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Nuclear Engineering and Design 237 (2007) 2210–2218
Nuclear Engineering and Design
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Experimental interpretation and code validation based on the PHEBUS-FP programme: Lessons learnt from the analysis of the containment scenario of FPT1 and FPT2 tests

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Received 5 May 2006; received in revised form 29 January 2007; accepted 22 March 2007

Abstract

The phenomenological scenario of a severe accident is extremely complex. Its simulation requires specific models of phenomena of different nature (i.e., materials behavior, thermal–hydraulics, aerosols, etc.) and their adequate coupling in safety computer codes. Therefore, an exhaustive and extensive validation against representative databases is mandatory. PHEBUS-FP project is, beyond any doubt, one of the more valuable data sources for this purpose.

The main lessons learnt from the containment simulations of FPT1 and FPT2 tests were summarized. Several safety computer codes: CONTAIN 2.0, MELCOR 1.8.5 and ASTEC 1.1 have been used. This diversity has allowed a "user-independent" cross comparison of codes and data. Overall, codes estimates have reproduced properly experimental trends and no variable has shown major discrepancies. By means of parametric studies, it has been demonstrated that the minor discrepancies found did not come from the hypotheses and approximations adopted. In addition, the analyses of codes results have assisted in the interpretation of experiments by showing potential experimental uncertainties (i.e., steam injection in FPT1) or even by crediting data from a specific measurement technique over other data sources (i.e., samplings over γ-spec in FPT1).

1. Introduction

The phenomenological scenario of a severe accident is extremely complex. For most than 20 years experimental and theoretical research has been, and is still, producing a good deal of results, most of which have been encapsulated in safety computer codes. Necessarily, these tools deal with subjects of a different nature, such as materials behavior, thermal–hydraulics, aerosol dynamics, etc. Specific modeling of phenomena and their coupling require an exhaustive validation against reliable and representative databases. This points the need of carrying out large scale experimental programs where those complex scenarios can be properly addressed.

PHEBUS-FP is one of the most important research projects in the area of severe accidents. It was devised to experimentally study key phenomena involved in light water reactor (LWR) severe accidents. In particular, the transport and deposition through the coolant system and in the containment of fission products, control and structural materials release from a degrading core are being throughoutly investigated. A total of five integral in-pile experiments have been executed in a facility scaled 1:5000 from a 900 MWe pressurized water reactor (PWR).

Experiments FPT1 and FPT2 of the PHEBUS-FP series, despite their similarity (low-pressure, cold leg break), provided substantially different containment scenarios. Conditions in the core and primary circuit during the fission product release and transport were different, so that the in-containment source terms in both experiments also changed. The steam injection in the FPT1 test was four times higher than during the FPT2.

This paper summarizes the main lessons learnt from the simulations of the above scenarios with several safety computer codes: CONTAIN 2.0 (Murata et al., 1997), MELCOR 1.8.5 (Gaunt, 2000) and ASTEC 1.1 (Bestele and Klein-He, 2000). This diversity has allowed a "user-independent" cross comparison of codes and data. The main outcome of this work is given in terms of test interpretation and model validation.

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doi:10.1016/j.nucengdes.2007.03.022

Nomenclature

A	area
AMMD	aerodynamic mass median diameter
c_p	specific heat capacity
C	concentration
d	diameter
$D_{s,nc}$	diffusion coefficient of steam in non-condensable
GSD	geometric standard deviation
h_g	gas enthalpy
h_{fg}	latent heat of condensation
i	element
L	characteristic length
m	mass
$\dot{m}$	mass rate
M	molecular weight
MMD	mass median diameter
N	molar flux
P	pressure
R	ideal gas constant
Sh	Sherwood number
t	time
T	temperature
X	molar fraction

Greek letters

$\boldsymbol{\Theta}$	suction factor
ρ	density

Subscripts and superscripts

avg	average value
bundle	fuel bundle
cond	condensation
conv	convection
Dph	diffusiophoresis
i	interface
in	inlet
MMD	mass median diameter
nc	non-condensable gases
0	interface
s	steam
t	total

2. Experimental program

2.1. Facility

The PHEBUS-FP facility (IRSN, 2002) is a modular rig that comprises mock-ups of the three main systems of a nuclear reactor: core, primary circuit and containment.

The PHEBUS-FP containment is a 10 m^3 vessel made of electro-polished stainless steel. Three cylindrical structures, hereafter called condensers, are attached to the ceiling in order to achieve a surface-to-volume ratio characteristic of a 900 MWe PWR. Each condenser has a painted surface divided in 0.336 m^2 dry-part and a 0.775 m^2 wet-part. The floor of the vessel is equipped with a sump containing approximately 100 l of water at a temperature similar to the wet condenser one. The injection point in the containment vessel is located at the lower region (0.8 m above the sump) and it is directed upward. Three independent organic loops control the thermal state of the vessel walls, sump and wet condensers temperatures. Fig. 1 shows a sketch of the containment vessel along with the boundary conditions set during the first 30,000 s of the PHEBUS FPT2 test.

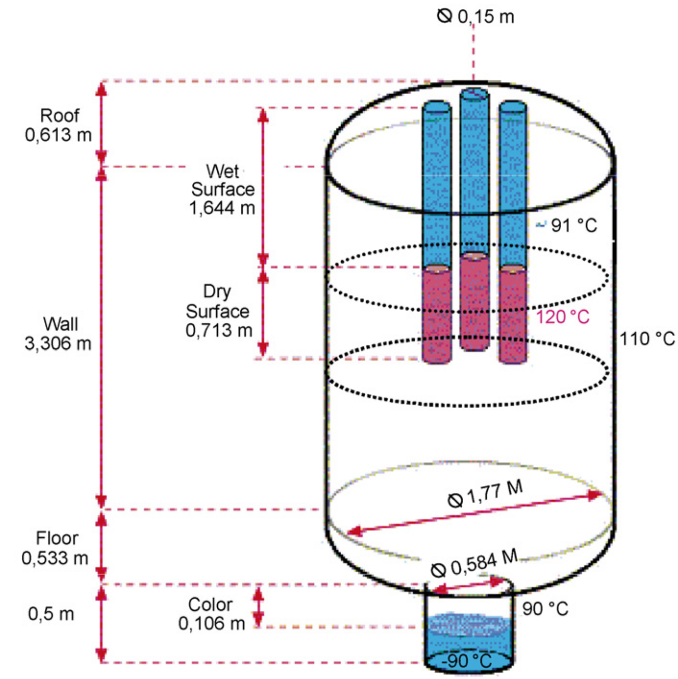

Fig. 1. Geometry and thermal conditions of containment vessel during the FPT2 test.

2.2. Test matrix

The PHEBUS test matrix consisted of five experiments, their main features are summarized in Table 1. A more exhaustive description of the program can be found at "Status of PHEBUS-FP program" (Schwarz and Zeyen, 2003).

The experiments FPT1 and FPT2 resulted in containment scenarios of interest to investigate how a representative in-containment source term behaves under moderate and weak condensing atmospheres, respectively. Both tests used irradiated fuel (23\32 GWd/tU for FPT1\FPT2 tests), Ag/In/Cd control rods and they had rather similar initial conditions (see Table 2). Differences in atmosphere composition came out as a consequence of steam and gas injections from the primary circuit along the experiments. Fig. 2 shows that FPT1 steam input was roughly four times higher than FPT2 and that hydrogen became even the dominant gas source into the vessel for about 1500 s in the FPT2 test.

Carried by these gases, most of fission products and structural and control rod materials were transported to the containment in aerosols form. In Table 3, the amount of relevant elements is represented. The total mass entered was about three times higher in FPT1 than in FPT2. The proportion of iodine and cae-

Table 1
PHEBUS-FP test matrix

	Date	Flow	Fuel	Containment
FPT-0	2/12/1993	Steam rich (oxidizing)	Fresh irradiated 9 d + Ag-In-Cd control rod	Acidic sump 90 °C
FPT-1	26/07/1996	Steam rich (oxidizing)	BR3 23 GWd/tU + Ag-In-Cd control rod	Acidic sump 90 °C
FPT-2	12/10/2000	Steam poor (steam starvation) + boric acid	BR3 32 GWd/tU + Ag-In-Cd control rod	Evaporating alkaline sump 90 °C (120 °C in chem. phase)
FPT-3	18/11/2004	Steam poor (steam starvation)	BR3 23 GWd/tU + B4C control rod	Evaporating alkaline sump 90 °C (120 °C in chem. phase) + recombiners
FPT-4	22/07/1999	Steam poor + H_2 (low volatile and actinides release)	Debris bed from Gravelines 38 GWd/tU + oxidized cladding shards	

sium was between three and four times higher in FPT2 than in FPT1.

3. Simulation approach

The evolution of in-containment source term has been analyzed in FPT1 and FPT2 tests during the first 8 h of the transient (i.e., the degradation phase and the first hours of the aerosol phase). Both tests have been simulated with the CONTAIN 2.0 code. In the analysis of FPT2, two more codes, MELCOR 1.8.5 and ASTEC 1.1, have been used. Thus, a “user-independent” cross comparison of codes and data has been feasible (the same set of approximations and hypotheses has been assumed).

All the codes share a lumped-parameter and multi-compartment approach to containment analysis. The conditions imposed in the FPT1 and FPT2 experiments were not particularly challenging for containment models, but they provided a good basis to test them when using a rather representative aerosol source under well controlled thermal–hydraulic conditions.

Table 2
The containment atmosphere at the beginning of the tests

	FPT1	FPT2
Relative humidity (%)	52.5	55.3
Temperature (°C)	108.0	108.7
Pressure (bar)	2.088	2.015

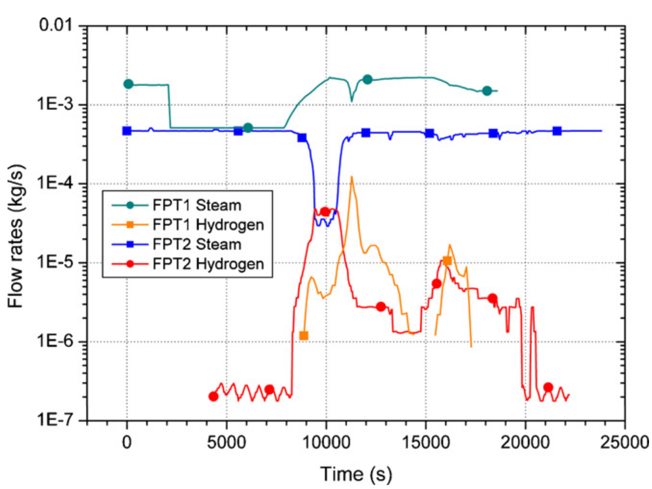

Fig. 2. FPT1 and FPT2 gas flows.

3.1. Nodalization

The MELCOR and CONTAIN codes have modeled the PHEBUS-FP containment vessel as a single compartment consisting of an upper and a lower zone where the sump is located. Contrarily, the ASTEC model has split the vessel into three cells.

The single volume modeling together with the 0-D nature of the codes (i.e., no resolution of momentum equation within a compartment), mean a qualitative deviation from the test. Experimentally, the steam was injected upward into the condenser region and, probably it would have descended adjacent to the vessel walls with a lower steam fraction. In the modeling, however, the “well mixed” approximation of lumped-parameter codes (i.e., vessel atmosphere is a homogeneous gas mixture) makes the injected steam available for heat and mass transfer with all the surfaces contacting the vessel atmosphere. This produces two counteracting artificial effects. On one side, the role played by pool region is enhanced, that is, the predicted condensation on sump surface would have been higher than

Table 3
In-containment element mass

	FPT1		FPT2	
Element	Mass (kg)	Containment inventory (%)	Mass (kg)	Containment inventory (%)
Iodine	7.14E−04	0.6	8.69E−04	2.04
Caesium	6.93E−03	6.0	8.98E−03	21.04
Tellurium	1.31E−03	1.1	1.83E−03	4.28
Silver	3.18E−02	27.8	6.31E−03	14.79
Indium	6.98E−03	6.1	1.07E−02	25.00
Cadmium	1.50E−02	13.1	4.76E−03	11.15
Rest of materials	5.18E−02	45.3	9.26E−03	21.71
Total	1.15E−01	100	4.27E−02	100

Table 4
Main characteristics of the surfaces

	ASTEC 1.1	MELCOR 1.8.5	CONTAIN 2.0
Heat structures surface (m^2)			
No. of heat structures	10	14	18
Vessel walls	18.4	18.4	18.4
Vessel vaults	7.3	7.3	7.3
Wet condensers	2.3	2.3	2.3
Dry condensers	1.0	1.0	1.0
Sump bottom	0.27	0.27	0.27

actually it was. On the other side, the steam content in the gas would be probably lower than the one in the injected gas, so that condensation onto wet condensers would have been lower. These two effects should compensate each other to some extent.

The three-cell nodding is used in ASTEC 1.1 to get information on aerosol deposition on the different walls. The three vessel slices are dotted in Fig. 1. The bottom cell includes the sump and extends from the vessel floor to the lower edge of dry condensers. The mid and top cells are facing the dry and wet condensers, respectively. Inter-cell junctions are defined to assure gas and aerosol mixing in the whole containment.

3.2. Structures and boundary conditions

Surfaces facing the vessel atmosphere have been described as shown in Table 4. As noted, there was no difference with respect to the total surface area exposed, regardless the number of structures used in each code. In Fig. 1, the quasi-steady values of containment structures temperatures during the first 30,000 s of the FPT2 test are shown (FPT1 surface temperatures were similar). Hence, most of surface temperatures have been considered constant in code input decks, except for the wet condenser one, which slight fluctuations have been described in detail.

3.3. Thermal–hydraulic variables

The change in atmosphere composition was governed by four gas flows: steam, hydrogen, other non-condensable gases and samplings. In Fig. 2, the two most important ones are plotted along time. Steam largely dominated injection in FPT1, whereas in FPT2 there was a period of around 1500 s in which H_2 produced by the oxidation reactions in the fuel bundle increased to even a higher rate than the steam one. The steam reaching the vessel is given by:

$$\dot{m}_{\text{steam}}(t) = \dot{m}_{\text{steam}}^{\text{bundle}}(t) - \frac{M_{\text{steam}}}{M_{H_2}}\dot{m}_{H_2}(t) \quad (1)$$

It has been assumed that steam and hydrogen entered the containment with the temperature measured at the closest point to the containment inlet. This temperature ranged from 157 to 177 °C in FPT1 and about 151–153 °C in FPT2. The other non-condensable gases were injected at a temperature near the atmosphere one (∼108.5 °C).

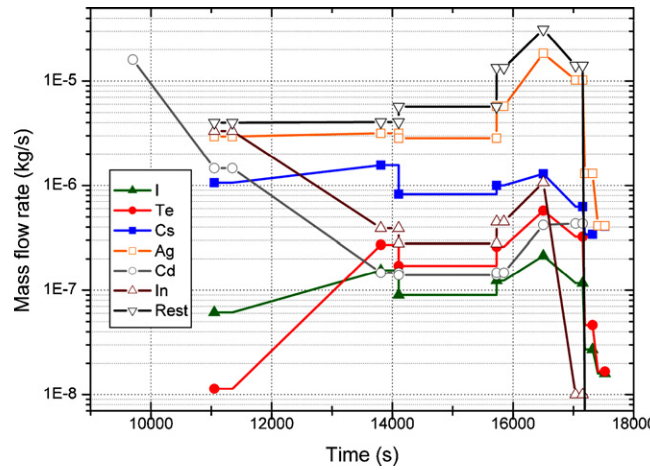

Fig. 3. FPT1 aerosol input rates.

The initial water volume of the sump was roughly the same in both tests (105 l in FPT1 and 110 l in FPT2). The sump was considered in the model as a boundary condition for the containment atmosphere. Given its role as a potential condensation sink, the experimental temperature recorded was imposed by setting sump walls temperature at 90 °C and adding a heat source to fit experimental evolution.

3.4. Aerosol characterization

The aerosol sources in codes are described in terms of composition, flow rates, density and size. Mass entering the containment vessel has been grouped differently in FPT1 and FPT2. In FPT1 seven aerosol types have been considered (i.e., I, Cs, Te, Ag, In, Cd and the rest), whereas in FPT2 they have been reduced to three (i.e., I, Cs and the rest). In both cases, other materials not explicitly accounted for have been included in "the rest". As noted, detailed description of iodine and caesium has been given the utmost interest. Input flow rates are shown in Figs. 3 and 4. The FPT1 data come from (Arreghini et al., 2000) and most of

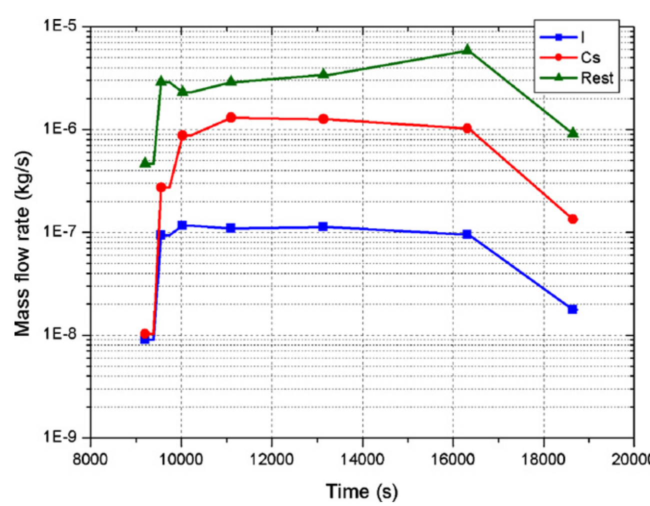

Fig. 4. FPT2 aerosol input rates.

the FPT2 data come from (IRSN, 2002) and from (Zabiego and Pantera, 2004).

The density has been estimated as a mass average of postulated specific chemical forms of the elements that made up aerosol particles (i.e., In_2O_3, CsOH, Ag, etc.). Both assumptions, the assumed speciation and the implicit zero-porosity one, have turned this approach into an approximate way to get an upper density value. The calculated densities were 7070 and 6350 kg/m^3 in FPT1 and FPT2, respectively.

Aerosol particles have been supposed to be spherical and to distribute log-normally along size domain with an aerodynamic mass median diameter (AMMD) of 2.8 μm and a geometric standard deviation (GSD) of 1.9 (Jacquemain et al., 2000). In the case of FPT1, caesium particles have been given a smaller value according to

$$d_{\text{MMD}}^{\text{Cs}} = d_{\text{MMD}}^{\text{aerosol}} \sqrt{\frac{\rho_{\text{Cs}}}{\rho_{\text{aerosol}}}} \qquad (2)$$

since during the test they behaved differently and kept identity. The result has been $d_{\text{MMD}}^{\text{Cs}} = 0.742\,\mu\text{m}$.

Aerosols have been defined as non-hygroscopic. The large under-saturation state of the atmosphere has not allowed to consider the water absorption by particles below saturation conditions. In addition, the great dependence that this code option would have had on unknown experimental information (i.e., chemical compounds in aerosol particles and their distribution all over the particle surface) would have enlarged input uncertainties.

4. Lessons learnt

The analyses of the FPT1 (Herranz and Del Prá, 2005) and FPT2 (Herranz et al., 2006a) tests have provided valuable insights into code performance and test interpretation. Overall, codes estimates have reproduced properly experimental trends and no variable has shown major discrepancies. The safety codes used (i.e., CONTAIN 2.0, MELCOR 1.8.5 and ASTEC 1.1) have been capable of capturing some of the most relevant phenomena anticipated in an actual reactor containment, like steam condensation and/or sedimentation. Hence, simplified approaches of in-containment PHEBUS-FP scenarios may be suitable to achieve a thorough understanding of governing thermal and aerosol phenomena. Nevertheless, the PHEBUS-FP containment vessel is far from the complexity of an actual containment building, which in turn would make aerosol transport rather more complex.

4.1. Test interpretation

Predictions-to-data comparisons have not been always straightforward. Lack of information regarding relevant input variables (like particle density or initial size distribution in FPT2 analyses, for instance) as well as preliminary nature of some data used (like the final mass distribution in FPT2) have made it difficult to set rigorous comparisons.

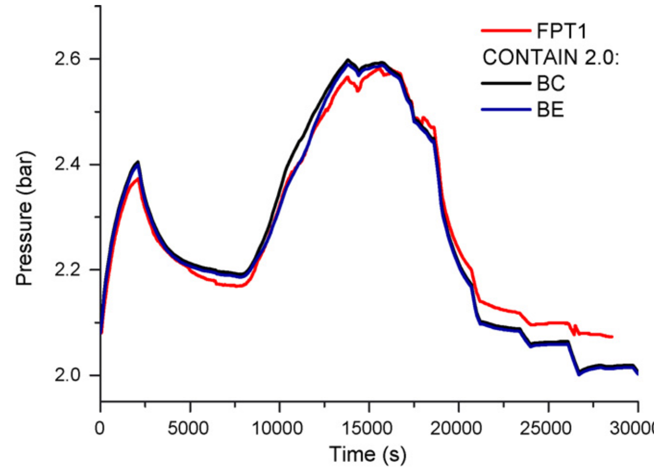

Fig. 5. FPT1 steam pressure vs. time.

4.1.1. FPT1 steam injection

During the FPT1 test, the vessel thermal–hydraulic behavior may be approximated by:

$$c_{\text{p}} \frac{\text{d}}{\text{d}t}(m_{\text{gas}} T_{\text{gas}}) = \dot{m}_{\text{steam}}^{\text{in}} h_{\text{g(steam)}}(T^{\text{in}}) - \sum_{k} \dot{m}_{k}^{\text{cond}} h_{\text{fg}}(T_k) \qquad (3)$$

where convective heat transport has been neglected. Namely, the time variations of atmosphere energy content depended essentially from the energy input through the steam injection and the energy output by steam condensation.

The CONTAIN 2.0 analyses of the test have provided a good quantitative agreement to data. However, predictions seem to point out potential data inconsistencies in the steam injection rates. CONTAIN slightly overpredicted pressure at around 10,000 s and at the same time it overestimated steam condensation (base case, BC in Figs. 5 and 6). Total pressure changes are mostly driven by steam content variation in the atmosphere. Then, an over estimate of steam condensation should lead forcefully to a lower pressure. As a consequence, a reduction of the steam source about 20%, experimental uncertainty band (Jacquemain et al., 2000), from 8000 to 12,500 s (best estimate,

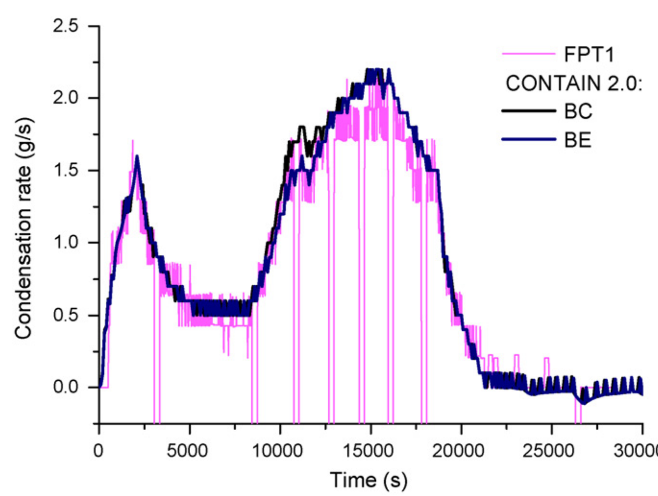

Fig. 6. FPT1 steam condensation rate.

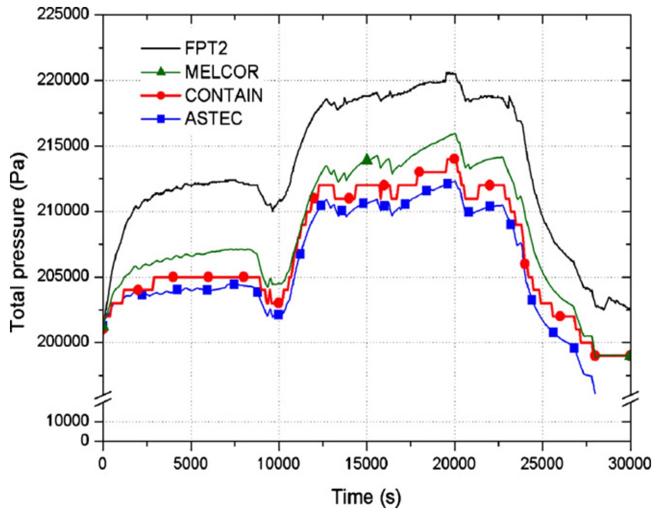

Fig. 7. FPT2 total pressure vs. time.

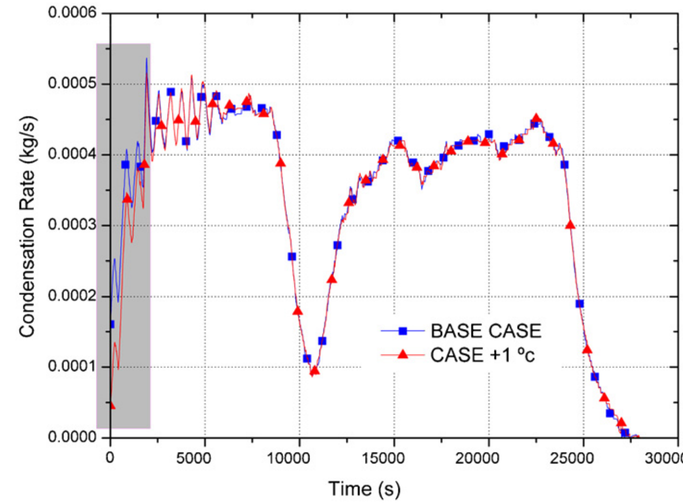

Fig. 9. Condensation rate varying the wet condenser temperature, MELCOR code.

BE) has been postulated and provided better and more consistent results. Therefore, a new steam input rate to the containment has been suggested.

4.1.2. FPT2 wet condenser temperature

As in the FPT1 analysis, all the codes have done a good job concerning the thermal–hydraulic behavior of the containment vessel. Nonetheless, a slight (∼5000 Pa) but systematic underprediction of total pressure has been observed (Fig. 7). This discrepancy developed during the first 2000 s of the transient and it kept nearly constant from then on (Fig. 8).

The reason has been found to be an overestimate of steam condensation during such a test period. Steam condensation governs the fraction of injected steam that remains airborne. As shown in Fig. 8, steam condensation has been satisfactorily predicted; however, no data were reported during the first 2000 s of the test. An exploratory study has demonstrated that a 1 °C increase in the wet condenser temperature would decrease steam condensation significantly in the first 2000 s (Fig. 9). As a result, steam and total pressure have got even closer to data (Fig. 10). Such a change in wet condenser temperature has seemed to be reasonable given data uncertainties, axial temperature gradients along the component and water film built-up on the structures.

Hence, the analyses seem to suggest that a bit higher wet condenser temperature than experiment proposed could have existed.

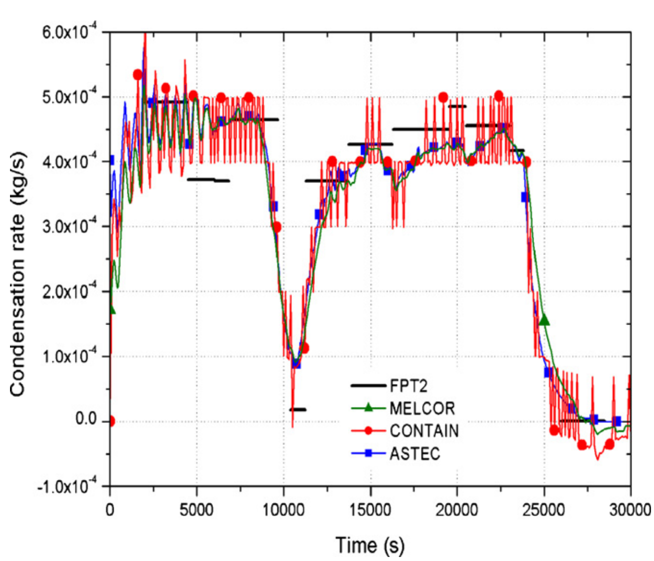

Fig. 8. FPT2 steam condensation rate.

4.1.3. FPT1 caesium airborne concentration

CONTAIN 2.0 prediction of aerosol mass distribution in the FPT1 test has been consistent (Fig. 11); deviations never have exceeded 10% in the BE case (i.e., steam input rate corrected as described above). As noted, in Fig. 12 experimental techniques provided quite different measurements of caesium concentration before 18,000 s. CONTAIN 2.0 predictions have been closer to samplings data. The good results of CONTAIN 2.0 regarding

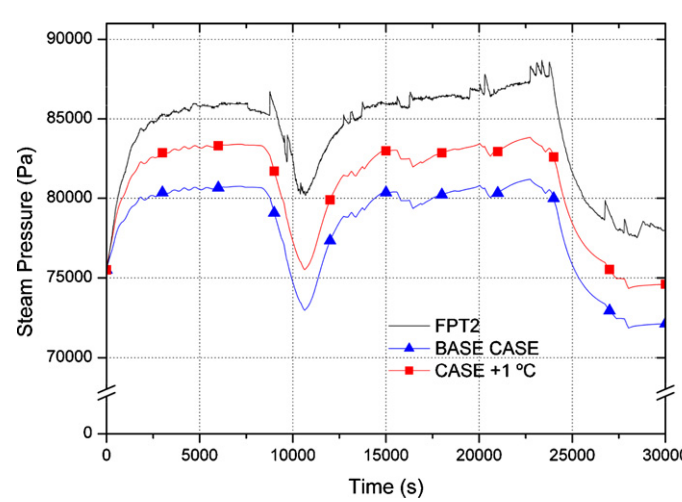

Fig. 10. Steam pressure varying the wet condenser temperature, MELCOR code.

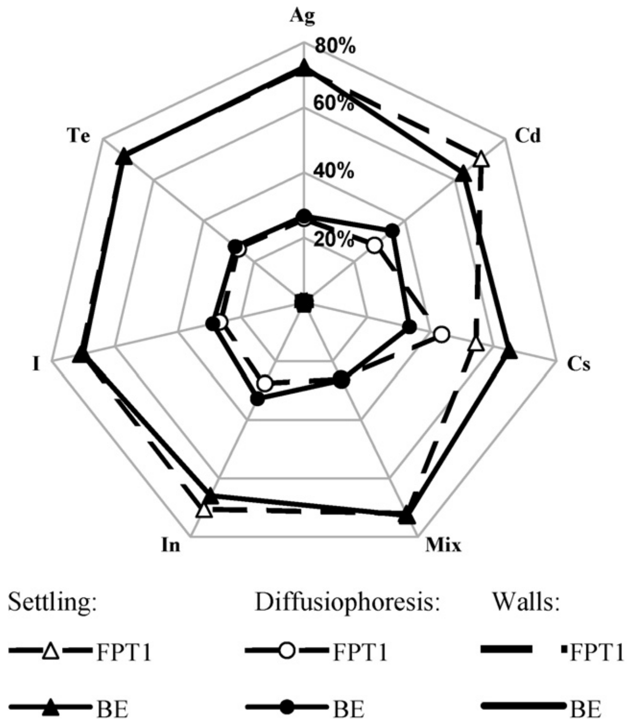

Fig. 11. Mass distribution (% of the total mass injected).

steam condensation and depleted mass by diffusiophoresis

$$\dot{m}_{\mathrm{Dph}}(i) \approx \dot{m}''_{\mathrm{cond}} \frac{A_{\mathrm{cond}}}{\rho_{\mathrm{steam}}} C(i) \quad (4)$$

support accuracy of CONTAIN 2.0 concentration estimates.

Therefore, this study seems to indicate that from aerosol injection till 18,000 s, sampling data are more reliable than γ-spec data.

4.1.4. FPT2 final mass distribution

Codes predictions of the evolution of airborne caesium and iodine concentrations have followed accurately the experimental data, as shown in Figs. 13 and 14.

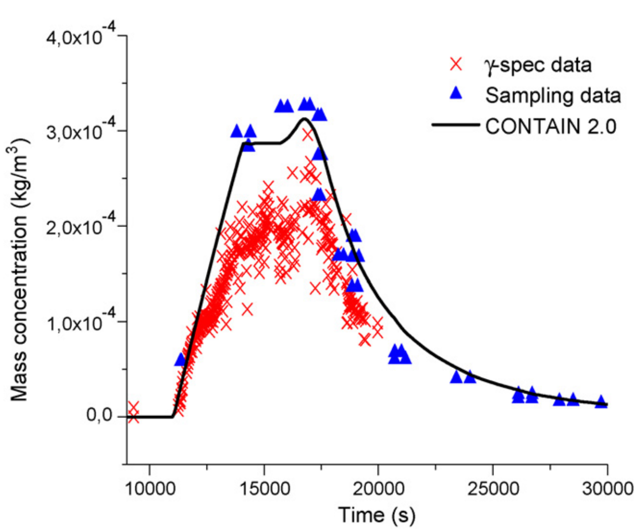

Fig. 12. Mass of Cs removed by diffusiophoresis.

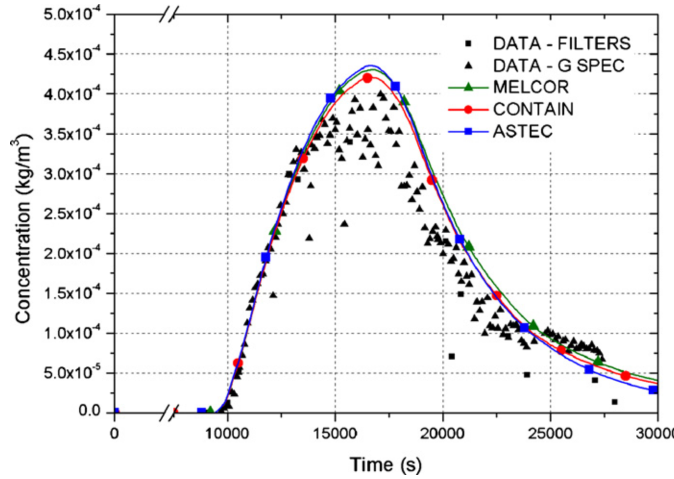

Fig. 13. Caesium airborne concentration.

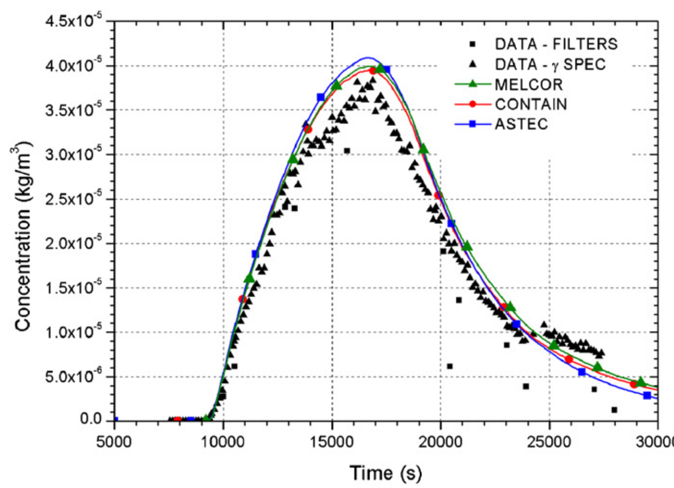

Fig. 14. Iodine airborne concentration.

Experimental preliminary estimates of aerosol mass distribution during the FPT2 test indicated that 60% was settled, 20% plated by diffusiophoresis and the other 20% split evenly between samplings and deposition on vessel walls. However, all the codes used indicate a significantly higher contribution of settling to aerosol removal and, as a consequence, rather less relevance of other retention mechanisms (Table 5).

In order to assess the potential impact of the hypotheses assumed in the codes input deck, a set of parametric calculations have been carried out on the effect of aerosol characterization (i.e., density, initial size distribution and shape). The final conclusion is that none of the assumptions could support such a decrease of sedimentation efficiency as experimentally anticipated (Figs. 15 and 16).

Table 5
Final mass distribution

	FPT2	MELCOR	ASTEC	CONTAIN
Floor and sump (%)	60	82.3	85.9	81.5
Wet condensers (%)	20	13.7	11.3	13.9
Wall (%)	10	1.4	0.2	2.4
Samplings (%)	10	2.7	2.6	2.2

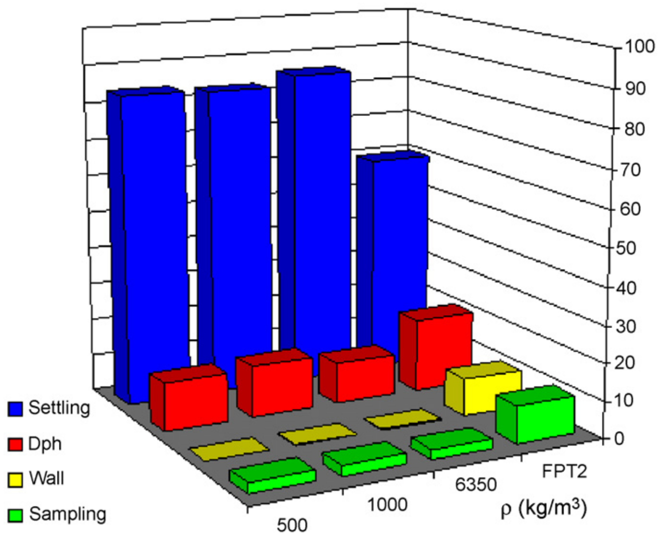

Fig. 15. Depletion mechanisms efficiency as a function of particle density (ASTEC).

Hence, final mass distribution estimates are foreseen to become closer to predictions; that is, around 80% of the mass should have been removed by sedimentation.

4.2. Models validation

The PHEBUS-FP simulations carried out have allowed to check code performance in two major regards: handling of prototypical in-containment source term and its coupling with thermal–hydraulics under unsaturated but condensing atmospheres. As in the FPT1 and FPT2 tests prevailed weak and moderate condensation conditions, respectively, specific attention has been drawn to the steam condensation model in the codes.

4.2.1. Steam condensation

Steam condensation modeling in the presence of non-condensables has been largely investigated under a wide range of conditions (Green and Almenas, 1996). The 0-D approach in all the codes used makes coupling of the diffusion-based theory (Collier and Thome, 1994) and the heat-mass transfer analogy, a suitable way to approximate heterogeneous steam condensation onto containment surfaces (Herranz and Campo, 2002).

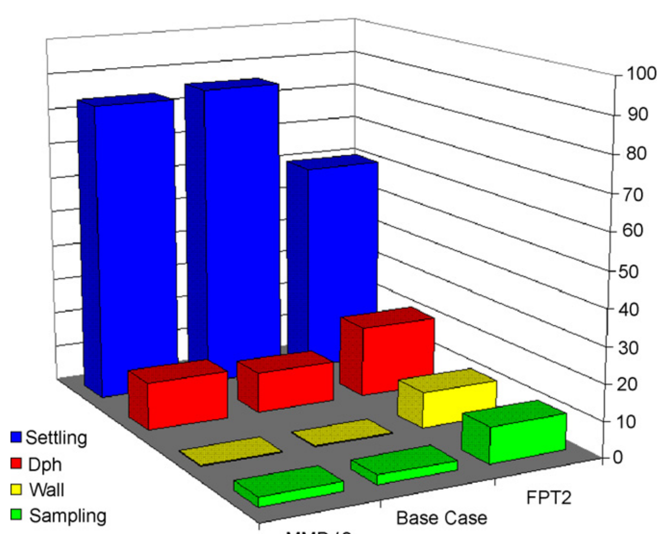

Fig. 16. Depletion mechanisms efficiency as a function of initial particle size (ASTEC).

By reviewing the fundamental grounds of the film theory (Bird et al., 1960) and the equations implemented in the codes (Murata et al., 1997), it has been confirmed that codes encapsulate properly the theoretical developments with equations like,

$$N_{\mathrm{s}}^{0}=\frac{Sh}{L}D_{\mathrm{s,nc}}\frac{P_{\mathrm{t}}}{RT}\ln\left(\frac{P_{\mathrm{t}}-P_{\mathrm{s}}^{0}}{P_{\mathrm{t}}-P_{\mathrm{s}}^{\infty}}\right) \tag{5}$$

where *Sh* is the non-dimensional Sherwood number.

The PHEBUS-FP simulations have extended the validation of this model. As shown in preceding sections, reasonably accurate predictions have been obtained both in moderate and weak condensing scenarios. Even further, when deviations have been reported, they have been always well within the experimental uncertainty range.

However, in the case of high mass flow rates heat-mass transfer analogy deviates and *Sh* estimate requires to be corrected by what has been termed suction factor.

$$\Theta=\frac{X_{\mathrm{nc}}^{\mathrm{i}}}{X_{\mathrm{nc}}^{\mathrm{avg}}} \tag{6}$$

Under the steam condensation rates prevailing in PHEBUS-FP scenarios, this factor is near 1.0. Nonetheless, under more intense condensing conditions, like those anticipated during coolant blowdown in mid-size LOCAs, this factor can become significant (Herranz et al., 2006b).

4.2.2. Wall deposition

Regarding aerosol behavior within the vessel, some of the figures shown in previous sections support the good codes predictive capability.

However, in some PHEBUS-FP tests (i.e., FPT0 and FPT2), a significant fraction of aerosols deposited onto the vessel walls (2–10%) (IRSN, 2002) and (Jacquemain et al., 2000). These walls were supposed to be neutral regarding aerosol deposition since their temperature was brought higher than the saturation one to avoid any plated mass by diffusiophoresis. The codes have been unable to drive particles onto the vessel walls. Many exploratory studies (Hontañon et al., 1996) have attempted to explain such a deposition based on aerosol mechanisms other than those implemented in the codes. However, presently there is neither consensus on the driving mechanism nor whether they would exist in actual containments during severe accidents.

5. Conclusions

The FPT1 and FPT2 tests provided significant information on in-containment behavior of an actual source term under condensing conditions. Their simulations have given valuable insights into code performance and test interpretation. The fact of using a set of computer codes (i.e., CONTAIN 2.0, MELCOR 1.8.5 and ASTEC 1.1) under the same assumptions and approximations, have ensured a "user-independent" cross comparison of codes and data.

Overall, codes estimates have reproduced properly experimental trends and no variable has shown major discrepancies. Some minor differences have been found, but they all have been well within the range of estimate uncertainties.

Concerning test interpretation, the analyses have resulted in several contributions:

- For FPT1 test a reduction of steam input rate to the lower bound of its uncertainty interval has been proposed.
- In FPT1, aerosol concentration measurements from sampling seem to be more reliable than those from γ-spec during the first 18,000 s of the transient. From then on, both experimental techniques provided similar results.
- The FPT2 test analyses suggest that a bit higher wet condenser temperature than the experimentally reported could have existed.
- In FPT2, aerosol sedimentation could have played a more significant role than first experimental estimates suggest, reaching shares around 80%.

Concerning modeling, code results and a peer review of condensation models confirm that steam condensation modeling in presence of non-condensable gases is adequately implemented in codes. Nonetheless, under more intense condensing scenarios than the ones in FPT1 and FPT2, the introduction of a correction factor to account for suction effects is recommended.

Acknowledgement

The authors thank the Spanish Nuclear Regulatory Body for their financial support.

References

Arreghini, F., Jacquemain, D., Garnier, Y., 2000. Summary of fission product behaviour and structural material behaviour in FPT1. In: 4th Technical Seminar on the PHEBUS-FP Programme, Marseille, France, March 20–22.

Bestele, J., Klein-He βLing, W., 2000. Containment Thermal–hydraulics and Aerosol and Fission Product Behaviour. User Guidelines. GRS Technical Note, ASTEC-V0/DOC/00-14.

Bird, R.B., Steward, W.E., Lightfoot, E.D., 1960. Transport Phenomena. Willey-Interscience, New York (Chapter 21).

Collier, J.G., Thome, J.R., 1994. Convective Boiling and Condensation, third ed. Oxford University Press, Oxford (Chapter 10).

Gaunt, R.O., 2000. MELCOR version 1.8.5., Reference Manuals. NUREG/GR-6119, SAND2000-2417. Sandia National Laboratories, Albuquerque.

Green, J., Almenas, K., 1996. An overview of the primary parameters and methods for determining condensation heat transfer to containment structures. Nucl. Saf. 37 (1), 26–47.

Herranz, L.E., Campo, A., 2002. Adequacy of the heat-mass transfer analogy to simulate containment atmospheric cooling in the new generation of advanced nuclear reactors: experimental confirmation. Nucl. Technol. 139, 221–232.

Herranz, L.E., Del Prá, C.L., 2005. Simulating in-containment aerosol behaviour during severe accidents: a validation of CONTAIN 2.0 Code Based on the PHEBUS-FPT1 Experiment. Proceedings of ICAPP '05, Paper 5025, Seoul, Korea, May 15–19, 2005.

Herranz, L.E., Fontanet, J., Vela-García, M., 2006a. In-containment thermal–hydraulic and aerosol behaviour during severe accidents: analysis of the PHEBUS-FPT2 experiment. Proceedings of ICAPP '06, Paper 6079, Reno, USA, June 4–8, 2006.

Herranz, L.E., Fontanet, J., Vela-García, M., 2006b. Assessment of heat mass transfer analogy in condensation models of nuclear safety codes. In: Proceedings of the International Heat Transfer Conference, Sydney, Australia, August 13–18.

Hontañon, E., Polo, J., Herranz, L.E., 1996. On the modeling capabilities to simulate aerosol behaviour in the PHEBUS-FP containment: lessons learned from FPT0. J. Aerosol Sci. 26 (Suppl. 1), 459–460.

IRSN, 2002. FPT2 Preliminary Report and Associated Data. Organized by the CSNI (Committee for the Safety of Nuclear Installations), is a compilation of code-to-data comparisons based on the FPT1 experiment. PHEBUS-FP.

Jacquemain, D., Bordon, S., Braemaeker, A., Barrachin, M., 2000. FPT1 Final Report (Final version). IPSN/DRS/SA/PDF report SA1/00, IP00/479, France.

Murata, K.K., Williams, D.C., Tills, J., Griffith, R.O., Gido, R.G., Tadios, E.L., Davis, F.J., Martinez, G.M., Washington, K.E., 1997. Code Manual for CONTAIN 2.0: A Computer Code for Nuclear Reactor Containment Analysis. Sandia National Laboratories Albuquerque, NM 87185.

Schwarz, M., Zeyen, R., 2003. Status of the PHEBUS-FP Program. Summarized the main results of a EU Project (sponsored through the 5th EURATOM Program) specifically aimed at interpreting analytically the PHEBUS-FP tests. 5th Technical Seminar on the PHEBUS-FP Programme, Aix-en-Provence, France.

Zabiego, M., Pantera, L., 2004. FPT2 Data: Latest Results for the Experimental Circuits. On-Line Measurements and Sequential Samplings. Presented at the PHEBUS meeting held in Bergen (The Netherlands), March.

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