SIMULATION OF FARO L-28 AND L-31 TESTS TO ASSESS MOLTEN JET FRAGMENTATION MODELING IN MAAP

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ABSTRACT

In the framework of severe accident analysis, Molten Fuel-Coolant Interaction (MFCI) is a major issue of concern for safety analysis regarding in- or ex-vessel melt retention (IVR and EVR) and corium coolability. As melt is relocated in the lower head or in the reactor pit, it may interact as a high-temperature jet with the remaining water. Fragmentation of a corium jet falling into water is of particular interest since it influences accident progression and consequences.

MAAP (Modular Accident Analysis Program) is an integral code used to simulate the response of pressurized water reactors to severe accident sequences. The present study aims at assessing the relevance of jet fragmentation modeling in MAAP based on FARO L-28 and L-31 tests simulation. These MFCI experiments, conducted with prototypical melt composition and under realistic accident conditions, provide consistent information on the underlying phenomena.

Calculation results are consistent with experimental measurements. Computed pressure and temperature levels as well as debris size are predicted within the correct order of magnitude. Furthermore, a sensitivity analysis has been conducted to evaluate the impact of some input parameters on jet fragmentation mechanism. This study has led to suggest improvements of jet fragmentation modeling in MAAP such as implementing new correlations describing jet fragmentation, improving the evaluation of debris size or of heat transfer between melt and the surrounding environment.

KEYWORDS

Jet fragmentation, MAAP code, FARO experiment, MFCI, Reactor safety analysis

1. INTRODUCTION

During a hypothetical severe accident in a Pressurized Water Reactor (PWR), molten corium resulting from core degradation can relocate in the lower head or in the reactor pit and interact with the remaining water. As corium jet penetrates water, it undergoes instabilities due to counter-current vapor flow resulting from water vaporization. This leads to jet break-up and droplet formation, whose description is required to evaluate Molten Fuel-Coolant Interaction (MFCI) consequences.

In the last thirty years, many experimental and theoretical studies have been performed on corium jet fragmentation in water to provide models and correlations in order to predict the accident progression [1]. However, some uncertainties remain regarding the interpretation of experimental data and their applicability to reactor-scale analysis [2]. Test conditions are not always representative of a severe accident in terms of masses, temperatures, pressure and simulant or prototypic corium composition. Besides, jet fragmentation modeling encounters difficulties due to a lack of knowledge but also to the complexity of physics.

MAAP (Modular Accident Analysis Program) is an integral code developed by Fauske & Associates, LLC which simulates an overall severe accident sequence [3]. EDF adapted it to French nuclear power plants and actively contributes to its development [4]. Jet fragmentation mechanism is taken into account in MAAP on the basis of entrainment similarity assumption. Besides, Saïto and Meignen correlations can be used to evaluate jet erosion depending on user-defined specifications. Other input parameters related to void fraction, debris size or final particle temperature may also influence fragmentation mechanism.

The present study aims at assessing the relevance of jet fragmentation modeling in MAAP (version 4.08a) based on the simulation of FARO L-28 and L-31 tests. FARO is a large-scale experimental program dedicated to MFCI analysis and quenching behavior. Experiments are conducted with prototypical melt composition, under conditions representative of a severe accident and hence provide consistent information on jet fragmentation mechanism.

After a brief description of the FARO facility and the experimental conditions, jet fragmentation modeling in MAAP is presented. L-28 and L-31 tests are simulated with MAAP and a sensitivity study is carried out to evaluate the impact of input parameters on jet fragmentation. Eventually, prospects of improvements are proposed for MAAP.

2. FARO EXPERIMENTAL PROGRAM

The large-scale FARO experimental program was conducted to investigate interaction of molten fuel with coolant under both in- and ex-vessel severe accident conditions. The test facility is composed of a furnace where melt is produced by direct electrical heating, intersection valves, a release vessel located above an interaction test section, and a venting system that regulates pressure.

A FARO test consists in pouring by gravity a large amount of corium melt into a pool of saturated or subcooled water [5]. The main quantities measured during a test are pressures and temperatures in the gas region, in the water pool and in the debris catcher bottom plate. Post-test debris analysis provides particle size distribution and unfragmented melt mass.

Among FARO tests, L-28 and L-31 tests have been selected to evaluate the capacity of MAAP to predict system pressurization in case of MFCI. Main experimental conditions are summarized in Table I [6]. Contrary to L-28 test carried out in saturated conditions (ΔT_{Sub} = 2 K), L-31 test was performed with subcooled water (ΔT_{Sub} = 105.9 K) and a lower corium mass (92 kg against 175 kg in L-28 test) (Table I). The difference in water subcooling enables to assess whether ΔT_{Sub} is correctly taken into account in MAAP when calculating jet fragmentation.

Most relevant experimental results regarding pressure and temperature levels in both tests [6] are discussed in paragraph 4, when compared to MAAP simulations.

Table I. Main experimental conditions in FARO L-28 and L-31 tests

	Unit	**L-28**	**L-31**
Corium composition	-	80 wt% UO_2 + 20 wt% ZrO_2	
Melt temperature (T_j)	K	3052	3003
Melt mass poured (m_j)	kg	175	92
Initial jet diameter ($D_{j,0}$)	mm	50	50
Gas temperature (T_g)	K	465	300
Initial pressure (P_0)	bar	5.1	2.2
Melt fall height in gas phase (h_g)	m	0.89	0.77
Freeboard volume (V_g)	m^3	3.53	3.49
Water mass (m_w)	kg	517	481
Water temperature (T_w)	K	423.7	290.8
Water subcooling (ΔT_{Sub})	K	2	105.9
Water depth (h_w)	m	1.44	1.45
Test section diameter (D_w)	m	0.71	0.71

3. JET FRAGMENTATION MODELING IN MAAP

Jet fragmentation modeling in MAAP is based on entrainment similarity assumption, using Ricou-Spalding correlation to evaluate the jet entrainment mass rate, $\dot{m}_{ent}$, expressed as:

$$\dot{m}_{ent} = E_0 A_{Sj} \left(\frac{\rho_w}{\rho_j} \right)^{1/2} \rho_j U_j \qquad (1)$$

with E_0 the entrainment coefficient, A_{Sj} the jet surface area in contact with water, U_j the jet velocity as it reaches water surface, ρ_j (resp. ρ_w) the jet (resp. water) density.

The jet break-up length is formulated as a dimensionless ratio, $L_r/D_{j,0}$, evaluated as follows:

$$\frac{L_r}{D_{j,0}} = \frac{1}{2E_0}\left(\frac{\rho_j}{\rho_w}\right)^{1/2} \quad (2)$$

where L_r is the jet break-up length and $D_{j,0}$ the initial jet diameter.

E_0 can assume different values in MAAP depending on I_{E0} input parameter value:

- if $I_{E0} = 0$: E_0 is a constant defined by $E_{0,Const}$ user-defined parameter,
- if $I_{E0} = 1$: E_0 is evaluated from Saïto correlation [8], established on experiments using water as melt simulant and Freon-11 or nitrogen as water pool simulant. E_0 is expressed as follows:

$$E_0 = \frac{(gD_{j,0})^{1/2}}{2F_{Saïto}U_j} \quad (3)$$

  where g is the gravitational acceleration and $F_{Saïto}$ a user-defined constant.

- if $I_{E0} = 2$: E_0 is determined using Meignen correlation [9] given by:

$$E_0 = \frac{0.1}{U_j}\left(\frac{\rho_j}{\rho_w}\right)^{1/2} \quad (4)$$

Other input parameters have a direct impact on jet fragmentation mechanism and heat transfer, affecting pressure and temperature levels. Among them, the average void fraction, the size of particles resulting from jet erosion and the final particle temperature have been identified in MAAP as impacting parameters.

- The average void fraction in the interaction zone is set to an initial value, α_V, and remains the same throughout MAAP calculation. The recommended void fraction value lies between 0.1 and 0.3 (the default value is 0.25).
- The particle diameter, D_p, is assumed to be at least:
  - the capillary length in case of gravity pour, $D_{p,g}$,
  - the stable particle diameter, $D_{p,We}$, defined as a function of the critical Weber number in case of a hydrodynamic fragmentation.

  D_p is expressed as follows:

$$D_p = \min\left(D_{p,g} = 2F_{Dp}\left(\frac{\sigma_j}{g\rho_j}\right)^{1/2}, D_{p,We} = F_{Dp}\frac{We^*\sigma_j}{\rho_w U_j^2}\right) \quad (5)$$

  where F_{Dp} is a user-defined parameter to adjust particle diameter, σ_j the surface tension and We^* the critical Weber number. We^* is set in MAAP to a value far beyond those found in related literature (classically, $We^* \approx 10\text{-}12$ whereas in MAAP We^* is an order of magnitude higher).

- The final particle temperature is either set to water saturation temperature (if $I_{Dp} = 0$) or is evaluated mechanistically considering mainly radiation heat transfer ($I_{Dp} = 1$).

Besides, it has been pointed out that heat transfer from corium to the surrounding environment during melt relocation is overestimated in MAAP benchmark mode. Actually, the delivered corium melt releases its whole energy to liquid water and vapor ($E_{transferred} = E_{corium}$), without taking into account the final particle temperature evaluated as mentioned above. Calculation of heat transfer from corium melt has been corrected by considering the final particle energy to evaluate the energy transferred to the surroundings ($E_{transferred} = E_{corium} – E_{particle}$). The impact of this modification has been assessed on FARO L-28 and L-31 tests (cf. paragraph 4).

4. SIMULATION OF L-28 AND L-31 TEST AND SENSITIVITY STUDY

In the present study, the impact of heat transfer from corium to the surroundings is evaluated as a result of its modification in MAAP. Moreover, a sensitivity analysis is performed to assess the influence of key parameters, listed in Table II, on jet fragmentation mechanism for both tests.

Table II. Parameters affecting jet fragmentation in MAAP

MAAP Parameter		**Default**	**Min.**	**Max.**
Entrainment coefficient if $I_{E0} = 0$	$E_{0,Const}$	0.045	0.025	0.06
Correlation used to evaluate E_0	I_{E0}	0	0	2
Saïto correlation coefficient	$F_{Saïto}$	2.1	2	2.2
Average void fraction in the interaction zone	α_V	0.25	0.1	0.3
Size of particle resulting from jet erosion	F_{Dp}	0.63	0.5	0.75
Final particle temperature	I_{Dp}	1	0	1
Evaluation of heat transfer from corium		With or without modification		

4.1. FARO L-28 test simulation

- **Initial calculation**

A first calculation is performed with default parameter values (Table II) and without modification of the corium released energy. Satisfactory results are obtained compared to experimental data, showing a consistent rise in pressure (Fig. 1) and in temperature (Fig. 2 and Fig. 3). Nonetheless, pressure is overestimated by a factor of 2 (Fig. 1), resulting in an over prediction of gas temperature of about 20 % (Fig. 2) and of water temperature, but to a lesser extent (Fig. 3).

In MAAP calculation, jet fragmentation is complete, as observed in the experiment, and the computed final particle size ($D_{p, MAAP}$ = 4.43 mm) is in agreement with the mean diameter of collected debris in L-28 test ($D_{p, L-28}$ = 3.64 mm).

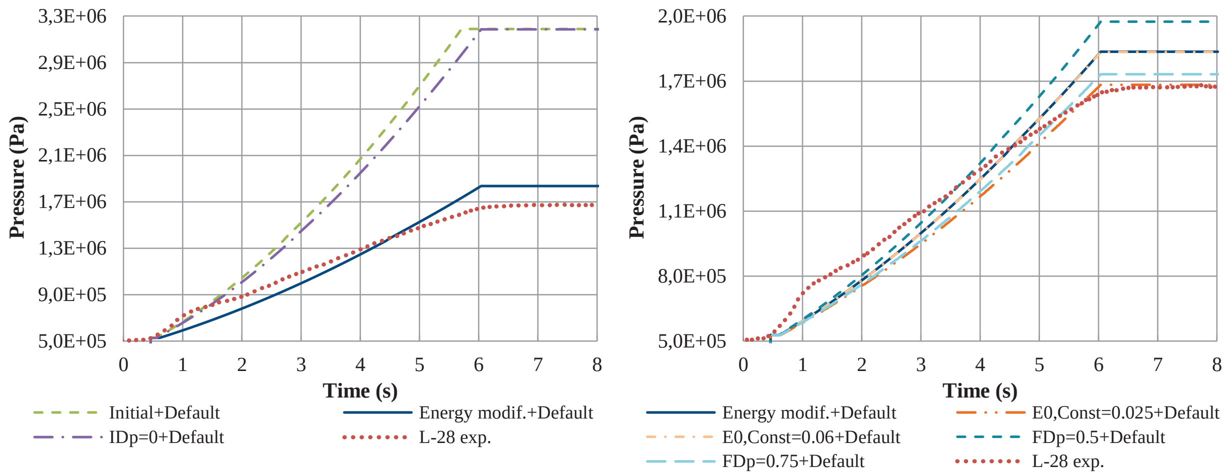

Figure 1. Pressure: comparison of L-28 test results to MAAP simulations

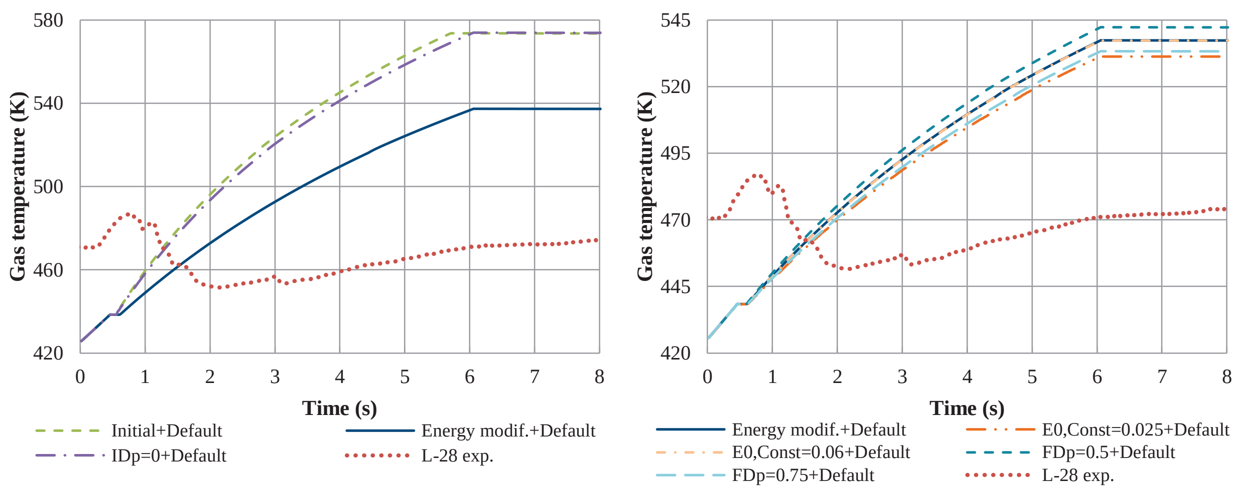

Figure 2. Gas temperature in L-28 test: comparison of L-28 test results to MAAP simulations

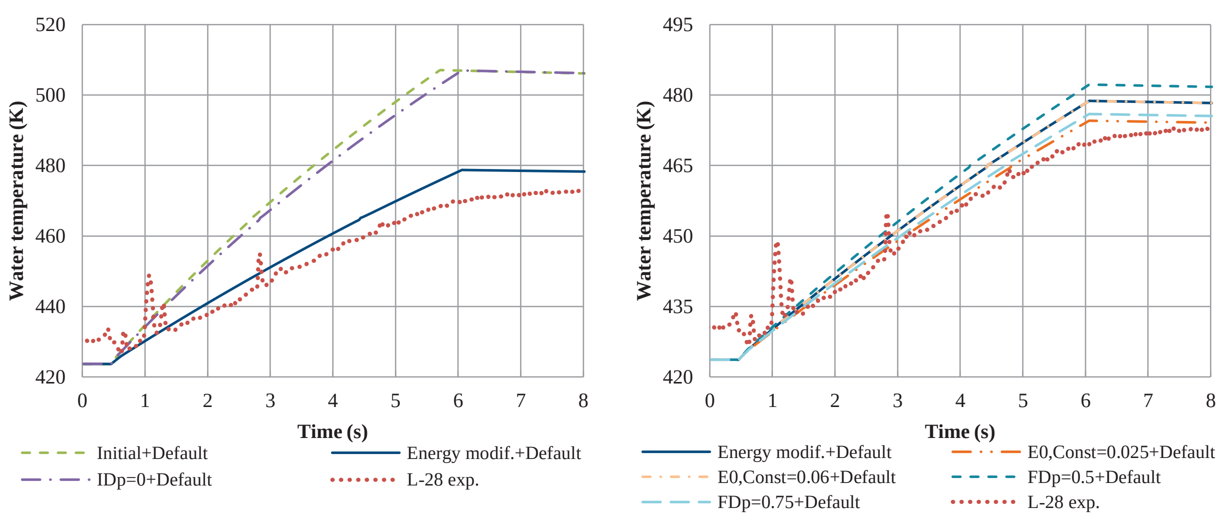

Figure 3. Water temperature: comparison of L-28 test results to MAAP simulations

- **Modification of corium released energy calculated in MAAP**

Quenching heat transfer rate during melt relocation is shown in Fig. 4. The initial calculation provides a significantly higher value compared to L-28 test results. It yields an increased vapor production and a higher pressure level than those obtained experimentally (Fig. 1) as previously mentioned. This is due to the fact that corium releases all its energy to the surrounding environment whatever debris cooling.

The modification of heat transfer calculation by taking into account final particle temperature improves considerably the results, not only for quenching heat transfer rate (Fig. 4) but also for pressure and temperature levels (Fig. 1 to Fig. 3). Computed pressure level is consistent with experimental data and the difference is not exceeding 10 %. Final water (resp. gas) temperature is 10 K (resp. 65 K) above the experimental value. Improved results are thus obtained as a result of the modification in calculating heat transfer from corium.

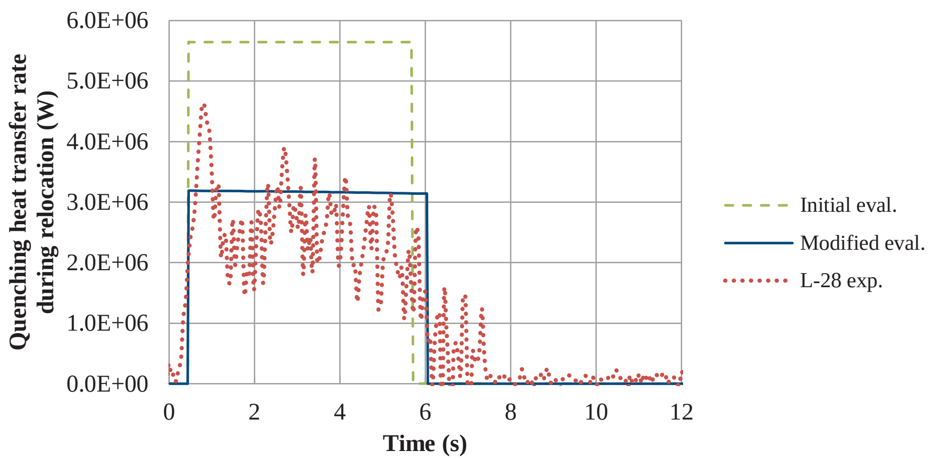

Figure 4. Quenching heat transfer rate during relocation: comparison of L-28 post-test results to MAAP simulations before and after modification of its evaluation

- **Effect of jet fragmentation modeling in MAAP (E_0, I_{E0} and $F_{Saïto}$)**

The influence of corium jet fragmentation modeling is analyzed through E_0, I_{E0} and $F_{Saïto}$ input parameters defined in Table II. As mentioned in paragraph 3, they have an impact on jet entrainment mass rate (Eq. 1) and thus on jet break-up length (Eq. 2).

E_0 decreases with increasing $F_{Saïto}$ and obviously decreasing $E_{0,Const}$. Besides, Saïto correlation provides a smaller entrainment coefficient (for L-28 test, $0.032 \leq E_0 \leq 0.035$ for $2.2 \geq F_{Saïto} \geq 2.0$) compared to Meignen correlation (for L-28 test, $E_0 = 0.076$).

The lower E_0 is, the greater the jet break-up length and consequently, the lower the fragmented mass. Therefore, vapor production is decreased as well as pressure and temperature levels. Beyond a threshold value of the entrainment coefficient E_0 (in L-28 test, $E_{0,\ threshold} \approx 0.034$), corium jet fragmentation is complete and E_0 has no more impact on jet fragmentation.

Calculation results for L-28 test are shown in Fig. 1 to Fig. 3 for $E_{0,Const}$ parameter ranging from 0.025 to 0.06. As discussed above, $E_{0,Const}$ values 0.045 and 0.06 yield identical results. The same results are also observed for I_{E0} and $F_{Saïto}$ values considered in Table II.

It is worth mentioning that Meignen correlation gives the best estimation of jet break-up length ($L_r/D_{j,0}$ = 20.3) with respect to the experimental value ($L_r/D_{j,0}$ = 16.2), while Saïto correlation leads to a less satisfactory result ($L_r/D_{j,0}$ = 46.2).

- **Effect of void fraction (α_V)**

The influence of average void fraction, α_V, is studied by varying its value from 0.1 to 0.4 (the default value is 0.25) (Fig. 5). No overall effect of α_V is observed, neither on pressure nor on temperature, which is unexpected. The higher the void fraction, the more stable the vapor film surrounding corium jet and droplets, and the lower the heat transfer. In addition, void fraction is assumed to have an impact on fragmentation mechanism.

Finally, it should be noted that void fraction remains constant all along melt injection in MAAP (Fig. 5). As a consequence, the evolution of water subcooling degree during corium relocation is not taken into account, which constitutes a weakness in heat transfer modeling.

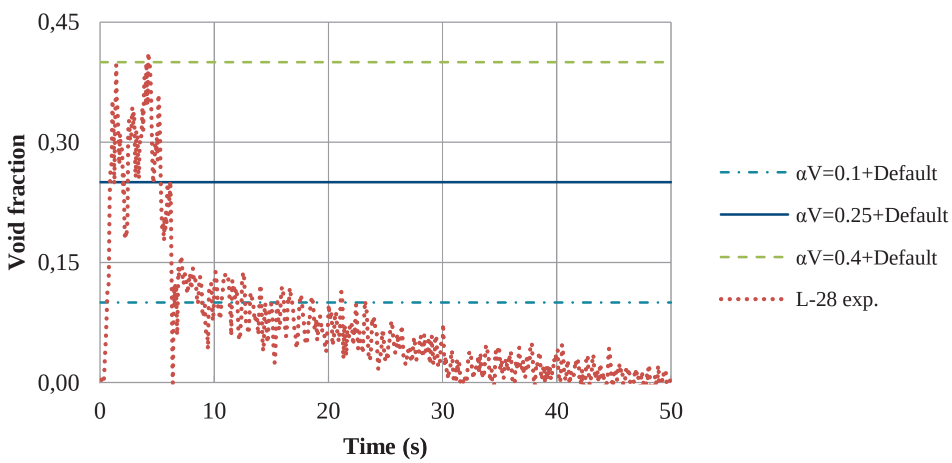

Figure 5. Void fraction: comparison of L-28 post-test results to MAAP simulations

- **Effect of size of particles resulting from jet erosion (F_{Dp})**

F_{Dp} parameter is a multiplier coefficient of the particle diameter, D_p. It is expected to have an impact on heat transfer evaluation: decreasing F_{Dp}, and consequently D_p, results in an increase of the heat transfer surface area for a given corium mass. This leads to an increase of system pressure, as illustrated in Fig. 1.

Moreover, particle settling velocity in water decreases with D_p, which promotes heat transfer between corium melt and the surroundings as well as debris cooling (Fig. 6). As a result, more vapor is generated and pressure level is higher (Fig. 1).

The effect of particle size on jet fragmentation is adequately considered in MAAP. Nonetheless, the use of an adjustment parameter, F_{Dp}, and of a high critical Weber number, We^{*}, should be further investigated. Under the current state of the MAAP code, F_{Dp} default value (F_{Dp} = 0.63) is recommended for use.

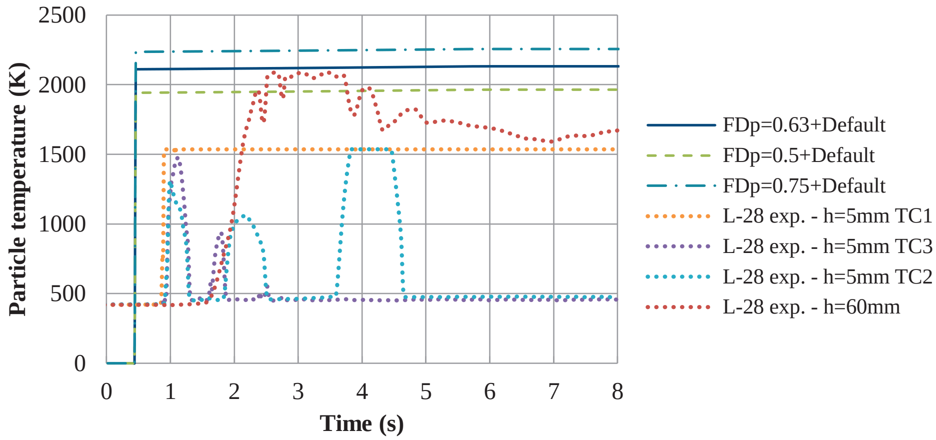

Figure 6. Particle temperature: comparison of L-28 test results to MAAP simulations

- **Effect of final particle temperature (I_{Dp})**

Debris cooling depends on I_{Dp} parameter, as mentioned in paragraph 3. If I_{Dp} = 0, corium melt transfers all its energy to the surrounding liquid water and vapor. This results in higher pressure and temperature levels than those computed with I_{Dp} = 1 (Fig. 1).

It seems more relevant to consider I_{Dp} = 1, particularly if water is closed to saturation. However, the evaluation of final particle temperature may be improved by taking into account film boiling convective heat transfer besides radiation.

4.2. FARO L-31 test simulation

L-31 test is calculated with MAAP mainly to evaluate the code capacity to account for water subcooling effect in jet fragmentation modeling. Water subcooling degree is initially high in L-31 test ($\Delta T_{Sub,L\text{-}31}$ = 105.9 K while $\Delta T_{Sub,L\text{-}28} \approx 0$ K, Table I), resulting in a supposedly low vapor production.

The same approach as for L-28 test is followed for L-31 test. First, the impact of corium released energy on system pressurization and temperature levels is discussed. Then, a sensitivity study is carried out in respect of the parameters listed in Table II.

- **Initial calculation**

An initial simulation of L-31 test is performed using default parameter values (Table II). In this calculation, heat transfer from corium to the surroundings is exclusively dedicated to heat up water. No steam is indeed produced: this is consistent with water subcooling degree which remains high on average all along the test (Fig. 7).

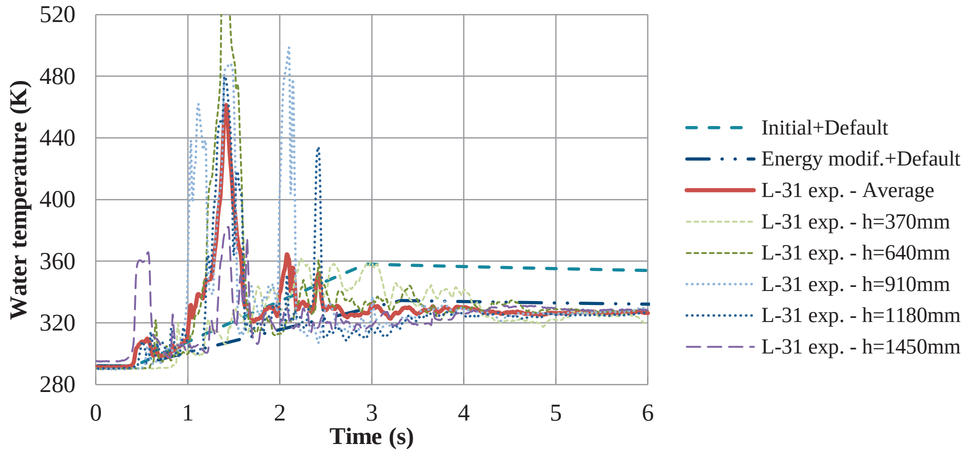

Figure 7. Water temperature: comparison of L-31 test results at different water pool height to MAAP simulations

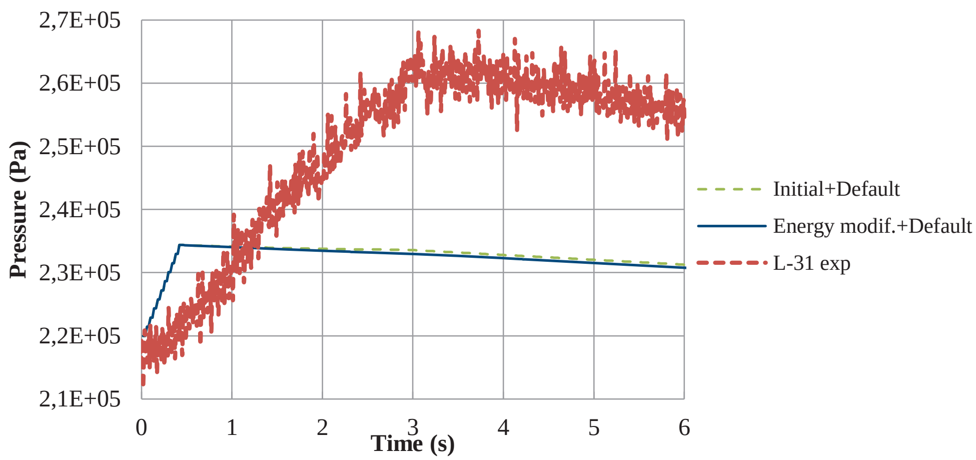

Figure 8. Pressure: comparison of L-31 test results to MAAP simulations

Besides, pressure is predicted within the correct order of magnitude, although slightly underestimated. This may be attributed either to a poor modeling of corium jet injection or to the absence of steam production during melt relocation. As for melt injection time, MAAP prediction seems in agreement with experimental results (Fig. 7 and Fig. 9). However, water can locally reach saturation in the interaction zone due to melt relocation (Fig. 7) so that it evaporates.

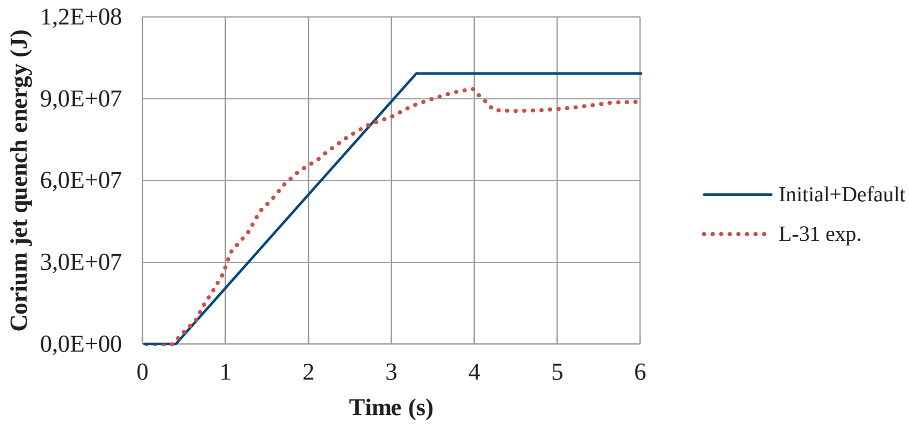

Figure 9. Corium jet quench energy: comparison of L-31 post-test results to MAAP simulation

- **Modification of corium released energy calculated in MAAP**

The modified evaluation of heat transfer from corium melt to the surroundings leads to a better prediction of the average quenching heat transfer rate during melt relocation compared to the experiment (Fig. 10). However, as no vapor is produced in MAAP calculation, pressure is not significantly impacted by this modification (Fig. 7).

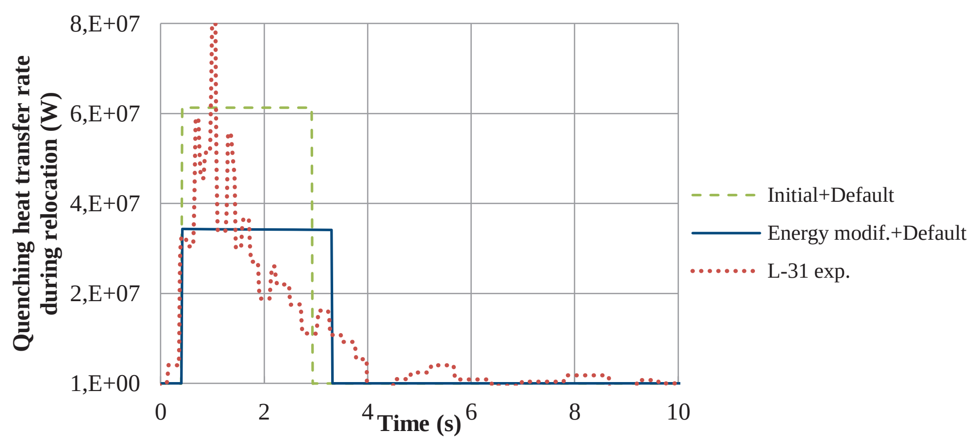

Figure 10. Quenching heat transfer rate during relocation: comparison of L-31 post-test results to MAAP simulations before and after modification of its evaluation

A sensitivity analysis is also carried out for L-31 test, dealing with the same input parameters as previously studied (Table II). Computed pressure and gas temperature are not affected by input parameter values since no water vaporization occurs in L-31 test. However, as corium transfers all its energy to liquid water, coolant temperature is impacted by the change in input parameters (Fig. 11). On the whole, conclusions are similar to those reached in the previous analysis for L-28 test (cf. paragraph 4.1).

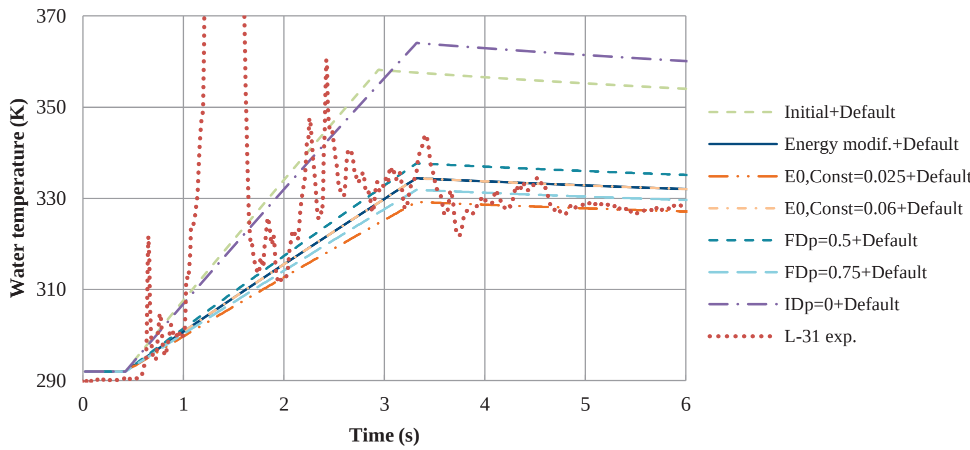

Figure 11. Water temperature: comparison of L-31 test results at different debris bed height to MAAP simulations

- **Effect of jet fragmentation modeling (E_0, I_{E0} and $F_{Saïto}$)**

Increasing E_0 results in a larger mass of fragmented corium debris, and therefore to a higher water temperature (Fig. 11). Threshold value of the entrainment coefficient E_0 for L-31 test is approximately 0.038. Meignen correlation provides once again the best prediction of the jet break-up length ($L_r/D_{j,0}$ = 19.4 against 20.3 experimentally) and is therefore recommended for use.

- **Effect of void fraction (α_V)**

The influence of average void fraction is studied with α_V ranging from 0.0 to 0.4 (the default value is 0.25), keeping in mind the high subcooling degree in L-31 test. This parameter has no impact on simulation results, whether for temperature or for pressure levels or for heat transfer from corium melt to vapor. Therefore, it would be relevant to take into account void fraction and its variation as a function of water subcooling in heat transfer calculation. In the absence of such advanced modeling, α_V should be adjusted depending on pressure and temperature conditions.

- **Effect of size of particles resulting from jet erosion (F_{Dp})**

Debris temperature increases with particle diameter (Fig. 12) while water temperature decreases (Fig. 11), which is consistent with the previous results. As already mentioned, some modeling aspects should be investigated, such as the relevance of F_{Dp} parameter as well as the critical Weber number value. Until then, F_{Dp} default value (F_{Dp} = 0.63) is recommended for use.

- **Effect of final particle temperature (I_{Dp})**

Results are similar to those obtained for L-28 test, except for pressure level which remains unchanged. Even though it could make more sense to impose I_{Dp} to 0 in case of highly subcooled water, it is nonetheless recommended to use the default value (I_{Dp} = 1).

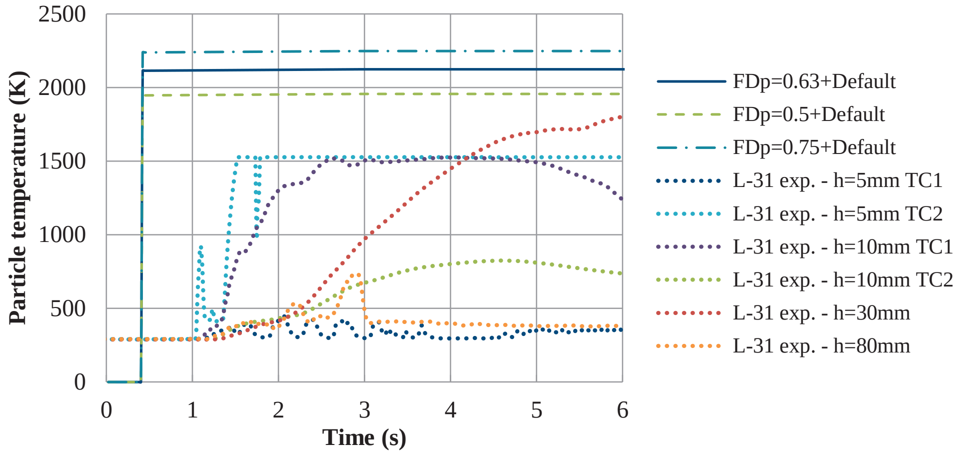

Figure 12. Particle temperature: comparison of L-28 test results to MAAP simulations

5. CONCLUSIONS AND PERSPECTIVES

Jet fragmentation modeling is taken into account in MAAP and enables to predict pressures and temperatures within the correct order of magnitude compared to FARO L-28 and L-31 tests, using a unique dataset. This is achieved through the modification of the corium released energy in MAAP benchmark mode and, to a lesser extent, a suitable choice of some user-defined parameters:

- Meignen correlation ($I_{E0} = 2$) gives the best estimation of the jet break-up length,
- F_{Dp} default value is recommended ($F_{Dp} = 0.63$),
- a consistent final particle temperature should be evaluated ($I_{Dp} = 1$).

This dataset allows to calculate FARO experiments and to obtain a good agreement with experimental data.

Nonetheless, this study, supplemented by a preliminary model analysis of MAAP subroutines, led to suggest improvements of jet fragmentation modeling in MAAP such as:

- implementing new correlations describing jet fragmentation,
- taking into account void fraction in jet fragmentation and heat transfer as well as its evolution during melt relocation,
- improving evaluation of debris size or heat transfer between melt and the surrounding environment.

Afterwards, enhancements identified as most relevant should be integrated in the next EDF released version of MAAP and validated against experimental data. Other phenomena involved in system pressurization and impacting jet fragmentation should be studied in the longer term, for instance metal oxidation or debris solidification. Finally, molten jet fragmentation is tightly linked to debris bed coolability as well as to high-pressure melt ejection and to molten concrete-corium interaction, which modeling in MAAP could directly benefit from these improvements. These issues are discussed further in [4].

REFERENCES

1. T.N. Dinh, V.A. Bui, R.R. Nourgaliev, J.A. Green, B.R. Sehgal, "Experimental and Analytical Studies of Melt Jet-Coolant Interactions: A Synthesis ", *Proceedings of the OECD/CSNI Specialists Meeting on Fuel-Coolant Interactions*, May 19–21,1997, Tokai-Mura, Japan, pp. 468–492 (1997).

2. W. Klein-Heßling et al., "Conclusions on severe accident research priorities", *Annals of Nuclear Energy*, 74, pp. 4–11 (2014).

3. F. Rahn, "Technical Foundation of Reactor Safety - Knowledge Base for Resolving Severe Accident Issues", *Technical Report 1020497*, EPRI, (2010).

4. E. Beuzet, N. Bakouta, M. Boissavit, F. Haurais, A. Le Belguet, V. Lombard, M. Torkhani, "Corium-related improvements in the EDF version of MAAP code in the frame of severe accident studies", *Proceedings of the 16th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, NURETH-16*, August 30–September 4, 2015, Chicago, U.S. (2015). *To be published.*

5. D. Magallon, I. Huhtiniemi, "Corium melt quenching tests at low pressure and subcooled water in FARO", *Nuclear Engineering and Design*, **204**, pp. 369–376 (2001).

6. The Stresa Database, http://stresa.jrc.ec.europa.eu/stresa/ (2000).

7. F.P. Ricou and D.B. Spalding, "Measurements of entrainment by axi-symmetric turbulent jets", *Journal of Fluid Mechanics*, **11**, pp. 21-32 (1961).

8. M. Saïto, K. Sato, K., S. Imahori, "Experimental study on penetration behaviors of water jet into freon-11 and liquid nitrogen", *ANS Proceedings National Heat Transfer Conference*, Houston, U.S., **3**, pp. 173-183 (1988).

9. R. Meignen, "Modélisation de la fragmentation d'un jet liquide à très haute température dans un liquide froid volatile", *PhD Thesis, INPG*, France (1995).