

SYNTHESIS OF ANALYTICAL ACTIVITIES FOR DIRECT CONTAINMENT HEATING

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SUMMARY

In the frame of SARNET, a joint analysis of comparison of lumped parameters code models and results was performed regarding the phenomena of Direct Containment Heating. The codes used were ASTEC (IRSN), MAAP (EDF) and CONTAIN (GRS). Focus was put on dispersal and thermal aspects and the EC-sponsored test DISCO-L1 (also FH-02), with a geometry representative of French P'4 reactors, was used. Results showed that the main characteristics of the test could be found only at the price of a hardly justified fitting of very important parameters (such as the geometry itself). Even the CONTAIN code, that can be considered by far as the most elaborate tool for this purpose could not provide adequate results without sensitive model fittings, which cannot currently be validated separately from each other. The present paper proposes a synthesis of this collaborative work.

A. INTRODUCTION

In a hypothetical severe accident in a Nuclear Power Plant, the core might melt down and lead to the rupture of the lower head. If the Reactor Pressure Vessel (RPV) and Reactor Coolant System (RCS) are still at elevated pressure when the failure happens, the subsequent blow-down will induce an ejection of the molten core into the cavity. Some portions of the molten core material can be entrained, fragmented and dispersed into the containment atmosphere. As a consequence, the fragmented fuel can liberate thermal energy to the containment and metallic components can be oxidized by steam, liberating both energy and hydrogen. Then the produced and initially present hydrogen can burn liberating further energy that would endanger the containment through the induced pressurization. Collectively, these phenomena are called Direct Containment Heating (DCH).

Most of the past studies of this phenomenon were based on geometries of US NPP's (Surry, Zion...). Only a moderate number of studies have been performed for geometries representative of European reactors. Unfortunately, DCH is known to be very dependant on the geometry. To overcome this difficulty the Forschungszentrum Karlsruhe (FZK) has built two facilities to perform scaled experiments that simulate melt ejection under low system pressure: DISCO-C (cold) is used to investigate hydrodynamic features and DISCO-H (hot) is used to study the coupled process including particle/gas heat transfer and hydrogen

production and combustion. DISCO-H is designed for the use of a high temperature corium simulant which is a mixture of alumina and iron produced by a thermite reaction. A first series of experiments was performed to study DCH potentials with the EPR geometry [1] [2] [3] .

In a second series, the DISCO facilities were modified to represent with high-level details the French 1300 MWe P'4 reactor geometry (scale 1/16). Figure. 1 gives a scheme of the used geometry with red arrows indicating the flow paths along which the corium may leave the lower part of the reactor pit. Results of the cold test with water as simulant can be found in reference [4] . One of the experiments done in the "hot" facility was funded by the European Commission in the frame of the LACOMERA platform [5] . This experiment is named DISCO L-1 (also FH-02) and involved a melt ejection by a neutral gas under 19 bars in a neutral environment. The use of a neutral gas reduces as much as possible the chemical processes and allows then a specific study of the dynamical and thermal aspects only.

In the frame of the second JPA of SARNET, it was decided to conduct a comparison of the 0-D integrated tools used for DCH evaluations, namely ASTEC, CONTAIN and MAAP. The general aim of the work was in fact 2-fold:

- use the L-1 test for a general comparison of the results and methods involved in the different codes,
- propose possible improvements of the ASTEC code.

This comparison was done thanks to cooperation between GRS (Gesellschaft für Anlagen und Reaktorsicherheit), EDF (Electricité De France) and IRSN (Institut de Radioprotection et de Sûreté Nucléaire). The complete analysis can be found in [6] . After a short description of the experiment, we will analyse the different models at hand and the results they give. We will finally give perspectives for the development/improvement of the ASTEC DCH modules.

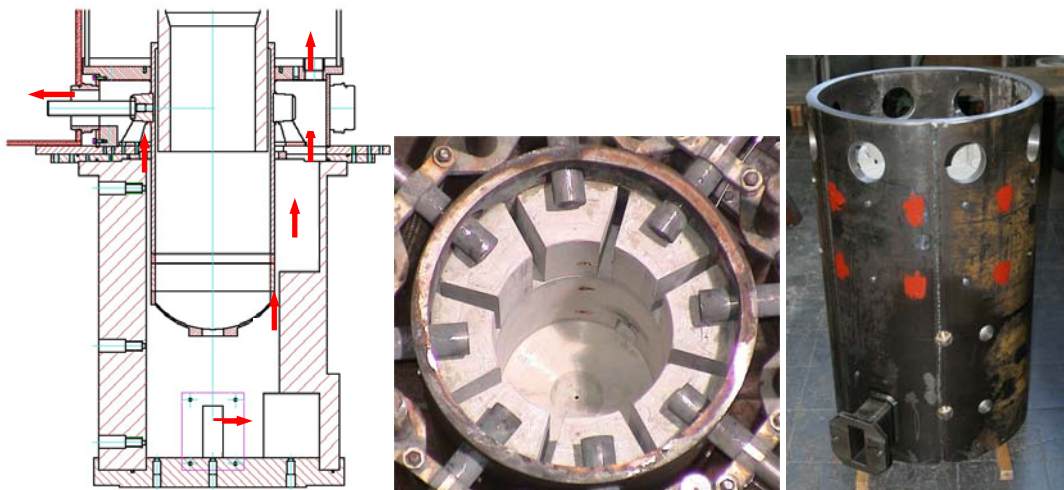


Figure. 1. Sketch of the P'4 geometry with main flow paths and pictures of part of the experimental facility : view into the pit + steel cavity cylinder and bottom access.

B. OVERVIEW OF FH02 EXPERIMENT RESULTS

The DISCO FH02 experiment has been carried out in an inert environment and focuses then on corium dispersion and containment pressurisation induced by the debris to gas heat exchanges. Note however that a small amount of oxidants was still available for

oxidation and combustion. The influence is nevertheless supposed to be small. The initial conditions of the test are summarized in the following table:

Breach hole diameter	60 mm
Thermite mass	10.64 kg
RPV pressure at failure	1.92 MPa
Gas composition in RPV	100% N ₂
Gas composition in containment	97% N ₂ 3% O ₂
Containment pressure	0.2 MPa
Containment temperature	303 K
Melt temperature	2200 K

The pressure histories for the main locations inside the facility are shown in Figure. 2. The maximum pressure recorded in the containment is 3.3 bars i.e. a pressurization of 1.3 bars. The pressurization in the pit reached 3 bars and 1.9 bars in the pit bottom access. The time derivative of the pressure in the vessel gives indications of the flow patterns occurring at the breach. Single-phase liquid flow is estimated to last for 0.1 s. This is rather long in comparison with isothermal tests [4] . It is however representative of all hot tests with thermite in the DISCO facility. The reason of such duration is still not clear. The two-phase flow is believed to last for 0.11 s. more. It can be seen that the pressurisation range in the cavity corresponds to the two-phase flow, giving us further confidence on this analysis.

The time scale for heat transfer is about half a second. In contrast to that the time scale for heat losses though the metallic containment is about 15 seconds (not visible on the figure). So we can estimate that heat losses, although present, do not perturb significantly the results.

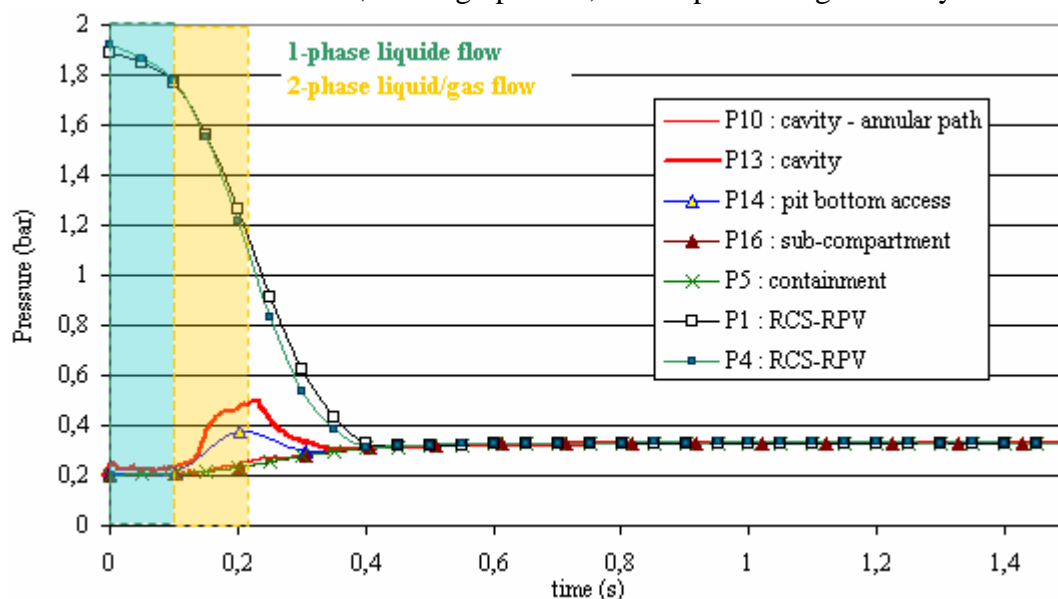


Figure. 2. Pressures transient in the main locations (RPV, cavity, compartment, containment and pit bottom access) and indicate of flow type at the breach.

Other important results are obtained with the analysis of the debris recovery. This is not possible with isothermal tests. Surprising results are found, as seen from Figure. 3. Despite the fact that particles going to sub-compartment have to make a 90 ° turn and a straight path leads to the containment, we find that the smaller particles are, by far, found in the containment. Considering the area average, i.e. mean Sauter diameter, as more representative, we find very small particles of the order of 100 µm in the containment and

about 1-2 mm in the sub-compartment. This means that the droplet size distribution found at the end of the experiment is not solely due to the fragmentation mechanisms during melt entrainment in the cavity. It indicates that there exists a supplementary fragmentation mechanism after or at the flow separation to containment/subcompartment. A possible explanation would be a second fragmentation process occurring at the nozzles of the various volumes.

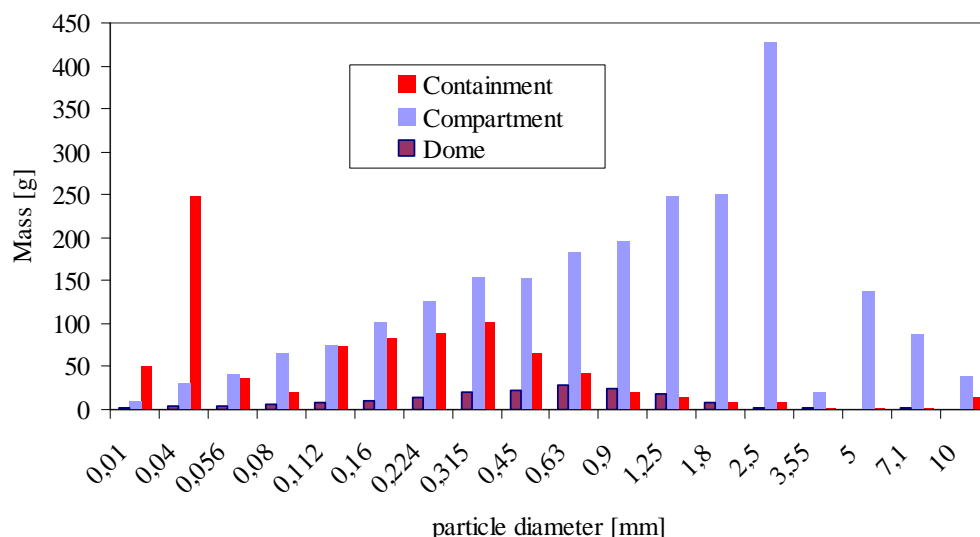


Figure 3. Particle mass distribution in containment, sub-compartments and recovered on the dome

The dispersion data are given in Figure. 4. About 60 % of the melt is dispersed out of the cavity, but only 15 % and 27 % are dispersed in containment and sub-compartment, i.e. volumes where a substantial heating can occur. Now, the thermal efficiency of the dispersion process in this experiment can be easily estimated with the assumption that the maximum efficiency is obtain with a thermal equilibration between the melt and the gases:

$$\eta \equiv \frac{\Delta P_{\text{effective}}}{\Delta P_{\text{thermal equilibrium}}}$$

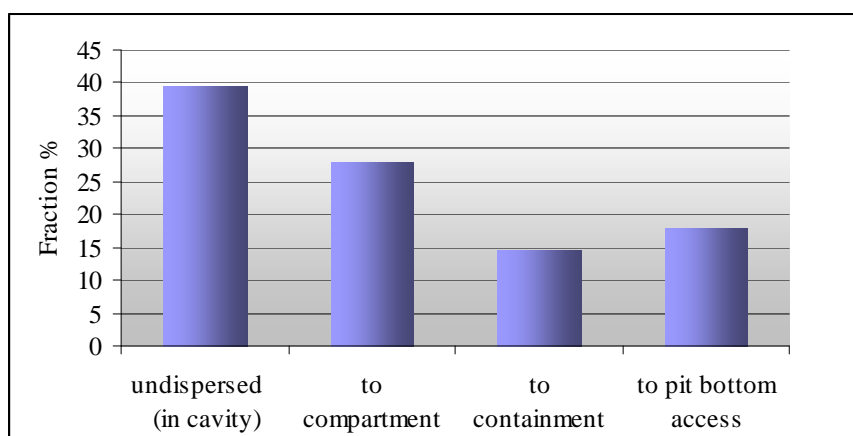


Figure 4. Melt dispersion data

We find that the overall efficiency of the experiment is about 25 %. If we take into account only the part of the fuel that was dispersed in containment and compartments, i.e. the part that should most actively participate to the heat transfer, we obtain a pressurization that is about 2.3 bar, i.e. a thermal efficiency of about 55 %. Then, the dispersed fuel gives

approximately half of its energy. Now, if we further make the hypothesis that, due to the small volume of the sub-compartments and to the relatively large diameter of the collected particles in these volumes, they do not play a significant role, and we obtain, considering only the 24 % going to the containment of the 60 % ejected melt, a rough estimation of the pressurisation of about 1.3 bar. This strong hypothesis would then imply a quasi equilibrium between melt and gas in the containment. We obtain in that case a temperature increase of 220 K in the dome, in qualitative agreement with measurements.

It should be concluded that, from the thermal point of view, presumed that the thermal energy exchange between melt and gas can be fast enough to reach full equilibrium within the time-scale of half a second, the efficiency in the containment seems at first sight quite complete. For the sub-compartments it is likely that the equilibrium is not reached despite the small volume, probably due to the large diameter of the melt drops.

C. MAJOR FEATURES OF ASTEC, MAAP AND CONTAIN WITH RESPECT TO DYNAMIC AND THERMAL ASPECTS.

The three codes have several options to estimate the DCH loads. We will then focus here on the methods which were chosen by the authors of the calculations.

C.1. Generalities

ASTEC (**A**ccident **S**ource **T**erm **E**valuation **C**ode) is a severe accident integral code developed jointly by IRSN and GRS to simulate the complete sequence of a severe accident. The CPA module calculates the containment atmosphere through heat transfers and chemical interactions between gases. However, currently, CPA is not designed to account for the corium transport in the atmosphere and subsequent heat transfers. Then, the RUPUICUV /CORIUM modules were designed to compute the phenomena related to DCH [7] [8] . CORIUM acts as an interface between RUPUICUV and CPA and provides the heat input source in CPA. The general modelling is rather crude and necessitates the setting a lot of parameters. The main models in application for the LACOMERA L1 test are as follow:

- Melt and gas ejection from the vessel in two steps : melt followed by gas;
- Melt dispersal from cavity evaluated from:
 - a correlation evaluated at time 0;
 - a kinetic based on an entrainment assumption with the gas;
- User-defined partition of ejected fuel in various compartments.
- The melt loading is not accounted for in the flow calculations.
- Parametric heat transfer from fuel to gas calculated from a single drop convection law: the time scale, drop diameter and heat transfer coefficient are user inputs.

MAAP (**M**odular **A**ccident **A**nalysis **P**rogram) is a commercial tool similar to ASTEC (but far older), developed for the US utilities, used in particular by EDF [9] . Note however that the open literature and documentation is very limited so we have an important lack of information. The DCH modelling has also a rather low level of complexity. The code however accounts for the presence of the fuel in the flow and heat transfer in a more natural way. The main dynamical and thermal features of the models are as follow :

- Melt and gas ejection from the vessel in two steps : melt followed by gas;
- Melt dispersal from cavity evaluated from:
 - a correlation evaluated at time 0;

- a kinetic based on the gas blow-down time;
- Dynamical and thermal equilibrium between gas and debris.

Note then the assumption of full equilibrium between gas and entrained debris. The partition of the fuel is identical as the partition of exit flow path sections in the cavity. As a consequence, the MAAP calculations do not need a fuel drop diameter for the purpose of dynamical and thermal aspects.

CONTAIN is also a system code developed for the USNRC for the evaluation of severe accidents impact on the containment (Corium-Concrete Interaction, aerosol, fission products, combustion). DCH modelling was an important focus of CONTAIN with quite detailed mechanistic models [10] [11] [12] [13]. DCH is thus the most well-known application of CONTAIN. Conversely, CONTAIN is one of the reference tools for DCH due to both the important work done and the large database for assessment. CONTAIN is being used by GRS with the perspective of getting familiar with the most relevant phenomena in DCH and develop models for the GRS system code COCOSYS (**Containment Code System**).

The dynamical and thermal models of CONTAIN are far more complex and mechanistic than those in ASTEC and MAAP. Some of the processes as entrainment and trapping can be calculated with several optional models.

- Melt and gas ejection from vessel incorporates a transient two-phase period.
- The melt fragmentation/trapping processes is calculated using:
 - A setting of different classes for debris according to their size (10 classes used in the GRS calculation) and their temperature. The shape of the spectrum is however parametric.
 - A process of fragmentation based on an entrainment rate correlation. Alternatively, the user could also specify an entrained fraction correlation, as for MAAP and ASTEC. Fragmentation can occur only in the cavity.
 - A trapping process based on a trapping time scale which can be specified for each cell. In the cavity, trapped debris can be re-entrained. Several trapping models exist, but the calculation was done with a user input rate.
- Inter-cell flow is evaluated taking into account the coupling between gases and melt with a dynamical equilibrium assumption.
- Convective heat transfer is evaluated with the standard Ranz & Marshall correlation.
- Radiative heat transfer to gases and structures is also accounted for.

C.2. Major conclusions on the comparison work

Calculation results and analysis can be found in addition in individual reports [8] [9] [13]. All calculations were done with an important parameter/geometry fitting and thus, since they all compute an adequate pressure, there is no necessity to show the corresponding curves. We will only give here the major conclusions of the study.

It is well-known that DCH is very sensitive to the geometry. As a consequence, the models of the different codes were in general built for quite specific geometries. The authors of the calculations were all confronted to difficulties in both representing the geometry and applying the various correlations. The most adequate representation was done with CONTAIN (Figure. 5). The major complexity comes from the co-existence of important downward (pit bottom access) and upward (containment, compartments) pathways. The second difficulty lays in the complex pathways to containment and compartments. At the top of the annular path around the vessel, there is an intermediate space where the flow separation occurs. This distinction was not adequately reproduced with MAAP whereas, as already said,

the partition is user-defined in ASTEC. It can be noticed that after the annular path, the pathways have an equal section going to containment and a 3-times larger section going to the subcompartment.

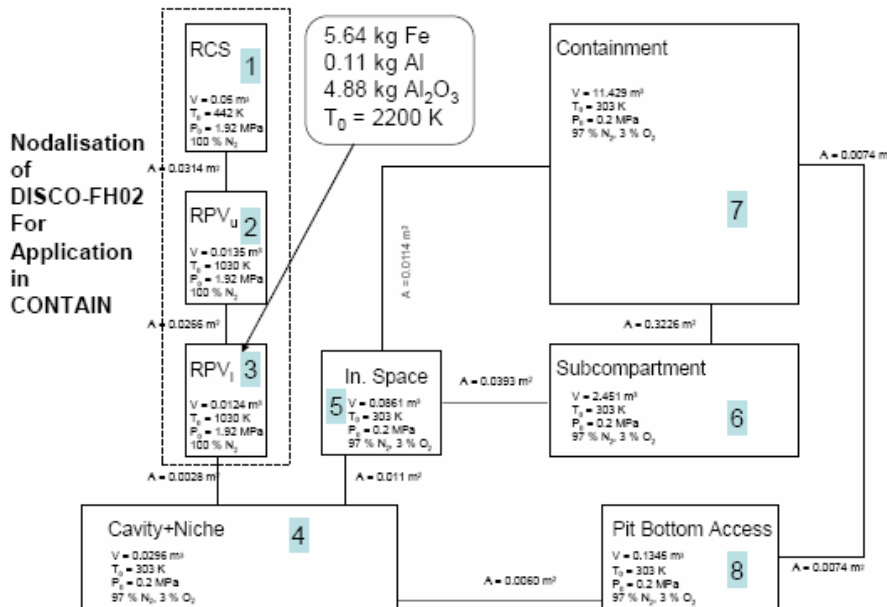


Figure 5. Nodalisation adopted for the revised calculation with CONTAIN.

C-2.a. Melt dispersal computation

MAAP and ASTEC make use of global correlations for the dispersion rates. Many dispersion correlations can be found in the literature. They are mostly based on experiments of ZION and SURRY cavity geometries (closed cavity with a large flow path into a subcompartment). CONTAIN itself provides about 5 different correlations. However, the intense assessment process of CONTAIN did not permit to select a good correlation that would fit the different geometries [11]. Then, there is quite little chance that they can fit a so different geometry.

In the present case of open cavity, efforts have been made by IRSN to evaluate the dispersion for the 900 MWe power plant. A correlation was derived from experiments made by KAERI and included in RUPUICUV:

$$\text{eq. (1)} \quad F_d = 0.45 \left\{ 1 + \tanh \left[2 \left(\log_{10} Y - 4.4 \right) \right] \right\}$$

$$\text{with } Y = We^{1.1058} Fr^{0.149} \left(\frac{\rho_g}{\rho_l} \right)^{0.327} \left(\frac{D_{cavity}}{D_b} \right)^{1.431}, \quad We = \frac{\rho_g \bar{U}^2 D_{cavity}}{\sigma}, \quad Fr = \frac{\rho_g \bar{U}^2}{\rho_l g D_{cavity}}$$

\bar{U} is the gas velocity in the annular space, evaluated for steady condition single-phase flows (Bernoulli). The correlation is difficult to read, with dimensionless numbers with quite unclear meanings. Although based on a quite similar geometry, the correlation clearly shows its limitation for its use for the 1300 MWe plant.

The correlation representing the dispersed phenomena in MAAP is also based on KAERI experiments [14]:

$$\text{eq. (2)} \quad F_d = 0.4 \left\{ 1 + \tanh \left[3.79 \left(\log_{10} t^* - 1.2 \right) \right] \right\}$$

$$\text{with } t^* = t_e u_{debris} / (R_{cavity} + H_{cavity}), \quad t_e = \frac{m_0}{Q_{cavity}} \frac{2}{1-\gamma} \left[1 - \left(\frac{u_{gc}}{u_g} \right)^{\frac{1-\gamma}{1+\gamma}} \right], \quad u_{debris} = u_g \sqrt{\frac{\rho_{H_2O}}{\rho_l}}$$

where m_0 is the initial gas mass in the vessel (RPV+RCS), Q_{cavity} is the gas flow in the cavity evaluated at the beginning of the gas blow-down evaluated with u_g a gas velocity. The MAAP correlation is not really more readable, making use of a dimensionless time scale based on an ejection time and a travelling time. Also, the significance of the velocity u_{debris} is very unclear (fluids lighter than water would travel faster than the gas).

Both ASTEC and MAAP correlations lead to a complete dispersion of the ejected melt, which is not correct¹.

The CONTAIN model used by GRS is more complex. This complexity however does lead to a clear greater accuracy. First, the size of the fuel drops need also to be specified. The particle size distribution (10 groups) was chosen according the experimental spectrum. The size distribution generated in the cavity during fragmentation does not change with time and, due to the uniform trapping rate for all particle size classes and all rooms, it does not vary with space. Reminding the conclusions from the experimental results that the spectrum was very different from one volume to another and that, probably, it does not reflect the actual size distribution in the cavity, we find that such choice is questionable.

Spengler, in the GRS calculations with CONTAIN, chose to use an entrainment rate model. This gives the fraction of airborne melt that will be dispersed in a second process with a flow calculation. Different correlations are provided as options for calculating the entrainment rate flow which is controlled by the dynamic feedback between corium entrainment and cavity conditions. The Whalley-Hewitt correlation was chosen :

$$\text{eq. (3) } \varepsilon = K_c \tau_t \frac{\mu_d}{\sigma} \quad [\text{kg s}^{-1} \text{ m}^{-2}], \quad \tau_t = \frac{1}{2} \Phi f \rho_g u_g^2, \quad \Phi = \left(1 + 360 \frac{\delta}{D_{cavity}} \right)$$

τ_t is the turbulent shear stress, f being the friction coefficient with the classical value of 0.005, and Φ is a two-phase flow friction factor for the annular flow. This term is supposed to account for the surface waviness, i.e. roughness. The correlation includes a cavity constant K_c as a multiplier. However, the Whalley-Hewitt correlation was build upon a value $K_c = 5$ (annular dispersed water flow in tubes). Values reported for the qualification of the model range from 43 to 130 [11] . Values used by Spengler in the present exercise were as high as 1000, indicating an inaccuracy.

Several additional comments can be made on this correlation, particularly for the friction term. First, it is based on the classical isothermal shear stress. Taking into account the high temperature gradient can increase considerably the shear [15] . Second, the use of the additional term f should be made with caution. The correlation is initially validated for steady flows, for which the film thickness is not really a parameter but a characteristic of the flow. In CONTAIN, the film thickness is computed from a mass balance. The correlation is then used for fully non-steady conditions. The dependency on the viscosity seems also quite doubtful: in eq. (3) the entrainment rate is proportional to the viscosity whereas one should have expected on the contrary a stabilising effect. This was recognized early by the users of CONTAIN. It is also very surprising that the fuel density does not appear in the models. In the shear flow instability studies (e.g. Kelvin-Helmholtz), the density of both fluids is always important.

¹ In the MAAP calculations, only 54 % of the fuel was molten and ejected out of the vessel.

Finally, the CONTAIN calculations were found very sensitive to the entrainment rate. This is probably due to the assumption of homogenous flow for the debris transportation.

For an adequate computing of the experiments, it should be a priori important to compute as closely as possible the melt ejection at the breach. Of particular interest is of course the modelling of the two-phase ejection stage. This is done in CONTAIN in two steps. First, a criterion for the onset must be met. Spengler has shown that it was rather correct for the isothermal tests, where the conditions are clear². However, the two-phase flow itself does not seem to be well reproduced as indicated by the vessel pressure computation (Figure. 6). At this stage of analysis, it is not clear if this has an important impact on the overall process. However, it can be seen in the experiment, that the two-phase flow stage (see Figure. 2) is marked by a slow depressurisation. As the depressurisation rate is the dominant factor for the gas velocity and then for the entrainment process, there is here a systematic error.

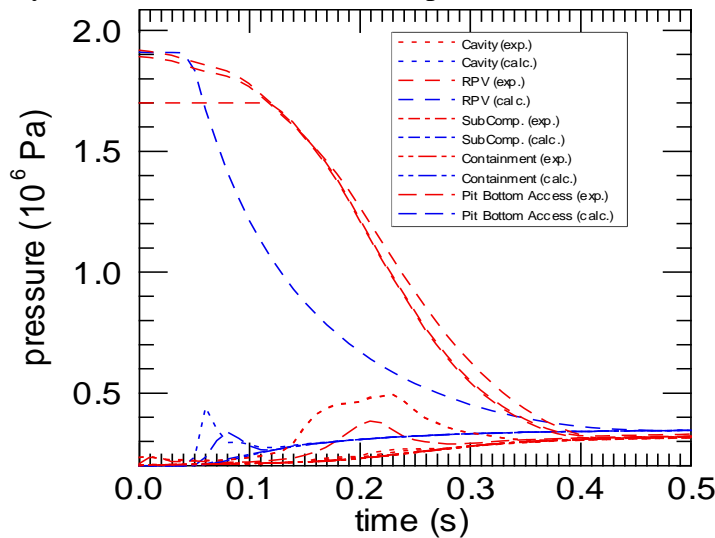


Figure. 6. Zoom on the first times of the CONTAIN calculated pressure transient as compared to experimental one

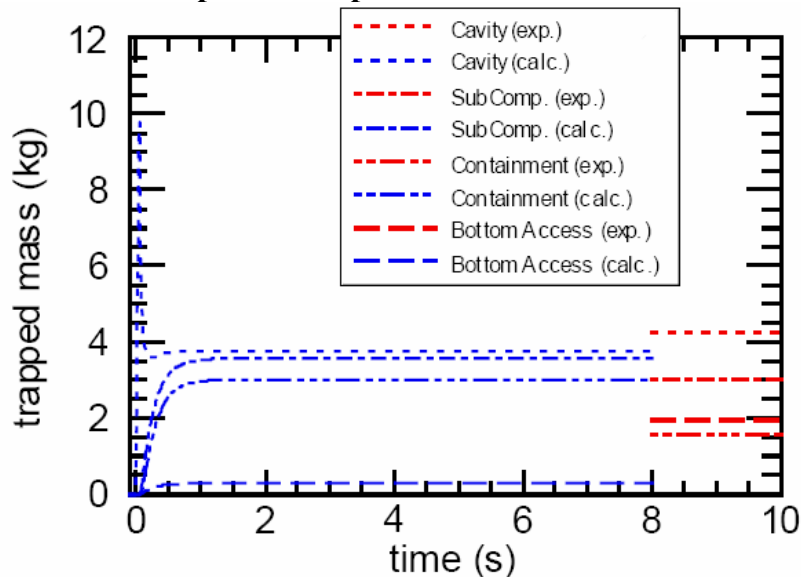


Figure. 7. Comparison of trapped mass in a CONTAIN calculation

² In the DISCO hot experiment, the breach is obtained with the melting of a brass plug. Also, there might be some stratification of the melt as well as bubbles in it. The experimental conditions are then not sufficiently clear to be used for qualification of the Pilch correlation.

Finally, the partition problem has to be discussed. In ASTEC, the user has to provide it. In MAAP and CONTAIN, a homogenous steady flow assumption is used³. Such hypothesis seems quite dubious. In the experiment, the partition is nonetheless roughly representative of the section ratios of the various flow paths. Although the reasons are not clear, and provided that the gas compression effects are not too important, a homogenous flow might then give roughly the good partition,. This was the case in the MAAP calculations but not for CONTAIN. In the latter case, if the global dispersion rate meets the experimental value (fitting of parameter K_c), the dispersal in each specific cell is not very satisfying. In light of the previous discussions, the amount ejected into the containment is probably of utmost importance. The calculation over-estimates this value by a factor of 2 (Figure. 7). In contrast, the dispersion towards the bottom access is very small. This is difficult to understand and more analysis is needed on this point.

C-2.b. Heat transfer

Again, the analysis for the case of ASTEC is complicated by the use of a combination of parameters to calculate heat transfer. The major information that can be gained is the high sensitivity to the parameters (Figure. 8, left). The fact that the pressure can rise to 4.7 bars for small diameters is difficult to interpret in light on the conclusions that were drawn relatively to heat transfer, i.e. that an equilibrium was probably reached in the containment. This might indicate that very small particles in the sub-compartments (which is actually not the case) would lead to a doubling of the total pressurisation. In contrast, in MAAP (Figure. 8, right), with the equilibrium assumption, the good overall pressurisation is obtained, thus indicating a small potential effect of the sub-compartments. A possible reason for the important sensitivity of ASTEC calculations might simply be due to numerical implementation in the interface module CORIUM. More investigations are necessary on this point. In CONTAIN calculations, it was found necessary to fit the heat transfer with a multiplicative coefficient of value 1/3. However, the amount of fuel in the containment is overestimated by a factor of 2, so the actual value of the required correction is about 2/3. This might be simply due to an overestimation of heat transfers in the sub-compartment, due to an underestimation of the drop diameter.

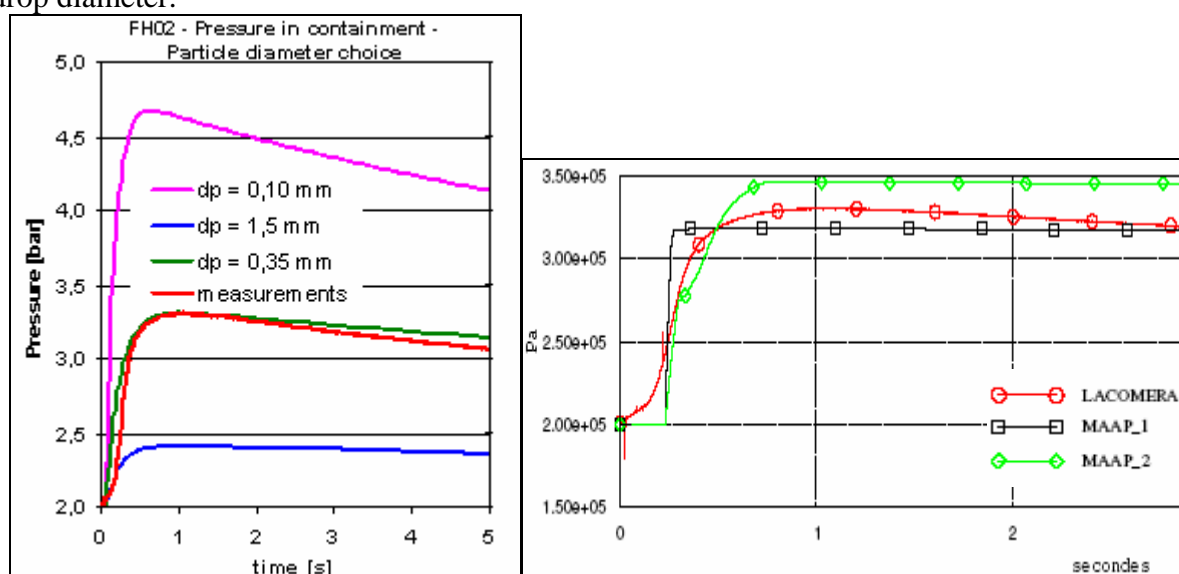


Figure. 8. Left : sensitivity of the pressurization to the fuel drop diameter in ASTEC calculations, right : pressure calculations with MAAP equilibrium model

³ We do not have a lot of information for MAAP.

D. CONCLUSIONS AND PERSPECTIVES FOR COMMON WORKS WITHIN SARNET

Despite the fact that none of the tested models can give accurate results without questionable assumptions, this exercise allowed us to draw interesting conclusions in perspective of the improvement of ASTEC (and also probably for COCOSYS).

1 – For the considered experiment, it is quite likely that the thermal aspect can be reasonably predicted with the use of a simple equilibrium model, as in MAAP, presumed that the heat transfer is fast enough to establish equilibrium on the time-scale for maximum pressurization of the containment. This hypothesis needs further checking but, if verified, it allows an important simplification in the modelling.

2 – The prediction of the dispersal must be accurate only for the fraction going to the containment. This does not necessarily simplify the problem.

3 – The use of global correlations for the prediction of the dispersal characteristics does not seem to give sufficient accuracy and confidence. More, they do not give information on the partition in the different compartments of the dispersal.

4 - The considered geometry with a lower pit bottom access together with an important path upwards is particularly challenging with this respect.

5 – More analysis should be performed with the CONTAIN code. Only a few of the models at disposal were tested. In particular, we recommend testing the flow models with a slip velocity. The importance of the entrainment models might then be lowered.

6 - RUPUCUV needs a lot of improvements. In particular, some inconsistencies were found regarding to the computation of the heat transfers. It is currently not possible to provide definitive conclusions regarding the extend of modifications that are required.

7 – Further analyses are necessary to improve the understanding of the dynamical mechanisms themselves that are important for the computation of the dispersal.

8 – The conservatism of the experiment regarding to the reactor case needs to be checked. It is however likely that thermal effects alone do not challenge the integrity of the containment. Thus the models do not require a very fine accuracy, regarding to these effects. These necessary requirements must be evaluated regarding to their impact of the oxidation and combustion processes.

The following perspectives can then be drawn, giving a roadmap for future work.

1 - The low energetic regarding to thermal aspects must be confirmed for the reactor problem. This will allow evaluating the necessary accuracy level of the models to be put into ASTEC.

In particular,

- a. the conditions for quasi-equilibrium must be checked,
- b. the role of the sub-compartments and pit bottom access must be checked when changing the scales.
- c. the accuracy level must be checked regarding to the chemical aspects.

2 - A better understanding of the processes of dispersal to the bottom (pit bottom access) and the top (containment and sub-compartments) is necessary. Particularly challenging are the mechanisms for dispersion towards the pit bottom access.

3 - The mechanisms of separation of the fuel flow into containment and sub-compartment must be understood. The actual separation is very likely to be geometry-dependent.

In order to fulfil this roadmap, the collaboration between GRS and IRSN is continued. GRS will focus on the evaluation of CONTAIN and COCOSYS whereas IRSN is using the multiphase flow code MC3D [16] .

Finally, it can be underlined that this comparison work is under continuation with the evaluation of two other experiments (FH-01 and FH-03) including chemistry, i.e. melt oxidation and combustion. This time, GRS and EDF will work under blind conditions.

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