COMPARISON OF AN ADVANCED ANALYTICAL TOOL WITH THE SIMMER CODE TO SUPPORT ASTRID SEVERE ACCIDENT MITIGATION STUDIES

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Abstract

The study presented in this paper deals with the assessment, against SIMMER results, of a physical-probabilistic tool dedicated to molten material core discharge. This 0D tool handles heat transfers from molten, possibly boiling, pools to mitigation tube walls, fuel crust evolution, segregation/mixing of fuel/steel pools, radial thermal erosion of mitigation tube wall, and discharge of molten material with axial thermal erosion of the transverse tube, coupled with neutronic evolution of the fuel power. This tool will be briefly described before presenting the comparison with SIMMER-III results, including a space-and energy-dependent neutron transport kinetics model, on several test cases. This tool, which is very low time consuming, will thus enable large sensitivity studies on different physical and design parameters.

Introduction

The current objectives of GenIV projects are to define a reactor design in order to improve reactor technology in terms of safety and reliability at an industrial scale. Design improvement studies of Sodium Fast Reactors (SFR) are ongoing in France. The core design studies are carried-out by the CEA with support from AREVA and EDF. A major innovation of the new SFR French concept concerns the core which is featured by a very low (even negative) neutronic effect caused by a potential sodium voiding. This is favorable to boiling prevention and core degradation and thus to the limitation of energy released in primary phase of a severe accident. Thus, on the contrary to fast reactors with former core concept, the molten materials would not be ejected during this primary phase and the entirety of the core materials should be considered in mitigation evaluations.

In the framework of the safety studies on molten pools, formed during a potential severe accident transient, a physico-statistical tool devoted to this issue has been developed. This tool is a part of a set of tools developed by CEA [1] to carry out uncertainty studies in parallel of the use of more complex mechanistic tools such as SIMMER [2] and SAS [3]. Indeed, each simulation of such complex codes requires a high CPU time, especially when neutron physics is calculated, which considerably limits the number of simulations. This prevents their direct use for uncertainty propagation and sensitivity studies, especially in the case of a high number of uncertain input parameters.

Thus this tool will be used to define mitigation provision needs (number of mitigation tubes, need of absorbent injection) to avoid large core recriticality.
The physical part of this tool, devoted to mitigation, handles heat transfer from molten pools to transverse tube surfaces, fuel crust evolution, segregation/mixing of fuel/steel pools, radial thermal erosion of mitigation tube wall, and discharge of molten material with axial thermal erosion of the transverse tube, coupled with neutronic evolution of the fuel power. This tool will be briefly described before presenting comparison on some transients with SIMMER-III results including a space-and energy-dependent neutron transport kinetics model.

1. Mitigation studies context

The new core concept (called CFV-low voiding effect core-) is an axial heterogeneous core [4] on the contrary to more classical homogeneous cores used in former SFR. The low void effect of the CFV core results mainly from the presence of a sodium plenum above the fissile zones combined to the presence of a fertile plate in the inner zone of the core encompassed by two fissile zones (Figure 1). The larger height of the outer fissile zone enables the void reactivity effect to be lowered due to neutron leak enhancement.

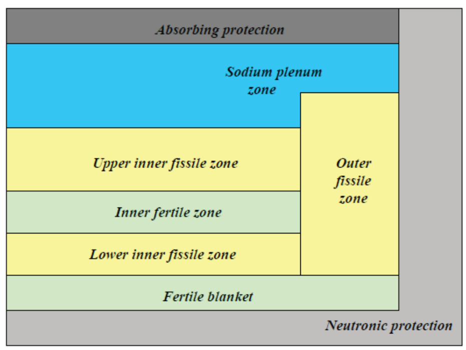
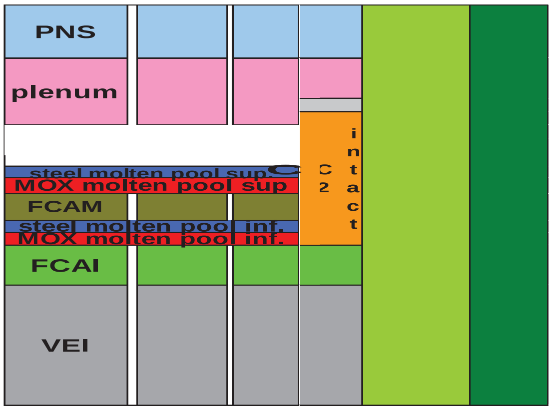


Figure 1: CFV general core geometry (radial cut)

In the framework of safety analysis, mitigation studies postulate an initial core state resulting of a mild UTOP transient [5] obtained from SUREX code results [5][1]. This degraded core state has also been obtained from SIMMER results of an ULOF transient [6]. It appears that a realistic and penalizing degraded core state presents two molten zones in the both fissile zones of the inner core (named C1). Moreover, the fertile zone, as well as the outer fissile zone (named C2), are not molten yet, but the inner fertile zone consists of not molten debris that have collapsed over the lower fissile zone. This degraded state is illustrated in Figure 2 and Figure 3. As represented in figure 3, following a mild UTOP (consequence of the ULOF), the mitigation tubes have not melted yet (because cooled by inner sodium). They are composed of 18 control rod tubes whose bottom could be filled by molten material and 3 crossing tubes (passing through the core, the diagrid, the strong back), especially devoted to mitigation purpose which enable to pour out molten material directly from to core directly to the core catcher. On the axial cut, the debris of the fertile zone have glided over the molten materials of the lower fissile zone. Between both zones, a plug of solidified materials is assumed to be formed. The formation of such a plug is also possible at the location of the upper neutron protection above the upper fissile.

[1] SUREX is a homemade code which calculates the evolution of the reactivity and core power during a specified reactivity transient.



Legend	medium name	temperature	comment
	VEI	900℃	
	void	900℃	
	FCAI	900℃	
	molten steel	2700℃	
	molten MOX	2770℃	enrichment PuO2/(U+Pu)O2 = 22,80%
	VES	900℃	
	PLENUM	900℃	
	PNLA	900℃	reflector
	PNLB	900℃	protection
	PNS	900℃	
	FCAM	2400℃	blanket w/o clad (40,85%UO2 + 59,15%void)
	C2	2000℃	

Figure 2: Compacted configurations calculated for CFV core (after a mild UTOP); see the glossary for the abbreviations

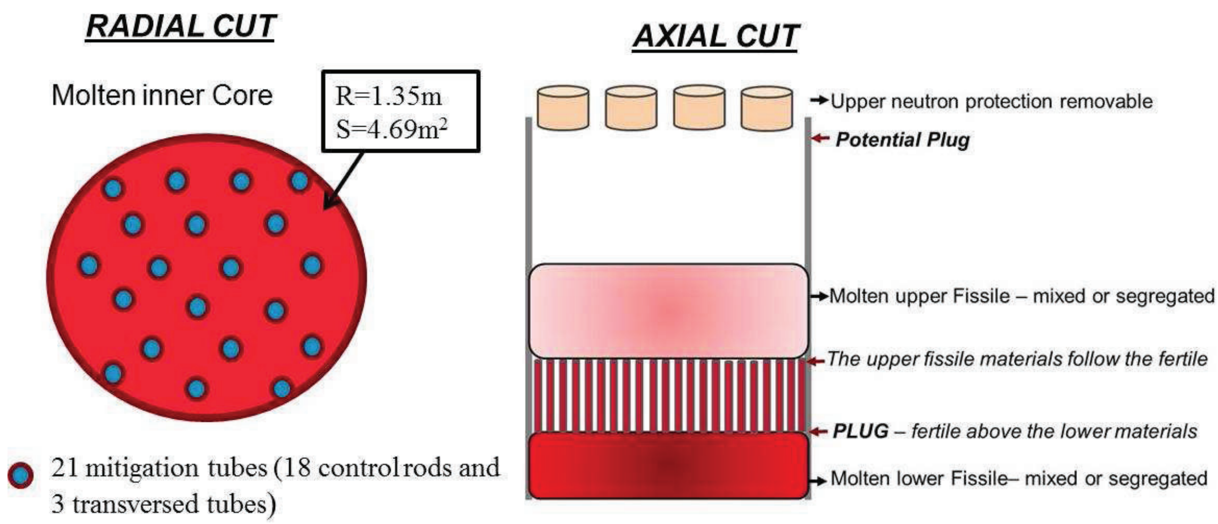


Figure 3: Considered initial degraded state (radial and axial cuts)

2. Physical models

The physical models and the calculation scheme of the physico-statistical (also called analytical) tool are generic to the treatment of various material molten pool of constant radius. This tool is parametrized to facilitate sensitivity evaluations (such as initial reactivity, wrapper thickness of the mitigation tubes, initial material masses, fuel power…).

This tool couples the temporal evolutions of materials located inside the upper and lower fissile zones to the evolution of the global core neutronics. The considered molten pools are composed of steel and fuel which could be mixed or segregated (steel layer above a fuel lower pool). The spatial distribution of materials between these two pools evolves during the transient depending on material temperature. As displayed in Figure 4, various configurations are treated: totally segregated materials, partially segregated configuration where the steel mass is distributed between a steel layer which is above and a lower mixed steel/fuel pool or totally mixed configuration where the pure steel layer has disappeared. The lower mixed pool is considered homogeneous with physical properties dependent on the proportions of the various materials inside the pool.

Figure 4: Various configuration of material repartition inside the upper or lower fissile zone.

As the fuel is located in the lower pool, the thermics and dynamics of this pool is transiently treated in order to evaluate its swelling related to steel vaporisation and material boiling and consequently the material ejection. Thus, at each time step, a mass, momentum, and energy balances over this pool volume are solved to evaluate the evolution of the height of the pool, the velocity of its upper interface[2] (between lower mixed pool and pure steel pool) and the homogeneous temperature. Heat losses toward the various sides of the pool are obtained thanks to convective heat transfer correlation derived from past experimental tests [7][8][9]. The transient evolution of the fuel crust surrounding the lower pool is also evaluated and the associated energy is assumed to be supplied to the wall of the mitigation tube to enhance its melting.

As the upper pure steel pool does not boil in most of the studied transients, the need of solving three balance equations has not been identified and only an energy balance is solved over this upper layer. Depending on the user choice, the upper boundary condition could either be a known temperature (crust of steel at melting temperature in case of sodium re-entry) or radiation to the upper neutron protections.

Models of segregation and mixing of the two materials are also coupled to the previously described evolution of the pools. Based on literature review [10][11][12], a simple model of mixing due to fuel boiling and steel driving in the hotter lower pool leading to its vaporization has been considered as well as a model of material segregation when boiling stops due to buoyancy resulting from material density difference. This literature review has also led to the definition of ranges of realistic slopes (in kg/s of segregated or mixed steel).

On the one hand, this tool handles no confined pools which are not plugged at its top. These pools remain at the local pressure imposed by the reactor vessel and the saturation pressure is fixed; this is the case for pools of materials inside the upper fissile zone (if not plugged). Once these pools heat up and that these components are vaporized (especially steel), the lower pool internal pressure increases and its upper interface rapidly rises. The molten material are then ejected by the top and spread out above the core. It is assumed that they do not fall again inside the core. On the other hand, this tool handles confined pools in case of re-solidified materials in the upper neutron protection zone forming a

[2] The velocity of materials is supposed to be unidirectional along the pool height (Z axis) and linear inside the pool: null velocity at Z=0m and maximum velocity at Z=upper interface.

plug. In this case, the local pressure rises due to materials vaporization and the homogeneous saturation temperature is evaluated at this local pressure. In this case, there is no ejection of materials by the top.
The failure of the wrapper of the mitigation tube is also modelled either due to thermal or mechanical loading. In case of thermal failure, the heat is convected from the pool to the wrapper until the total steel thickness of the wrapper is melted. As any mechanical criterion has been derived until now, the mechanical rupture is assumed to occur when a threshold on the difference of pressure on both sides of the wrapper is exceeded.
Once the tube failure is achieved, the pools are drained away in the mitigation tubes. This draining is caused, once again, by the over-pressure between the molten pools and the tube. The draining velocity is thus evaluated as well as the enlarging of the failure diameter due to the axial thermal erosion of the wrapper tube.
Finally a 0D eight groups model is used for the calculation of the neutron population evolution and the associated core global power variation. The Doppler effect, the material segregation and mixing, material ejection and draining are also considered as inducing reactivity effects. That is why, the reactivity variation linked to each phenomenon, independently of the others, has been evaluated from static ERANOS calculations [13] for a reference configuration where 7430kg molten fuel and 4910kg molten steel are respectively inside the upper fissile zone and 5307kg molten fuel and 2052kg molten steel are respectively inside the lower fissile zone. Reactivity variations related to some material movements are given in Table 1. These separated effects have been introduced in the analytical tool while waiting for a more complex and accurate way to handle these effects thanks to a surrogated model[3]. A particular time step management has been implemented to deal with states near prompt-criticality. The evolution of the residual power is given by an exponential law established for the CFV core.

Effects	***Inserted reactivity (pcm)***
Materials segregation in lower fissile zone	-510
Materials segregation in upper fissile zone	+2950
Complete emptying of mixed material of the upper fissile zone	-7600
Complete emptying of only fuel in the upper fissile zone (stratified configuration)	-9700
Complete emptying of only steel in the upper fissile zone (stratified configuration)	-1600
Complete emptying of only steel of the lower fissile zone : • Segregated materials in both fissile zones • Segregated materials in lower fissile zones, mixed in upper fissile zone	 +1250 +515

Table 1: Summary of reactivity inserted by separated effects (carried out in reference case configuration)

The main objective of this following paragraph is to demonstrate the validity of its results and then its high potentiality for sensibility studies and later statistical treatment of uncertainties enabling to consolidate mitigation features.

[3] This surrogate model is under establishment.

3. Validation on SIMMER results

The degraded core state already described in paragraph 1 is considered. For the reference case, the core is assumed at residual power[4] and at initial time. The reactivity is null. It is assumed also no reactivity supply during the transient (caused for example by a sodium return inside the plenum). To evaluate the radiative heat transfers above the upper fissile zone, the upper neutron protection temperature is taken at 1000K owing to possible liquid sodium contact. The 21 mitigation tubes have a perimeter of 0.575m, an area of 0.023m^2, a thickness of 4.5mm and an initial temperature of 1173K. The thermal failure model is also selected. Moreover, the fuel initial crust thickness is 50µm, and when wrapper failure occurs, the initial hole diameter is 3cm. Obviously, all these initial parameters could be changed for sensitivity evaluation purpose. The degraded configurations in each fissile zone are given by Table 2.

parameters	Upper fissile zone	Lower fissile zone
Fuel mass	7430 kg	4910 kg
Steel mass	5307 kg	2052 kg
Confined	NO	YES
materials	mixed	mixed
Lower pool temperature	3050 K	3050 K
Upper pool temperature	no upper pool at the beginning	
Upper surface	radiation	Steel crust
Pressure	1.7 bar	2 bar
Complete segregation period	3s	0.3s
Complete mixing period	2s	0.3s

Table 2: Parameters of configurations of materials within the upper and lower fissile zones.

The data of this reference case are the same as those of SIMMER calculation, in particular the duration required for complete segregation and mixing in both fissile zones. The SIMMER calculation starts with an initial degraded state similar to the one considered, with the same concentration in neutron precursors (Figure 5).

3.1 Comparison results on reference case

The results obtained with the analytical tool are compared to SIMMER results on the reference case. The calculated transients are very similar (Table 3).

	Analytical tool [s]	SIMMER [s]
Re criticality (ρ>0 pcm)	0.52	0.6
Prompt criticality (ρ>364.5 pcm)	0.89	1.17
Wrapper failure at upper fissile zone	1.22 (on the lower pool)	1.15
Start of materials mixing - Upper fissile zone	0.92	-
Fuel ejection from upper fissile zone	0.97	1.17
Wrapper failure at lower fissile zone	1.6 (on the upper pool)	1.13

Table 3: Transient evolution in the reference case.

[4] Nominal power is 1500MWth

The reactivity becomes positive around 0.55s and the core gets prompt critical at 0.89s with the analytical tool and 1.17s with SIMMER where the material ejection is immediate. In the analytical tool the materials ejection occurs 0.08s after prompt-criticality and 0.05s after the materials mixing in the upper fissile zone (i.e. after boiling). The failure times of the wrapper of the mitigation tubes are also quite similar.

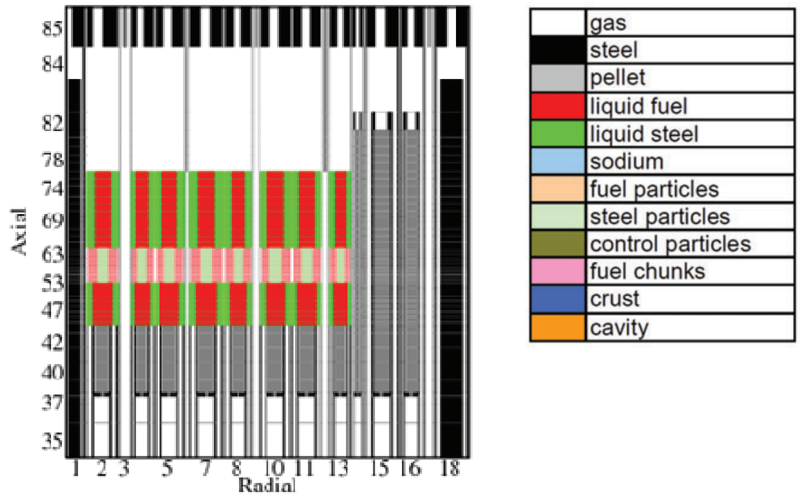


Figure 5: Sketch of the initial state in SIMMER nodalization (molten fuel in red, molten steel in green)

These similar behaviors are also illustrated in Figure 6 which gives the reactivity evolution in both tools. At the transient beginning (phase 1), the reactivity drops due to the important contribution in anti-reactivity induced by material segregation within the lower fissile zone (very fast: 0.3s). Then (phase 2), the reactivity increases because only the materials inside the upper fissile zone go on been segregated that induces a great reactivity supply (2950pcm in 3s). The reactivity becomes positive and when 1$ is reached, the core gets prompt-critical and the power rises in an exponential way (Figure 6) and the pool temperatures highly increase.

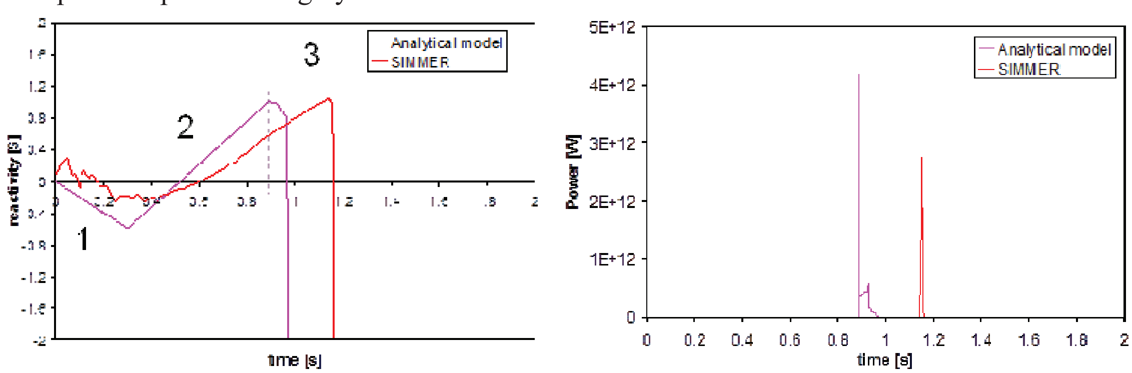


Figure 6: reactivity evolutions in the reference case

The fuel temperature increasing, the Doppler effect becomes important and counter-balances the reactivity insertion due to material segregation inside the upper fissile. That is why, in the analytical tool, the reactivity slightly decreases from 0.89 to 0.92s. At 0.92s, the materials in the upper fissile zone mix because the boiling criterion is exceeded (related to the boiling temperature of the homogeneous lower pool). This mixing inserts some anti-reactivity leading to a large reactivity drop. The reactivity

remains however positive, near 1$. Thus the power, although lower than at 0.89s, remains high. At 0.97s, following boiling and pool height increase, materials are ejected from the upper fissile zone, leading to an important loss of reactivity.
Thus, on the contrary to SIMMER results where materials are ejected immediately after the prompt-criticality, this duration is evaluated to 0.08s with the analytical tool. This delay takes into account the heating-up of material during the power excursion. This also influences the Doppler effect and the power. Owing to the thermal inertial of materials, 0.03s are necessary for reaching the homogeneous pool saturation temperature and then 0.05s more for the vaporization of steel to induce pool upper surface elevation and finally material ejection. This time delay does not seem unrealistic since the BALL-TRAP experiments have shown that around 0.2s are required for the steel vaporization once reached its melting temperature[5] [14].

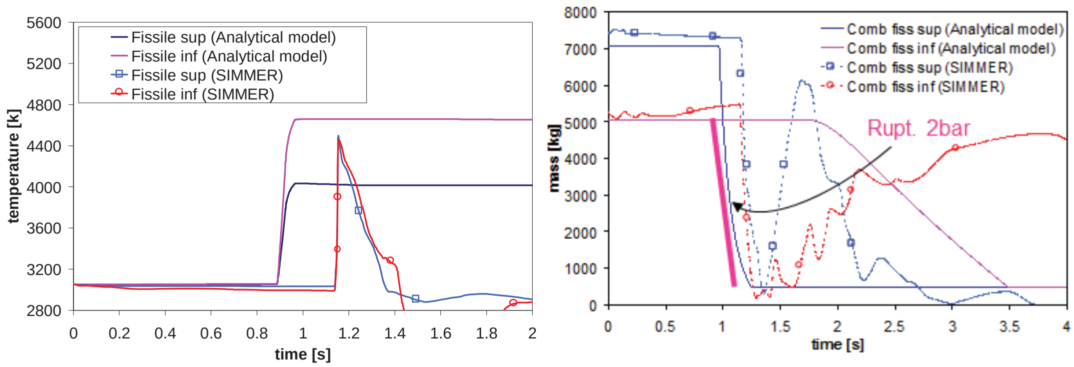


Figure 7: Fuel temperature and mass evolutions in the lower pool of each fissile zone (comb: fuel, sup:upper; inf:lower)[6]

The evolutions of fuel average temperature and mass in the lower pool of each fissile zone are displayed in Figure 7. The orders of magnitude of temperatures calculated with both tools are consistent. In SIMMER, the temperatures of pools, however located in different fissile zones, are the same. This leads to think that the cavity inside the lower fissile zone is not confined as it should.
Concerning the mass evolution, the material ejection from the upper fissile zone is consistent between SIMMER and the analytical model. The fuel mass evolutions in the lower fissile zone are different. In SIMMER, the fuel mass quickly decreases around 1.2s (when the wrapper failed). In the analytical tool, the wrapper fails tardily (1.6s) and the fuel draining is slower; it is governed by the pressure difference around the failed wrapper, the size of the hole, the heat exchanges which lead to this hole enlarging. In Figure 7 are also plotted the results of mass draining when a mechanical failure criterion of 2 bar, directly leading to a large breach, is considered. This latter result is very close to SIMMER results.

3.2 Reference case but confined upper fissile zone

A second comparison between results obtained with the analytical tool and with SIMMER is performed on the same reference case but with a confined upper fissile zone. The calculated transients are then the same as the ones given in Table 3 except the material ejection which does not occur. The reactivity evolution, as well as its various contributions, are mentioned in Figure 8. At the beginning, the material segregation in the lower fissile zone contributes in a dominating negative way to the core reactivity. After ~0.35s the materials are completely segregated in the lower fissile zone and only the

[5] Under lower power than the one of this case.
[6] In the analytical tool, the temperature remains constant after fuel mass vanishes.

segregation in the upper fissile zone induces reactivity increase. Then, in the analytical tool, the lower pool boiling in the upper fissile zone leads at 0.92s to material mixing and anti-reactivity insertion. Following the wrapper failure, the materials draining induces an important anti-reactivity supply.

The evolutions of fuel average temperature and mass in the lower pools of each fissile zone are displayed in Figure 9. As in the reference case, the results are globally consistent. The previous observations remain true; the draining evaluated with the analytical tool is slower than with SIMMER.

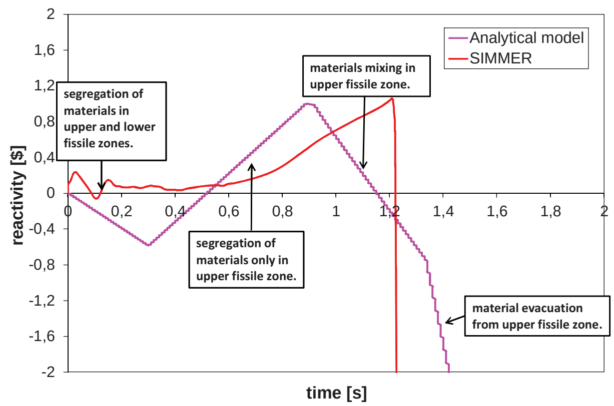


Figure 8: Reactivity evolution and its various contributions.

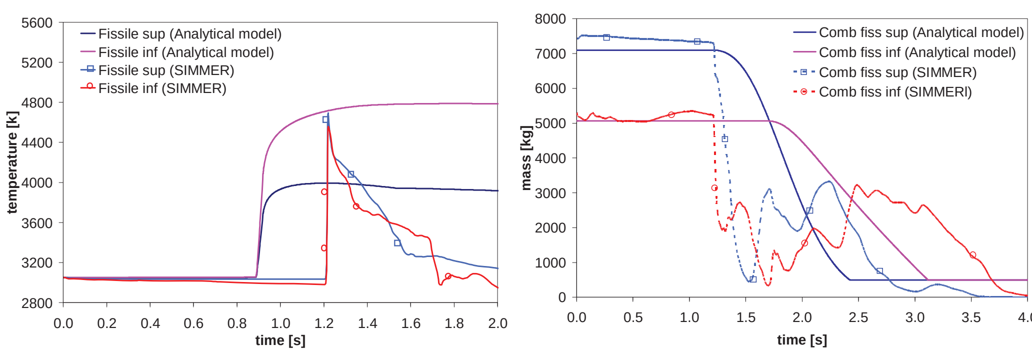


Figure 9: Fuel temperature and mass evolutions in the lower pools of each fissile zone – upper zone confined

3.3 Reference case but initial reactivity of -2000pcm (-5.49$)

The third comparison between results from the analytical tool and SIMMER is carried out on the same reference case but with an important initial anti-reactivity (-2000pcm).

	reference [s]	reference -5.49$ [s]
Criticality (ρ>0 pcm)	0.52	2,67
Prompt criticality (ρ>364.5 pcm)	0.89	NO
Wrapper failure at upper fissile zone	1.22 (on the lower pool)	1.31
Start of materials mixing - Upper fissile zone	0.92	-
Fuel ejection from upper fissile zone	0.97	-
Wrapper failure at lower fissile zone	1.6 (on the upper pool)	1.6 (on the upper pool)

Table 4: Comparison of transients between the reference case and the same case with -5.49$ of initial anti-reactivity

The main transient obtained with the analytical tool is given in Table 4. In spite of the important anti-reactivity already inserted at the beginning, the core gets criticality at 2.67s but never gets prompt critical. A breach in the wrapper of the mitigation tubes is opened at 1.31s at the height of the upper fissile. In SIMMER, on the contrary, the core does not get critical and the wrappers fail at 1.2s.
The evolutions of the global reactivity obtained with the analytical tool and SIMMER are displayed in Figure 10. These evolutions are similar before 2s and the beginning of a large fuel draining is observed in SIMMER whereas this draining is slower in the analytical tool and thus not enough to compensate the reactivity inserted by material segregation. Indeed, as the lower pool temperature is close to the saturation temperature, the materials do not boil and the pressure is low; the draining velocity is small. Moreover, the flowing materials supply little energy to the wrapper and the hole remains small leading to small draining volume.

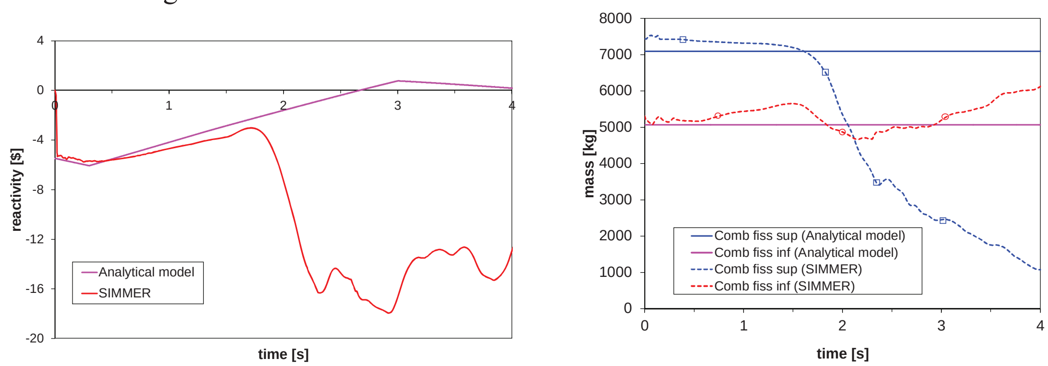


Figure 10: Reactivity and fuel mass evolutions with -5.49$ of initial anti-reactivity (hole diameter: 3cm).

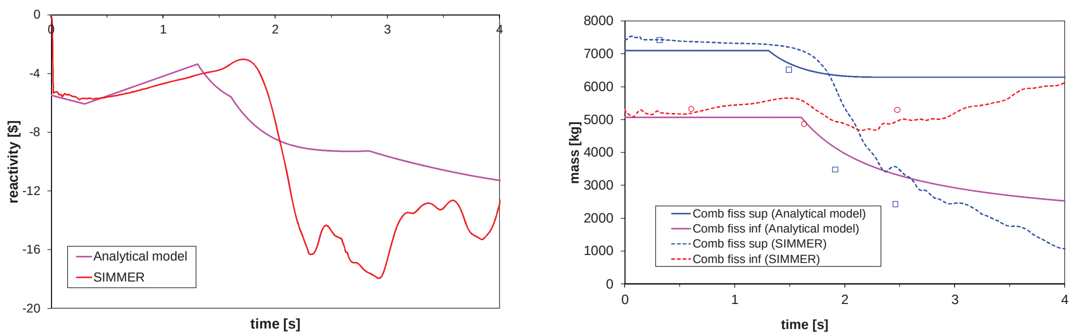


Figure 11: Reactivity and fuel mass evolutions with -5.49$ of initial anti-reactivity and initial failure diameter 25cm.

Same results are presented in Figure 11 as in Figure 10 but with an initial failure diameter of 25cm instead of 3cm. The mass draining is quite faster with a larger wrapper hole. This draining plays an important role on the reactivity evolution which is consistent with the evolution obtained with SIMMER. Indeed, in SIMMER, once the failure criterion is reached, the wrapper breach is already large.

4. Conclusion and Prospects

In the framework of the safety studies on molten pools mitigation in the new SFR French reactor, formed during a potential severe accident transient, a physic-statistical tool devoted to this issue has been developed. This tool is a part of a set of tools developed by CEA to carry out uncertainty studies and margin assessment in parallel of the use of more complex mechanistic tools such as SIMMER and SAS. Indeed, each simulation of such complex codes requires a high CPU time, especially when neutron physics is calculated, which considerably limits the number of simulations. This prevents their direct use for uncertainty propagation and sensitivity studies, especially in the case of a high number of uncertain inputs.

This 0D tool is briefly presented in this paper. It handles heat transfers from molten pools to mitigation tube surfaces, fuel crust evolution, segregation/ mixing of materials (fuel/steel), radial thermal erosion of wrapper tube wall or mechanical failure and discharge of molten material with axial thermal erosion of the mitigation tube, coupled with neutronic evolution of the fuel power.

The final objective of this tool is to assess mitigation needs (number of mitigation tubes inside the core, need of absorbent injection and way of injection) to avoid large core recriticality.

Before performing intensive sensitivity studies, this tool has been validated on SIMMER-III evaluations including a space-and energy-dependent neutron transport kinetics model. Three test cases results have been compared. The transient evolutions calculated with the analytical tool and SIMMER are similar and the same reactivity contributions are observed. The material ejection in the analytical tool takes few tenth of seconds where as it is instantaneous in SIMMER. This behavior has been explained and seems realistic according to some past experimental results. Finally, it has been demonstrated that this analytical code will be a valuable tool to perform sensitivity studies and highlights the most influent parameters (such as the initial size of the wrapper breach or the tube failure criterion). This tool will thus help the core conception, regarding the mitigation features, and will enable to perform large statistical treatment of uncertainty.

In a near future, a surrogate model giving the global reactivity in function of the various masses of material and pool height will be implemented and sensitivity studies to initial configurations (temperature, radiation, pressure, material segregated or mixed…) will be carried out.

Acknowledgment

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<u>Glossary</u>

C1	inner fissile zone (non degraded)
C2	outer fissile zone (non degraded)
CAI	lower neutronic axial protection (reflector)
FCAI	lower fertile zone
FCAM	median fertile zone
PLN	sodium plenum zone
PNS	upper neutronic protection
SA	sub-assembly
SFR	sodium fast reactor
ULOF	unprotected loss of flow accident
UTOP	unprotected transient overpower accident
VEI	lower gas expansion zone
VES	upper gas expansion zone

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