressure signal, or a high SG pressure drop. The safety injection pumps are turned on when the very low primary pressure signal is triggered. The RCP trip is actuated by the containment high pressure signal. For small breaks, this threshold cannot be reached.

### 3.3. Reference MSLB transients

The complete safety demonstration considers a whole range of steam line breaks depending on their size and their position. Two reference MSLB transients can be identified as the more limiting scenarios.

A double-ended guillotine MSLB (2A-SLB) leads to a severe and swift transient. All SGs have flow restrictors at the beginning of the MSL, which reduce the effective size of the break. This break is assumed to occur inside the containment. Thus, the RCP trip will be triggered in that case. The RCP trip induces a significant positive impact on the transient. Therefore, the second limiting reference transient is identified as the largest break which does not result in RCP trip. This break results in the biggest cooldown with the RCP switched on (SB-SLB).

The 2A-SLB and SB-SLB MSLB transients have been considered and reported in this paper. These two scenarios constitute the main pillars of the EPR MSLB safety demonstration.

All transients have been performed according the MTC3D methodology. This methodology has been developed in cooperation with AREVA to deal with the MSLB accident analysis. It defines all the steps and the inherent hypotheses which have to be followed to carry out a complete MSLB analysis. More information can be found in AREVA's publication [9]. The initial RCS and SG conditions are those of the hot shutdown state. The initial state can be slightly different between the two MSLB transients in order to have the most limiting hypotheses.

## 4. OVERVIEW OF THE OSCARD SOFTWARE

### 4.1. Main features

EDF have developed the software OSCARD which is devoted to simulating the MSLB transients. The simulation solution couples three qualified codes. Each of them is in charge of simulating one part of the physical phenomena involved in a MSLB transient. Each code simulates the physics fields it is qualified in. The main purpose of coupling these codes is to improve the quality of the MSLB simulations by combining the strengths of all three of the coupled codes.

The neutronic behavior of the core is solved by the COCCINELLE code. This code was developed by EDF. COCCINELLE is a three-dimensional neutronic code based on solving the two-group neutron diffusion equation. COCCINELLE is provided with a reactivity feedback model. COCCINELLE can calculate the spatial power distribution at the rod scale. The reader may refer to [3] and [4] for further information.

The three dimensional thermal hydraulic flows in the core are solved by the code THYC, which is also an EDF code. THYC is able to simulate two phase flows. It includes the simulation of boron transport and the thermal transfers between the fuel rods and the coolant. Several physical models are available. In particular, THYC includes several critical heat flux correlations in order to assess the DNBR. THYC is qualified to perform simulations at the sub channel scale. The reader may refer to [5] and [6] for further information.

CATHARE2 is a two-phase thermal hydraulic code, which was developed by the CEA as part of an agreement between the CEA, EDF, AREVA and the IRSN. It has a modular structure capable of simulations in 0D, 1D or 3D. CATHARE2 is able to simulate the whole NSSS behavior including the actuation of the safeguard systems. The software is based on a two-phase model with six equations (please see [7] and [8] for further information).

A complete three dimensional simulation of the main phenomena in the core can be obtained by coupling COCCINELLE with THYC. THYC improves the simplified thermal hydraulic module of COCCINELLE, which may not be accurate enough for the MSLB transient simulations. This coupling is suited for industrial applications, and EDF use it to perform the MSLB safety calculations French PWR fuel reloads.

The whole MSLB transient could be simulated by CATHARE2 though with serious limitations. The basic neutron point-kinetics model and the 1D hydraulic modeling of the core are not fully suited for local core behavior simulation during MSLB transients. These models are not able to accurately simulate the significant 3D neutronic and hydraulic phenomena. Thus, OSCARD, which couples CATHARE2 with the 3D thermal hydraulic and neutronic codes, increases the quality of the simulation.

## 4.2. OSCARD software architecture

OSCARD has a modular structure with a coupling unit. Its architecture is mainly made of the calculation codes (i.e. CATHARE2, COCCINELLE and THYC), and the coupling units. The coupling units consist of converters and a supervisor. These are in charge of data exchanges and of global simulation managing. The inter-code communication is based on a shared buffer and tool protocols developed by EDF. Each code simply reads and publishes data fields with its own meshing and format to the unique buffer interface. Thus, the internal convergence algorithms of each code are not affected (see *Figure 3*).

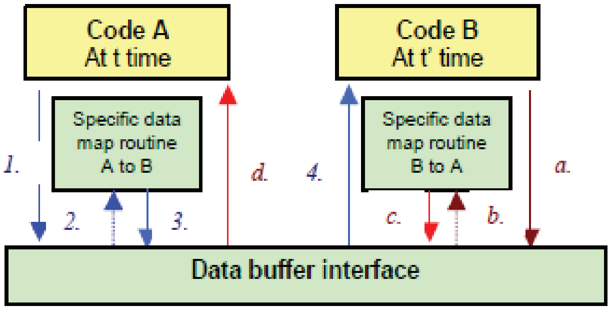


**Figure 3 – OSCARD architecture**

At the end of each calculation step, the codes transfer data to the shared buffer. Conversely, the codes obtain input data they require from the buffer. If input information is not available, the code is put on stand-by until the required data becomes available.

The coupling architecture has been designed to reduce the modifications of the standard source code as much as possible. Concerning CATHARE2, all data fluxes are managed in the dataset by calling specific routines whereas the official releases of THYC and COCCINELLE have been configured to be able to exchange the required physical data.

## 4.3. OSCARD coupling scheme

CATHARE2 models the whole NSSS, including the core. OSCARD thus involves an overlapping coupling scheme, since the core has been modeled twice. There is a coarse core modeling inside CATHARE2 (1D), however the accurate physical core simulation is performed by the coupling of the two 3D core simulation codes.

The main features of the coupling topology are presented hereafter. CATHARE2 provides the core boundary conditions to the 3D codes. They simulate the core behavior and assess the physical variables. Some 1D or 0D physical parameters, such as the global power level, are then provided back to CATHARE2 in order to keep the 1D core consistent with the 3D simulation. Nevertheless, discrepancies still exist between the CATHARE2 core and the 3D core. An overview of the OSCARD coupling topology is given in *Figure 4*.

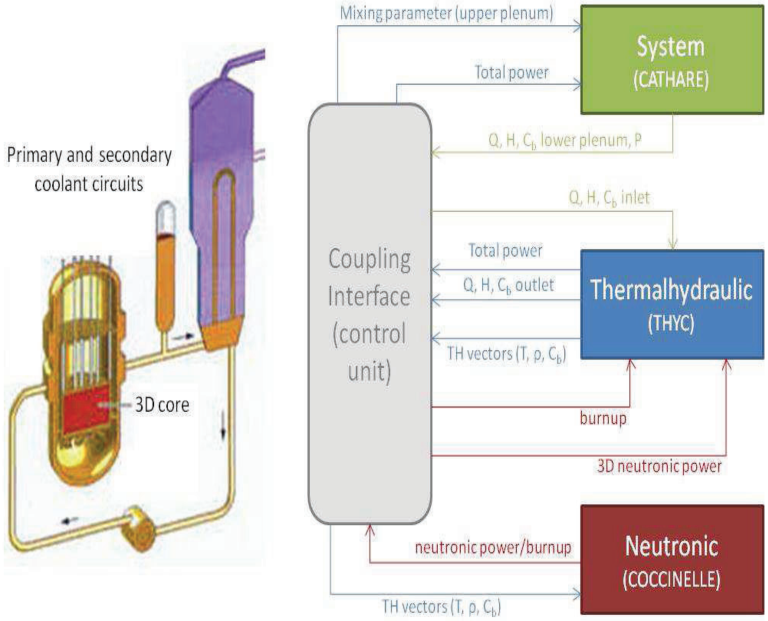


**Figure 4 – Overview of the OSCARD coupling topology**

## 4.4. Vessel modeling in CATHARE2

The vessel modeling in CATHARE2 has recently been simplified, since CATHARE2 does not have to predict with accuracy the core behavior. Each part of the vessel (e.g. the down comer, or the plenums) is represented using 1D or 0D modules.

The previous modeling split the vessel into several parts, to keep the physical heterogeneities induced by the asymmetrical cooling. However, this approach was not suitable for RCP trip configurations because discrepancies could occur as a result of mass and energy cross flows being ignored.

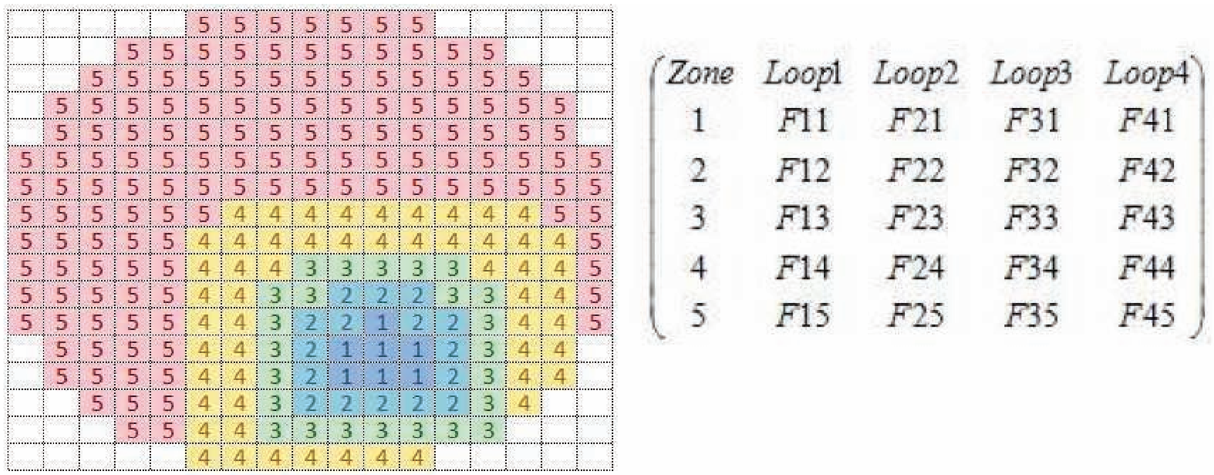
## 4.5. Mixing models in the vessel

### 4.5.1. Lower plenum

Despite this “unified” vessel modeling in CATHARE2, the lower plenum mixing phenomena are taken into consideration. The thermal hydraulic variables from each loop (cold leg) upstream of the vessel are used. A specific mixing model has been designed to build the 2D enthalpy and flow rate distributions at the core inlet. These distributions are used by the 3D core codes as boundary conditions. Several models can be used.

Each of them works essentially in the same way. Every fuel assembly channel is linked to a set of mixing parameters via a core map (mixing map). Then, the models use the provided parameters to define the temperature, the flow rate and the boron concentration of the corresponding fuel assembly channel. The models also ensure that the energy and mass conservation equations are respected. The OSCARD models are confidential, and thus cannot be shown in this paper.

The following figure (*Figure 5*) gives an example of input parameters which can be provided by the user.



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| | | | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | | | |
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$$\begin{pmatrix} Zone & Loop1 & Loop2 & Loop3 & Loop4 \\ 1 & F11 & F21 & F31 & F41 \\ 2 & F12 & F22 & F32 & F42 \\ 3 & F13 & F23 & F33 & F43 \\ 4 & F14 & F24 & F34 & F44 \\ 5 & F15 & F25 & F35 & F45 \end{pmatrix}$$

**Figure 5 – Example of input mixing parameters**

It should be noted that all intrinsic laws of the models are part of the OSCARD code, and thus cannot be changed by the user. However, the mixing map and the mixing parameters are provided by the user. Several mixing configurations can thus be represented by changing the mixing map or the values of the *Fij* parameters. The laws and the parameters which are considered in the safety demonstration have been qualified from experimental results, and cannot be shown in this paper.

### 4.5.2. Upper plenum

A new OSCARD feature is used to predict the upper plenum mixing.

The upper plenum was first provided with a mixing model similar to that of the lower plenum model. Therefore, a mixing map which describes the core outlet is given with a set of mixing parameters. These parameters represent the mass contribution of each fuel assembly channel to a given hot leg. Assuming that the energy (enthalpy) and the boron concentration for each fuel assembly channel is transported with the outgoing mass flow rate, the enthalpy and the boron concentration of each hot leg can thus be defined. These values are taken into account by CATHARE2 in the equations of the plenum 0D module.

It should be noted that this model also indirectly assumes a hot leg flow rate. Nevertheless, this value is purposely ignored in CATHARE2.

The flow rate of each loop actually depends on both its hydraulic resistance and the pressure head (from pumps or density gradients), and should be consistent with the pressure balance between the loops. Of course, the upper plenum mixing phenomena can affect both these terms, in particular in the natural circulation phase, but it cannot be a circulation driving force. Forcing a flow rate value in the hot legs would be inconsistent with the CATHARE2 physical equations and correlations. Therefore, the flow rates in the hot legs may be different from those which are implicitly assumed by the upper plenum mixing model.

The flow rate discrepancies are the main issue associated with this model. In order to overcome them, CATHARE2 has to adjust the original enthalpy values to ensure the conservation of energy in the system. However, the values used in the simulation are unlikely to be the same as the original user-defined variables. Therefore, the user must be attentive when choosing the mixing map and parameters.

In a further phase, another solution has been considered to solve the upper plenum mixing. This solution assesses the maximum, the average, and the minimum enthalpy value of each hot leg with the core outlet information from THYC and the hot leg flow rates from CATHARE2. A "mixing cursor" is defined by the user to adjust the enthalpy value between these extreme values.

This model is still under development, and is not yet part of the latest release of OSCARD. It may be well suited to perform sensitivity studies.

# 5. VESSEL MIXING MODELS ANALYSIS

## 5.1. Basic verification

### 5.1.1. Functional check

The new developments have undergone the usual verification process with the same level of requirement as the other units of OSCARD. This verification process ensures that the completed developments are consistent with the required technical specifications. To confirm this, several specific test cases and regression test cases are generally run. More information on the verification process can be found in [2].

### 5.1.2. Global behavior check

Further tests have been run in order to assess numerical effects due to the use of the upper plenum mixing model inside the OSCARD coupling. In particular, the use of the developed mixing module inside CATHARE2 must not induce any side effect which may affect the CATHARE2 standard equation calculation.

A few MSLB transients have been simulated without enabling the upper plenum mixing model. Due to the 0D modeling of the upper plenum in CATHARE2 dataset, a homogeneous temperature distribution in the hot legs is assumed. The same MSLB transients have been performed again when the mixing model is activated with parameters that assume a homogeneous temperature distribution in the hot legs. The two simulations are expected to lead to identical transients.

The comparison shows that some undesirable numerical effects are induced. These effects are very weak and their origin has been identified. They derive from a time explicit scheme, and from the energy balance equations which have been slightly simplified. No significant impacts on the parameters have been identified during the whole simulation of the transient.

## 5.2. Sensitivity to plenum mixing models

### 5.2.1. Main objectives

A large number of sensitivity calculations to the mixing models and parameters have been performed. The main purpose of these calculations is to demonstrate the ability of the OSCARD coupling software to predict a wide range of mixing configurations in both the upper and the lower plenum. The mixing models have been developed to be suited to the safety analysis of the MSLB fault, but also to scoping studies, such as raw sensitivity calculations.

The cumulated physical effects of all the vessel mixing phenomena during a MSLB transient can also be analyzed with these sensitivity calculations. The main point is to ensure that each mixing configuration leads to a consistent simulation. The calculations cover the two MSLB reference transients; with and without RCP trip. The analyses have examined several physical parameters, but this paper will lay the emphasis on a few of them.

This work should not be considered as part of a validation program. The physical validation justifies the relevance of the models used and ensures that they are sufficiently limiting considering the uncertainties associated with the phenomena and the experimental data. This work does not seek to validate the use of a specific set of mixing parameters.

Significant validation analysis concerning mixing in the lower and the upper plenums have already been made available. Most of them rely on experimental data and on CFD simulations. Advanced studies concerning the vessel mixing phenomena are still in progress, in particular when the RCP trip is considered. The natural circulation which results from the RCP trip may induce complex phenomena.

### 5.2.2. Upper plenum mixing sensitivities

During the first phase of the analysis, the calculations only focused on the upper plenum mixing modeling. This is the most significant development that has been done in the latest release of OSCARD, since a lower plenum mixing model was already available in OSCARD.

Several sensitivities have been carried out by only changing the level of mixing in the upper plenum. The two mixing modeling approaches have been investigated. The lower plenum mixing is predicted in the same way as in the safety demonstration. It is derived from experimental results and adjusted in a conservative way in order to have the coldest area at the core inlet in front of the assembly with the RCCA bank stuck out of the core.

The following paragraphs give examples of simulations that OSCARD is currently able to perform, and of new issues which can be investigated in the future.

**a) Using the original mixing model**

Several mixing maps and parameters have been considered, thus a full range of mixing configurations are modeled. The contribution of each fuel assembly channel to a given hot leg can be easily modified. Moreover, in the case of limited mixing, the affected hot leg can be associated with either the warmest or the coldest areas of the core outlet.

All the simulations have resulted in different hot leg temperatures. Each of them is consistent with the given mixing parameters, which was the expected effect. The full analysis of the simulations may be complex, but it has shown a consistent global behavior depending on the chosen mixing models.

The time evolution of the MLPD depending on three sets of mixing data is shown in *Figure 6*. The red curve represents the perfect mixing configuration. Conversely, the green curve represents a no mixing configuration in which the core is “split” into four parts; each of them associated with a hot leg. The part to which the hot fuel assembly channel belongs is linked to the affected loop. The purple curve is an example of an intermediate level of mixing.

The core quarter to which the hot fuel assembly channel belongs is significantly influenced by the affected cold leg. It should be reminded that the lower plenum model assumes that the affected loop mainly contributes to this part of the core inlet. Despite the few overheating fuel assemblies (“small core” effect) and the cross flows, the average outlet temperature of this core quarter remains colder than the other parts of the core. Therefore, the green curve assumption leads to a colder temperature in the affected hot leg than assuming full mixing.

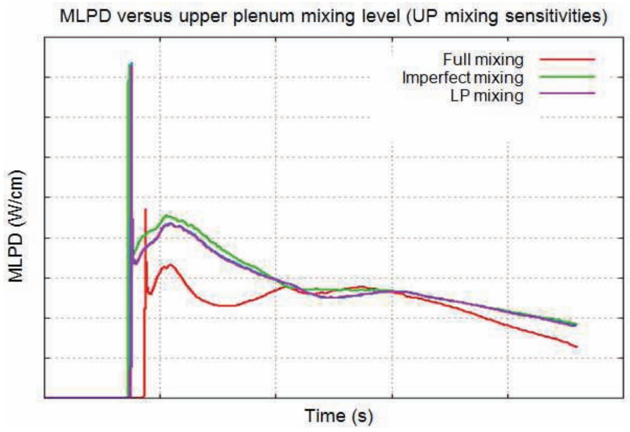


**Figure 6 – Evolution of the MLPD with different mixing parameters in the upper plenum (2A-SLB transient)**

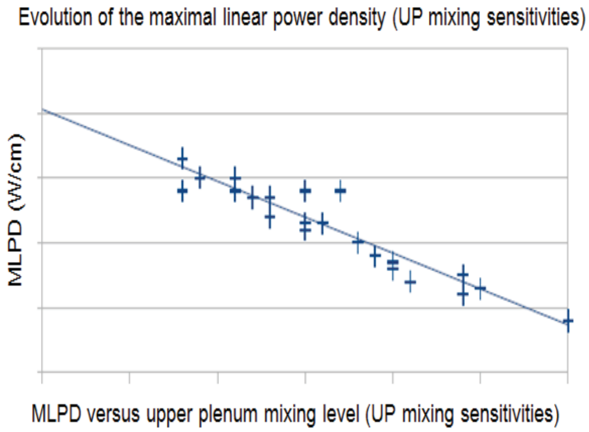


**Figure 7 – MLPD scattering with different mixing coefficients in the upper plenum (2A-SLB transient)**

Using all the sensitivity calculations performed, the MLPD scattering depending on the level of mixing in the upper plenum has been plotted in *Figure 7*. The level of mixing is assessed by the difference of temperature of the affected hot leg and the average value of the upper plenum 0D module. The colder the affected hot leg, the colder the affected cold leg is as a result. This leads to a more serious neutronic feedback in the core and a higher MLPD. Therefore, the differences between the green and the red curve can be accounted for. This is consistent with the trend shown in *Figure 6* and *Figure 7*.

**b) Using the second mixing model**

Scoping studies have also been performed using the second mixing model. The point of this part is also to demonstrate that the second mixing model can represent a great range of mixing configurations. Several mixing maps and parameters have thus been considered.

Extreme configurations and a homogeneous mixing ("*Hmg*") have been modeled. In the following figures, "*min*" represents the minimum temperature in the affected hot leg, whereas "*max*" represents the maximum temperature in the affected hot leg. These studies show the increased reliability when using this second mixing model. The following paragraphs and figures (*Figures 8 to 12*) give an example of physical analysis.

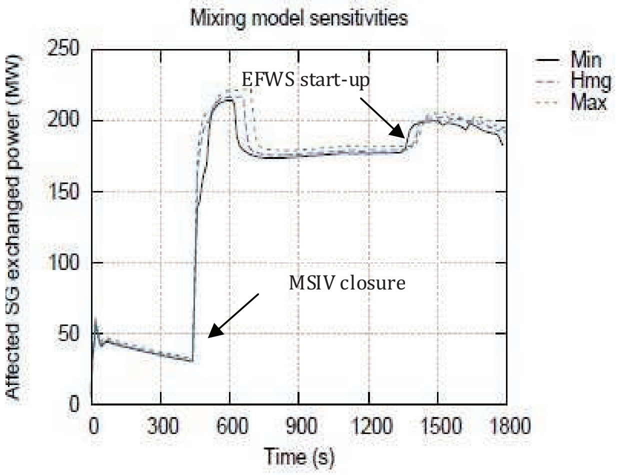


**Figure 8 – Affected SG exchanged power during a SB-SLB transient**

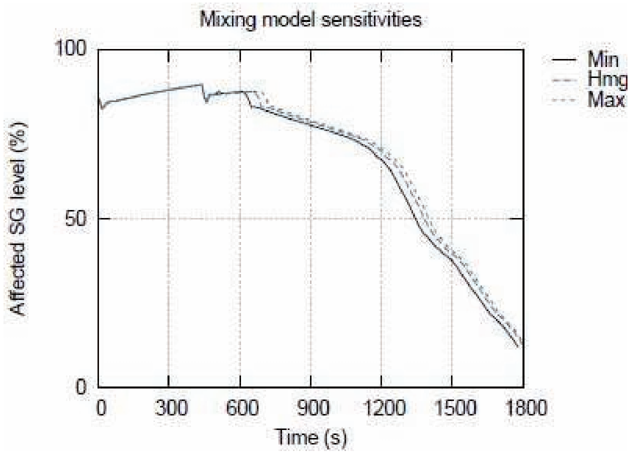


**Figure 9 – Affected SG level during a SB-SLB transient**

The hotter the water in the affected hot leg, the higher the exchanged power with the affected SG, as shown in *Figure 8*. In those cases, the affected SG would therefore reach dryout sooner, but its depressurization is also slower. The MFWS isolation is delayed, and the water level of the affected SG thus remains slightly higher (see *Figure 9*).

The higher temperature in the affected hot leg results in the warmer temperature of the affected cold leg despite a higher exchanged power. Thus, it leads to a more moderate neutronic power increase in the core and to a delayed time of critically (see on *Figure 10*).

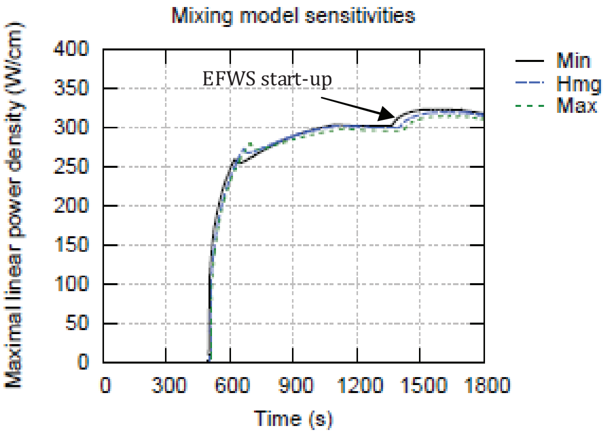
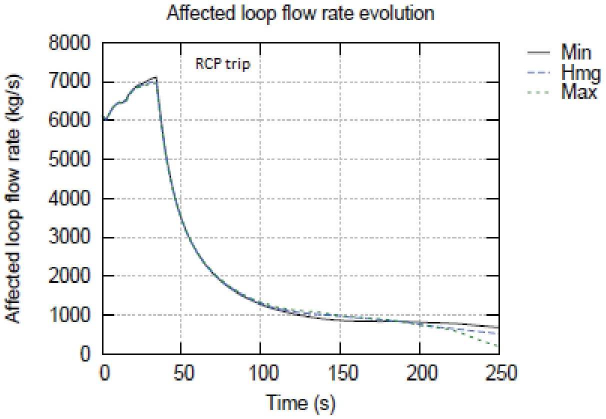


**Figure 10 – Evolution of the MLPD during a SB-SLB transient**

In case of RCP trip, the primary flow rate decreases until natural circulation occurs. The nuclear power level and the ability of the SGs to cool the primary circuit drive the natural circulation regime. Both of these can be influenced by the mixing phenomena (see *Figure 11* and *Figure 12*). The heterogeneities of temperature in the hot legs can stop or even reverse the flow in the unaffected hot legs.



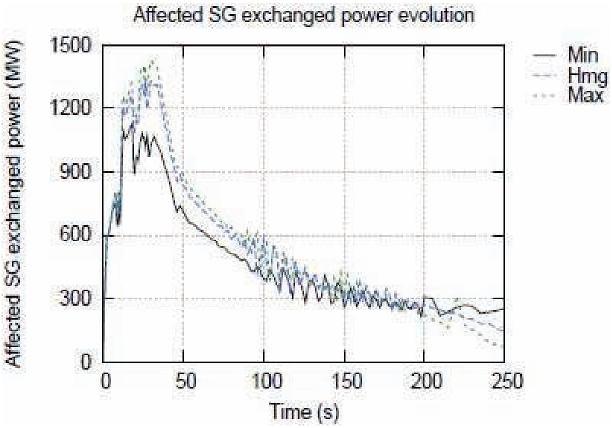


**Figure 11 – Affected loop flow rate during a 2A-SLB transient**

**Figure 12 – Affected SG exchanged power during a 2A-SLB transient**

### c) Main conclusions

The analysis of all the performed calculations has not shown any inconsistent behavior. Thus, the OSCARD mixing modeling is consistent inside the coupling scheme. Furthermore, all the sensitivity calculations that have been performed also show that a lot of mixing configurations can be represented. A limitation may be that the mixing parameters cannot be defined as a function of time yet.

The sensitivity calculation analysis show that the upper plenum mixing has a moderate effect on the MLSB transient in most investigated cases, although this conclusion can depend on the transient considered and the mixing configuration used. For instance, the discrepancies are more significant for the 2A-SLB transient.

These calculations have also shown the significance of the mixing phenomena in the core. Cross flows inside the core actually make the temperature gradients at the core outlet much weaker than they are at the core inlet. As a result, in most cases, the upper plenum mixing has moderate consequences on the SB-SLB transient and during the short term of the 2A-SLB transient.

### 5.2.3. Combined sensitivities to the upper and lower plenum mixing models

During a second step of the analysis, the calculations have been completed including sensitivities to the lower plenum mixing. Several temperature and flow rate distributions at core inlet have been considered. For each of these distributions three different mixing configurations have been used in the upper plenum via the second mixing model.

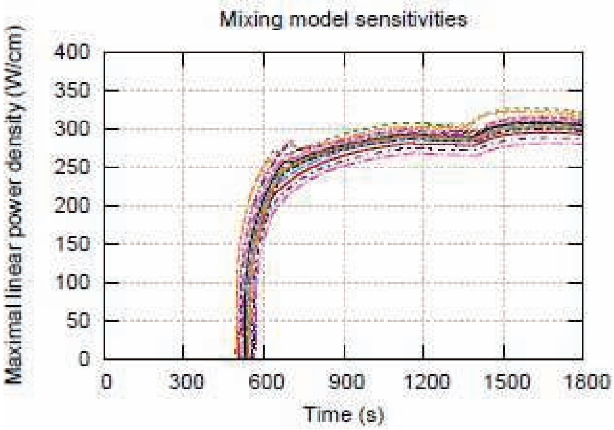


**Figure 13 – Complete mixing model sensitivity calculations (SB-SLB transient)**

*Figure 13* shows that OSCARD is capable of simulating all sensitivities. The simulations show a relatively consistent physical behavior. The analysis of these calculations is still in progress. The mixing in the lower plenum has a more significant impact on the MSLB transient than the upper plenum mixing.

The core inlet distribution has a strong influence on both the radial distortion of the neutronic flux and the reactivity insertion. Thus, it can lead to a significant or moderate return-to-power. Moreover, the flow rate distribution at the core inlet also has an effect on the hydraulic phenomena in the core by inducing cross flows, in particular in the case of RCP trip.

The upper plenum mixing influences the power exchange with the SGs, especially the affected SG. It can therefore speed up or slow down the global kinetics of the transient. In most cases, it has a moderate effect on the safety criteria. Both the upper and the lower plenum mixing effects are more significant for 2A-SLB transients, possibly a result of the RCP trip.

It should be reminded that a lot of these sensitivity calculations are not realistic. The purpose is only to demonstrate that OSCARD is capable of simulating all combinations of mixing in the plenums. This paper demonstrates that OSCARD is capable to model all physical phenomena investigated. The simulation scope of OSCARD has therefore been extended.

## 6. CONCLUSION

OSCARD has been improved to predict the relevant physical phenomena during the MSLB transients. It can be used as an industrial tool to perform MSLB transient simulations.

The main strengths of EDF's coupling software are:

- the coupling of three qualified codes, each of them simulating the MSLB physics for which it is qualified,
- simple and consistent vessel modeling to cover most of the transients,
- flexible plenum mixing models to represent the mixing phenomena.

Plenty of sensitivity calculations have been performed to assess the ability of OSCARD to cope with several MSLB transients, and with several mixing models in both the upper and lower plenums. The simulations show consistent results.

The validation of a limiting set of mixing parameters for these models is the next issue to be investigated. This work has already started, and will rely on both experimental results and CFD simulations.

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