# Development of methodology to evaluate mechanical consequences of vapor expansion in SFR severe accident transients:

# *Lessons learned from previous France-Japan collaboration and future objectives and milestones*

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**Abstract**

In the frame of France-Japan collaboration, one of the objectives is to define and assess the calculation methodologies, and to investigate the phenomenology and the consequences of severe accident scenarios in sodium fast reactors (SFRs). A methodology whose purpose is to assess the loadings of the structures induced by a Fuel Coolant Interaction (FCI) taking place in the sodium plenum of SFR has been defined in the frame of the collaboration between France and Japan during 2014-2019. The work progress will be spread over the period 2020-2024 and the main objectives and milestones will be introduced in the paper. The objective of studies is to comprehensively address the margin between the limit of integrity of the main vessel structures and the loadings resulting from severe accidents.

For this purpose, the SIMMER mechanistic calculation code simulates core disruptive accident sequences in SFRs. However, SIMMER cannot be used for main vessel loading assessment while it does not take into account fluid structure interactions. That is the reason why, associated with SIMMER code, a fluid structure dynamics tool evaluates this interaction i.e. EUROPLEXUS is used in CEA studies and AUTODYN tool is used in JAEA studies. In the paper, a benchmark study is described in order to illustrate the evaluation of vapour expansion phase in the hot plenum. To do that, joint input data are used on the basis of an ASTRID 1500 MWth core degraded state after the power excursion which leads to vapour expansion. The most penalizing case was evidenced in this study by suppressing the action of transfer tube in-core mitigation devices in SIMMER input deck and thus privileging the upward molten core ejection. Since the risk of main vessel failure by cumulative stresses is an issue often discussed in the SFR concepts, the calculation methodology presented in the paper based on chaining of SIMMER code with another fluid/structure evaluation tool is very promising. The future perspectives are highlighted.

Even if the most penalizing case was evidenced in this paper, privileging the upward molten core ejection; no significant RV deformation was observed in both EUROPLEXUS and AUTODYN calculation results. The assumed mechanical energy was small for the core expansion phase.

## INTRODUCTION

Sodium-cooled fast reactors (SFRs) are operated at low pressure and with subcooled single-phase sodium. Due to the high heat-transport characteristics of liquid sodium, the reactors generally have large safety margins against abnormal conditions before coolant boiling and fuel melting take place, compared with the light water reactors (LWRs). However, historically, the consequence of postulated core disruptive accidents (CDAs) (see FIG.1) under hypothetical conditions where a serious power-to-flow mismatch is postulated has been one of the major concerns in the safety of SFRs. Although the extensive safety design effort for accident prevention has made the occurrence of such an event extremely unlikely, the importance of CDAs is still emphasized from the viewpoint of safety design and evaluation to appropriately mitigate and accommodate the consequences and thereby to minimize the risk to the public since CDAs potentially lead to significant mechanical energy releases as a result of exceeding prompt criticality.

Fuel melting during CDA leads to interactions between molten fuel and liquid sodium so called fuel-coolant interactions (FCIs). FCI is considered as one of the dominating phenomena in accident progression in SFRs. In a disrupted reactor core, FCIs at the failure of a control rod guide tube (CRGT) or transfer tubes located near the radial center of the core, will move molten fuel outward and then molten fuel flows back to the radial center. Such slosh motions have a possibility to insert positive reactivity leading to discharging of large amount of molten-core toward the upper plenum and large scale FCI there. If such a positive reactivity is not inserted, molten-core will relocate into the subcooled sodium plenum and FCI will take place there. Therefore, the consequences of FCIs must be evaluated with respect to a challenging factor to the integrity of the primary system boundary and in-vessel structures such as the core catcher (CC).

From the above background, the one of the objectives of the France-Japan collaboration launched in 2014 and planned till 2024 [1][2] is to define the methodology and tools to be used to calculate FCI consequences on mitigation devices (a molten material dispersion duct and in-vessel core-catcher) and on the primary vessel. The present paper aims at describing the proposed methodologies to ASTRID [3] for investigating FCI consequences in the upper or plenum. The evaluations on ASTRID are performed in parallel by France (FRN) and Japan (JPN). The case is calculated using the SIMMER-III code, and then, consequent structure responses of the reactor vessel (RV) due to the mechanical loading through FCIs are evaluated using EUROPLEXUS (FRN) and AUTODYN (JPN). In this paper, the methods for the calculation including the ways to connect results from SIMMER-III to the code for evaluating structure responses and calculation results by FRN and JPN are presented. The future perspectives are highlighted.



Fig. 1. Core disruptive accident at SFR without consideration of mitigation devices

## STUDIED domain

The study presented in this paper focuses on fuel ejection into the upper sodium pool (hot pool). Thus, the strong-back and core catcher zone are not necessary to be represented. We focus on the core region and the sodium hot pool up to the argon cover gas. The sketch of whole reactor geometry is shown in Fig. 2.



Fig. 2. Sketch of the primary vessel geometry

In our study, the objective is to evaluate the mechanical consequences of upwards fuel/steel ejection and vapor propagation in the hot pool. Generally, coping with the French SFR concept severe accident approach, the objective is to limit the amount of fuel ejected above the core and dedicated mitigation devices so called transfer tubes are placed within the core [4]. Their purpose is to discharge the molten fuel and steel from the core region (high neutron flux region) and secondarily to drive the core materials onto the core catcher. Within severe accident analyses on ASTRID core, some sensitivity studies were realized in order to test the core behavior when transfer tubes are not presented within the core. The unprotected loss-of-flow (ULOF) transient of such a core design resulted in high reactivity insertions and thus in power increase, core melting and discharge of core inventory into the upper core region [5]. For the study presented in this document, this previous ULOF study without these transfer tubes in the core was taken as a reference to enhance the material discharge into the hot pool as well as its enthalpy. This is a penalizing case where these transfer tubes are considered not active. Within the current simulated geometry, nor transfer tubes neither CRGT are presented into the core in order to enhance the axial fuel upwards ejection and the energy transferred to the sodium of the hot pool.

## SCENARIO of upward core MATERIAL discharge

In order to simulate the severe accident transient leading to core discharge, the SIMMER-III calculation tool is used. The SIMMER is a multi-dimensional code (2D for SIMMER-III and 3D for SIMMER IV, recently both implemented into SIMMER-V [6] and multi-field (solid, liquid and vapor for fuel and steel and liquid / vapor for sodium) which couples the state of the materials of the core and their movement with evolution of the reactor power using a quasi-static neutron model.

The departure calculation case for demonstration presented in this paper is represented Fig. 3. In Fig. 3.-left the liquid fuel temperature field is illustrated (scale in K) and in Fig. 3.-right the material field is illustrated (liquid fuel is in red colour, liquid steel in green, intact pins in grey, sodium in blue, steel structures in black and vapour in white colour). The degraded core is closed (at top) with a virtual wall up to a time of its suppression, defined as a user input parameter. The objective of this suppression is to continue the core heating and to avoid upwards expansion until the desired temperature is reached. Moreover, there are some additional hypotheses:

* The upper core structure (UCS) is modelled but this domain is simulated as a virtual wall i.e. no bubble propagation into this domain is authorized. The UCS is thus considered as no porous;
* There is no liquid sodium presented within the upper shielding (PNS) nor in the sodium plena;

>0.3 seconds, suppression of upper virtual wall in all FAs



Fig. 3. Suppression of virtual wall above molten core at 0.3 seconds, leading to fuel heating up to 5100 K (temperature field on left) and fuel upward discharge (material field on right)

The choice to suppress the core confinement at 0.3 seconds leads to fuel heating up to 5100 K. This local fuel over-heating is supposed to occur in a representative core disruption accident, especially in scenario with reactivity insertion as it was observed in whole scenario calculations [5]. The molten material discharge to the upper parts (out of the flux region) is leading to a decrease of power insertion calculated by SIMMER-III. The bubble formation and its expansion within the hot sodium plenum is shown in Fig. 4.



*Bubble escaped core region*

Fig. 4. Bubble propagation in the upper hot sodium plenum during the transient

## DEscription of chaining methodology

In this section, the methodology to evaluate energy release in expansion phase calculation in SIMMER-III is summarized. This methodology was established by JPN partners [7] and is being applied on both sides in the frame of FRN-JPN collaboration on mechanical energy studies.

The pressure near the interface between liquid sodium and the CDA bubble actually acts on the sodium slug. Thus, the pressure at the surface of the CDA bubble should be used in the evaluation of the mechanical work done by the CDA bubble expansion, .

The CDA bubble has a steep pressure gradient in it and its average pressure is not relevant regarding the pressure-volume (P-V) curve to be implemented in mechanistic tool. So the pressure near the bubble interface should be considered. In this study, the surface of the CDA bubble was judged with the volume fraction of the liquid sodium in a cell and W\_CDABB was calculated by summing up the work done by the CDA bubble using the pressure at the surface of the CDA bubble as follows:

(1)

(2)

(3)

(4)

(5)

Where is the void fraction in the mesh number i (-); , pressure in the bubble at the time step n (Pa);

, average pressure in the bubble (Pa); , pressure in the mesh number i (Pa); , volume of the bubble at the time step number n (m3); , variation of the volume bubble during a time step (m3); , volume of a mesh number i (m3); *n* is the time step.

In calculating , summation in space was done only at the surface of the CDA bubble whereas all the voiding volume included in the CDA bubble was taken into account for the summation of .

### Identification of the bubble surface

In principle, mechanical work done by the CDA bubble should be equal to the sum of the kinetic energy transferred to the sodium, (J), and of the compression energy increase in cover gas, (J), assuming that the structure is not deformed nor absorbs some mechanical energy.

(6)

was obtained by summing up the kinetic energy of the liquid sodium in each cell *i*, as follows:

(7)

(8)

where is the sodium density (kg/m3); is the sodium volume fraction (-); is the sodium velocity in each cell (m/s); x, y and z are the coordinates in the cartesian system[[1]](#footnote-2). was obtained by summing up the work done by the cover gas at each time step as follows:

(9)

(10)

(11)

(12)

(13)

In calculating , summation in space was done within all the cover gas volume because there is almost no pressure gradient in the cover gas region.

A good agreement of with was obtained when only certain cells are regarded as the boundary ones. In the study, the best match between the curves was obtained by regarding the cells that have more than e.g. 75% (JPN study) or 60-80% (CEA study) of void fraction as boundary ones (Fig. 5).

The additional JPN analyses showed the better match between the Mechanical energy and P-V work in Fig. 5-right by simplifying the flow pattern in SIMMER-III input deck. This represents the elimination of a part of sodium flow toward different directions of the bubble expansion (e.g. inflowing of liquid sodium into the core and the reflector/shielding subassemblies). This exercise was not completed on CEA side thus is not illustrated in this paper.

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Fig. 5. Example of mechanical energy balance during the calculated expansion stage, CEA SIMMER-III result with bubble filter criterion on cells with 60-80% void (left), JPN SIMMER-III result with bubble filter criterion on cells with more than 75% void (right)

The verification procedure in Fig. 5 enables to confirm that the mechanical energy released by the bubble and the energy transmitted to the sodium and to the cover gas are almost balanced up to certain time which is the time period of interest for the expansion phase. As a result, it confirms that bubble pressure and volume evolutions that are the SIMMER-III output parameters well represent the expansion mechanical features.

To be in agreement with JPN approach, the bubble interface in this study was tracked once the bubble escaped from the core region (see Fig. 4- left). The bubble within the core region was not considered. In the further studies we may consider to include the bubble within the core region into our balance to be more conservative.

## PRELIMINARY application

The SIMMER-III cannot be used for main vessel loading assessment because it does not take into account fluid structure interactions. Thus a fluid structure dynamics tool evaluates this interaction i.e. EUROPLEXUS [8] is used in CEA studies and AUTODYN [9] tool is used in JPN studies.

The above presented methodology provides the SIMMER-III output that is used as input for the mechanistic codes. This includes: the position and form of bubble at instant of chaining, bubble volume evolution and pressure evolution in time.

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Fig. 6. Pressure and volume evolutions of the vapor phase generated by the FCI during bubble expansion in hot sodium plenum, CEA SIMMER-III result (left), JPN SIMMER-III result (right)

The bubble pressure and bubble volume evolution in time illustrated in Fig. 6- right are the direct input for AUTODYN calculation. As for EUROPLEXUS, a pressure versus volume evolution law must be input. A limitation of this case, as it is now, is the shape of this law that can be only expressed as a polytropic law: PVk = cste (where k is constant).

So, by considering pressure and volume versus time evolutions (Fig. 6-left) calculated by SIMMER-III, a curve expressing the logarithm of the pressure versus the logarithm of the volume has been plotted in order to estimate the k value step by step during the expansion phase. In the frame of this paper, the considered time period ranged from 0.43 to 0.51 s. This value has been obtained by integrating the evolution of the pressure into the bubble versus its volume. Two remarks can be done regarding this expansion modelling in EUROPLEXUS:

The determination coefficient, R-squared, featuring the matching of the bubble law with the P-V curve obtained with SIMMER-III in CEA study is not very close to one (R-squared = 0.69)[[2]](#footnote-3). So, it means that for next studies, an improvement of EUROPLEXUS should be done in order to be able to input any bubble law in the code and not only polytropic laws. This EUROPLEXUS development is ongoing on CEA side. Moreover, the expansion period simulated here does only cover a stage of the expansion and in the future it will be interesting to assess, the expansion by successive polytropic expansions, each one being associated to a different value of k. In such a way, the whole expansion period could be calculated.

### Preliminary benchmark EUROPLEXUS/AUTODYN on expansion phase

The EUROPLEXUS mesh is adapted to fit as much as possible the SIMMER-III mesh while respecting the sodium volume. In order to consider the core presence, a fictive structure is used to represent the core. This structure is assumed to have the same mechanical properties as the inner vessel. Moreover, this structure and the UCS are considered as closed and no-flow structures.

The model used in EUROPLEXUS for the calculation is the ADCR model (model for Core Disruptive Accident). It was developed for modelling the behaviour of a liquid-gas mixture. The mixture, which has three components and includes two phases is assumed to be homogeneous. By using this model, it is possible to analyse the consequences of an explosion (fast expansion of a high pressure zone) in a liquid contained within a tank in the presence of a cover gas. The mechanical behaviour of the structures is modelled with an elasto-plastic behaviour, except for the strong-back in which an elastic model is applied because of its high stiffness.

The main EUROPLEXUS results provide: evolution of the void fraction in the primary vessel, pressure in the primary vessel during the acoustic and inertial phase of the expansion of the bubble, Von Mises Equivalent Stress and Equivalent Plastic Strain in the structures during the expansion of the bubble.

The Fig. 7-left shows maximum equivalent plastic deformation in EUROPLEXUS calculation. The areas where deformations appear are on the junction and on the angle of structures especially on the UCS, the inner vessel and the junction between the core structure and the diagrid. In this latter spot, the maximum plastic deformation occurs with a value of 2.4%. For this case of bubble expansion, the maximum plastic deformation of the primary vessel walls is low, with a value of 0.5% on its lower part. The cylindrical upper part of the vessel and the slab are not at all deformed by the expansion calculated here.

The AUTODYN calculation was realised by JPN partners. Concerning analyses of the structure response against the sodium vapor expansion as a result of FCIs, AUTODYN with the gas-bag model is applicable when the sodium vapor expands in the hot pool. The sodium and the cover gas in the hot pool are Euler elements to calculate the fluids motions in detail, and the sodium in the cold pool is Lagrange element since the fluid mildly moves. To evaluate appropriately the effect of compression of the cover gas on the sodium-impact, the surrounding structures of the gas-bag (the strongback, the UCS, the upper-internal structure, and the plug) are treated as fixed ones. Also, the junction of the redan and the strongback, the junction of the upper end of the RV and the plug, and the lower surface of the RV are treated as fixed end.

The main AUTODYN results provide: evolution of material distribution (sodium, gasbag, argon), pressure distribution, sodium velocity distribution, transitions of effective plastic strains.

The Fig. 7-right shows maximum equivalent plastic deformation in AUTODYN calculation. No significant RV plastic deformation was observed because the assumed mechanical energy was small for inducing the significant reactor vessel deformation. Further study including more precise bench mark calculation is planned.

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Fig. 7. Equivalent plastic strain during the expansion, EUROPLEXUS result (left), AUTODYN result (right)- the general result is 0% on vessel and structures

## conclusions and perspectives

In this paper the current status of proposed methodology for investigating FCI consequences in the upper plenum started in 2014 is summarised. The case of fuel discharge to hot pool was defined as benchmark. This case was calculated using the SIMMER-III code at first based on an input prepared by CEA to quantify impact FCIs, and then, consequent structure responses of the reactor vessel (RV) and the in-vessel structures due to the mechanical loading through FCIs were evaluated using EUROPLEXUS (CEA) and AUTODYN (JPN).

JPN and FRN performed structure response analyses using P-V curves obtained by each SIMMER-III analysis of JPN and FRN. The preliminary study described in this paper indicated that the assumed mechanical energy (P-V curve) slightly differed between JPN and FRN. This may be related to different filter criterion applied in methodology in order to set the bubble boundary. Moreover, some additional improvements on SIMMER-III initial conditions are being proposed by JPN partners. This represents the elimination of a part of sodium flow toward different directions of the bubble expansion (e.g. inflowing of liquid sodium into the core and the reflector/shielding subassemblies). These improvements will be taken further into account and might contribute to improvement of match between mechanical energy and P-V curve (methodology verification criterion).

Even if the most penalizing case was evidenced in this paper study by suppressing the action of transfer tube in-core mitigation devices in SIMMER-III input deck and thus privileging the upward molten core ejection; no significant RV deformation was observed in both EUROPLEXUS and AUTODYN calculation results. The analyses of slight difference between EUROPLEXUS and AUTODYN on equivalent plastic strain are the scope of further investigation and may come from different material properties and models in the codes. In conclusion, the assumed mechanical energy was small for this core expansion phase.

The FRN-JPN collaboration on studies as support to mechanical consequences assessment of energetic expansion phase is now programmed up to 2024. The future objectives and milestones are defined based on lessons learned from studies 2014-2019. Between the further objectives it can be highlighted: the new EUROPLEXUS models allowing to define directly pressure and volume evolution in time, AUTODYN geometry improvement representing the rounded vessel, studies applying 3D calculations, new benchmark on CDA bubble expansion into lower sodium plenum (type core-catcher). The studies will be followed by sensitivity studies on geometry, initial considered bubble region etc.

Moreover, it has been concluded that the further work will start by pure benchmark between EUROPLEXUS and AUTODYN codes under the same analysis conditions (P-V condition, boundary condition, modeling of structures). In this case, the SIMMER code will not be applied for chaining and both mechanistic codes will have the same simple-case P-V setup.

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1. Since the calculations presented in this note have been performed with SIMMER-III, KENa is actually expressed in a cylindrical system. [↑](#footnote-ref-2)
2. Coefficient of determination, also referred to as R-squared (or R2) is a measure of the relationship between two data sets used in a mathematical model. In Microsoft Excel, the RSQ function is used to determine the R-squared value for two sets of data points. The return value from the RSQ function is between 0 and 1, sometimes expressed as a percentage from 0 to 100. [↑](#footnote-ref-3)