IYNC 2008
Interlaken, Switzerland, 20 – 26 September 2008
Paper No. 224

Validation of Code ASTEC with LIVE-L1 Experimental Results

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ABSTRACT

The severe accidents with core melting are considered at the design stage of project at Generation 3+ of Nuclear Power Plants (NPP). Moreover, there is an effort to apply the severe accident management to the operated NPP. The one of main goals of severe accidents mitigation is corium localization and stabilization. The two strategies that fulfil this requirement are: the in-vessel retention (e.g. AP-600, AP-1000) and the ex-vessel retention (e.g. EPR). To study the scenario of in-vessel retention, a large experimental program and the integrated codes have been developed. The LIVE-L1 experimental facility studied the formation of melt pools and the melt accumulation in the lower head using different cooling conditions. Nowadays, a new European computer code ASTEC is being developed jointly in France and Germany. One of the important steps in ASTEC development in the area of in-vessel retention of corium is its validation with LIVE-L1 experimental results. Details of the experiment are reported. Results of the ASTEC (module DIVA) application to the analysis of the test are presented.

1 INTRODUCTION

In a case of severe accident, the core melts and relocates to the lower head. After melt relocates into the residual water in the lower head its fragmentation and quenching will eventually lead to a partially fragmented and cooled melt in water called particulate debris bed. The water will eventually evaporate and the fragmented and cooled debris will heat-up to form a melt pool. As a consequence, the high temperatures of melt pool endanger the integrity of the reactor pressure vessel wall [1].

The aim of the severe accident management is to prevent the development of above-mentioned scenario to the more serious conditions. The combination of engineering judgment and probabilistic methods is used to determine the preventive and mitigatory measures. The measures should be based on realistic or best estimate assumptions, methods and analytical criteria.

At first, a number of studies have been performed to pursue the understanding of a severe accident with core melting, its course, major critical phases and timing, and the influence of these processes on the accident progression. To complement the experimental data on melt pool behavior in the vessel lower head Forschungszentrum Karlsruhe performs large-scale tests through the LIVE program [2].

Secondly, the safety analysis uses a large number of computer codes. The integral severe accident analyses codes model the progression of an accident sequence from core damage through the containment failure. To study a core debris-vessel interactions integrated models and codes have been developed and applied. Nowadays, a European computer code ASTEC is being developed jointly in France and Germany. The validation and application of this code is an important part of SARNET project that began in 2002 [3]. However, the aim of SARNET (Network of Excellence) is to resolve the most important remaining uncertainties and safety issues for enhancing the safety of existing and future NPPs.

This work is concerning validation of code ASTEC with LIVE-L1 experimental data. The stand-alone DIVA module (in-vessel core degradation and reactor vessel thermal hydraulics during a severe accident) is applied to the analysis of the molten pool behavior. The simulations represent a further step in ASTEC code development. As a consequence, this code can be used to predict scenarios of severe accident with in-vessel retention strategy in real NPP.

2 EXPERIMENT LIVE-L1

Experiment LIVE (Late In-Vessel Phase Experiments) was performed in the frame of the LACOMERA Project of the EU 5th Framework Programme. In the LIVE experimental program, different important phenomena during *the late phase* of core melt progression were being investigated. The late phase of core melt progression is characterized by substantial melting of fuel, formation of melt pools and melt accumulation in the lower head of the reactor pressure vessel. The results of LIVE experiment, enhanced the database of the transient processes during core melting, melt relocation and accumulation. Thanks to this experimental program, there is more information about e.g. transient heat fluxes to the vessel wall; crust formation, stability and re-melting of melt crusts in 3D geometry [4].

2.1 Parameters of the test vessel and of the test melt

LIVE-L1 is a 1:5 scale test facility representing a reactor pressure vessel of a typical pressurized water reactor (see *Figure 1*). The inner diameter of the test vessel was 1m and the wall thickness was 25 mm. The material of the test vessel was stainless steel.

The vessel wall was equipped with instrumented plugs that consisted of a heat flux sensor and thermocouples. Thanks to that, the heat flux, inner and outer temperatures of the vessel wall could be measured. The infrared and video camera were installed to observe the melt surface. The mechanical sensors detected the crust thickness at the vessel wall.

The decay heat was produced by volumetric heating system. For homogeneous production of the heat, a heater grid was constructed (see *Figure 2*). The maximum temperature that the heating system could provide was limited to 1100°C. All heating planes together provide a maximum power of about 28 kW.

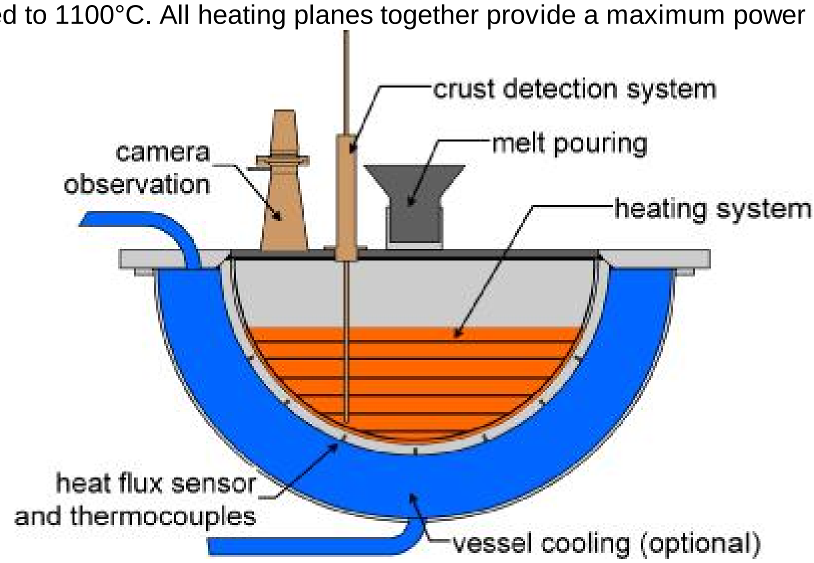

Figure 1: LIVE test vessel

To simulate the corium melt a binary mixture of 20 mole% of $NaNO_3$ and 80 mole% of KNO_3 with liquidus temperature ~300°C and solidification range of about 60K has been used. The mixture has been melted in the separate heating furnace and when the temperature reached ~350°C, 120 l of the melt has been centrally poured into the LIVE test vessel (corresponds to ~31 cm melt height).

Figure 2: LIVE volumetric heating system

2.2 Experimental results

The experiment LIVE-L1 investigated the core melt behaviour in the lover plenum of reactor pressure vessel. The influence of different cooling conditions on the outer surface of the vessel wall was studied. These cooling conditions are summarized in a paragraph below.

- **Phase 1.** Homogeneous heat generation (0-7210 s): boundary condition air, heating power 18kW at the beginning, reduced to 10kW at 3720 s.
- **Phase 2.** Start of the outer vessel wall cooling (7210 s): boundary condition water, cooling water flowrate 1.5kg/s then 47 g/s, water temperature at the inlet 10°C, heating power 10kW.
- **Phase 3.** Reduction of heat generation (82 675 s): boundary condition water, heating power reduced to 7kW.
- **Phase 4.** Test termination and melt extraction (102 620 s): heating power 0kW.

The *Figure 3* was drawn for better understanding of measured values and its positions. The measurements were realized at different positions along 4 meridians 0°, 90°, 180°, and 270°.

The results from the LIVE-L1 experiment includes melt temperature evolution during different stages of the test, inner and outer temperatures of the wall and heat flux distribution along the reactor pressure vessel wall in transient and steady state conditions. In the post-test analysis crust thickness profile along the vessel wall, crust composition and morphology was determined. In a Section 3.2, the results of DIVA stand-alone calculations are compared with these experimental data.

3 SIMULATIONS OF LIVE-L1 EXPERIMENT WITH ASTEC V1.3

ASTEC (accident source term evaluation code) is an integral source term code for severe accidents in Light Water Reactors. The ASTEC code is playing a central role in SARNET (6^{th} EU Framework Programme) in order to progressively become the reference European integral code for analysis of severe accident. The ASTEC code consists of several computational modules, devoted to analysis of specific problems (e.g. thermal-hydraulics, core degradation, fission product release and transport, etc.). The DIVA module simulates the corium behavior in the lower head.

The DIVA stand-alone module could be applied to the in-vessel retention analysis, when using a proper boundary condition (prescribed coolant temperature and heat transfer coefficient) in order to simulate the external cooling of reactor pressure vessel surface. This module has been applied for simulation of thermal behavior during LIVE-L1 experiment. The external reactor cooling has been simulated using boundary conditions for temperature and heat transfer coefficient at different elevations of vessel wall. The results obtained from DIVA calculations (temperatures of the wall, temperature of corium, heat flux distribution and thickness of the crust) were compared with experimental data.

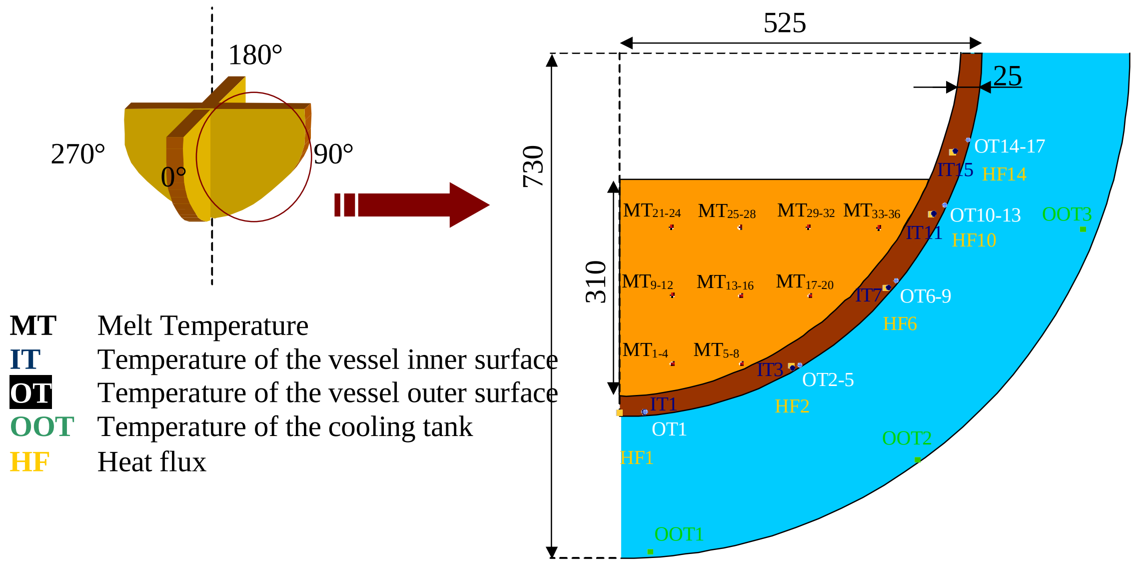

Figure 3: Illustration of measurements in LIVE-L1 experiment in [mm]

3.1 Modeling of LIVE-L1 in DIVA

The real dimensions of LIVE-L1 experimental facility were respected. The inner diameter of the lower head was 1m. The thickness of the vessel wall was 25 mm. A vessel lower plenum material was steel. The vessel wall was divided in axial direction into 15 segments. Each segment was divided in radial direction into 5 meshes (see *Figure 4*). The beginning time of calculations was set to 0 s. The final time of calculations was 102 620 s.
The different cooling conditions on the outer surface during LIVE-L1 experiment were simulated using time-dependent boundary conditions. These boundary conditions represented the*outer temperatures* and the *heat transfer coefficients* at *different elevations* on the wall. Because of simulation of transient processes, these boundary conditions were defined at *different instants*. The important boundary conditions were taken from the experimental measurements.

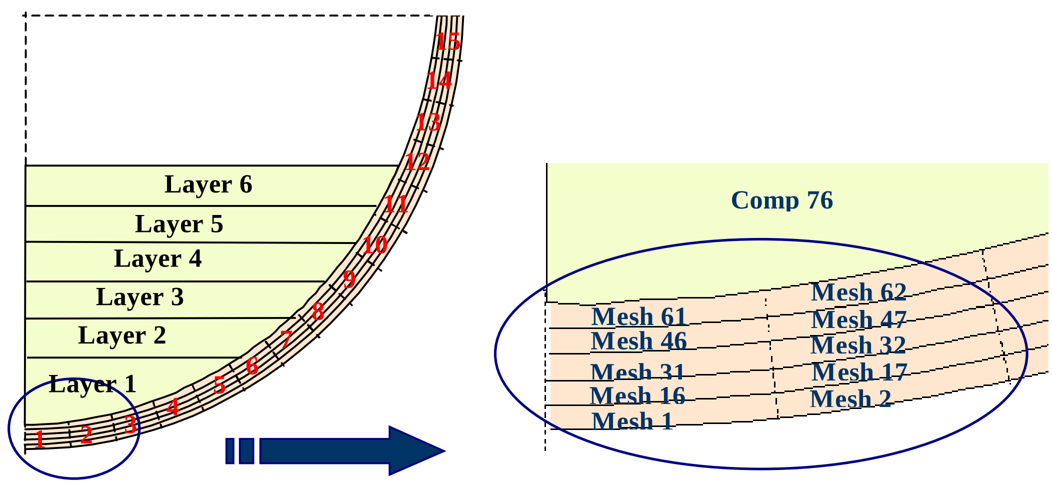

Figure 4: Meshing in DIVA for LIVE-L1 experiment, wall divided into 5x15 meshes

The melt used in the LIVE-L1 experiment was briefly described in Section 2.1. The material properties of the melt for DIVA modelling were obtained from the literature [5].
At LIVE-L1 experiment, the volumetric heating system had to simulate the decay heat released from the corium melt (see *Figure 2*). To allow the homogeneous heating of the melt pool, the heating system had six heating planes at different elevations with a distance of about 45 mm [4]. At DIVA's input deck, this fact was respected in dividing the melt pool to six corium layers as is illustrated on *Figure 4*. Every corium layer had a residual power as was measured during LIVE-L1 experiment.
Moreover, to simulate the real conditions that occurred during LIVE-L1 experiment, the upper plate and fluid gas above melt were simulated. In DIVA stand-alone module, there is a possibility of modelling a plate element, which represents boundary condition for radiative heat exchange from uppermost corium layer. When we look on *Figure 1* we can see that the experimental facility was really covered at the top. Secondly, a fluid gas was modeled in the volume between this plate and the corium layer. Two channels were modeled in order to enable gas circulation. A convection heat transfer was modeled between this fluid channel and the internal vessel surface at the upper part. This modeling improved the calculations of temperature distribution in the upper part of the vessel wall.

3.2 Experimental results

In this section, the results of DIVA calculations will be presented. The calculations of the vessel wall temperature, the corium temperature and the heat flux distribution were compared with the experimental results. The nomenclature used on the figures below corresponds to the illustration on *Figure 3* and *Figure 4*. There have been tendencies to find the meshes on the vessel wall that correspond with the position of the experimental measurements.
The DIVA calculations followed correctly the conditions during LIVE-L1 experiment (Phases 1. - 4. presented in Section 2.2). Only the calculated peak of temperatures during the Phase 2 does not correspond with the experimental results. The temperature comparison during the later phases (from ~7400 s) is fair. Some differences (maximum 15 K) might be caused due to the inaccuracies: e.g. in the placement of axial elevation of boundary conditions; in the estimation of an axial elevation of layers.
The discrepancy during the peak of temperatures T-mesh 9 and T-mesh 11 was studied. During the Phase 2 the heating system that belonged to these walls was switching off and switching on. This failure was not modeled very strictly in the DIVA´s input deck. Moreover, there is an assumption that this failure influenced also the temperatures T-mesh 16 and T-mesh 5.
In DIVA modeling, the flow of energy between the corium layers is simulated. On the other hand, a mass flow between the layers is not simulated. There is an assumption, that the possible mass flow during LIVE-L1 experiment has influenced the distribution of temperatures during Phase 2 especially at the positions OT1 and OT2-5 (IT1 and IT3). There can be an explanation, that the corium at the upper part of the vessel (Layer 6 see *Figure 3*) has started to cool off and due to a higher density relocated to the bottom. Consequently, it may cause that the corium at the lower part of the vessel (Layer 1 see *Figure 3*) got colder and the temperature T-mesh 16 and T-mesh 5 decreased. The same explanation is for *Figure 6*. This influence may cause only during the Phase 2 when the failure of two heating powers was revealed. The *Figure 8* enhanced this theory. The measured corium temperature at the bottom of the vessel was lower that the calculated one.
Concerning the heat flux distribution, the comparison can be seen on *Figure 7*. The heat flux is calculated by DIVA using the outer temperature of the wall and the boundary conditions of heat transfer coefficient and of temperature of ambiance (air, water). We can state, that the boundary conditions were good implemented expecting HF-mesh 9. At this position, there was no experimental measurement of the temperature of ambiance. The needed value has been computed as the average of two adjoining outer temperatures.

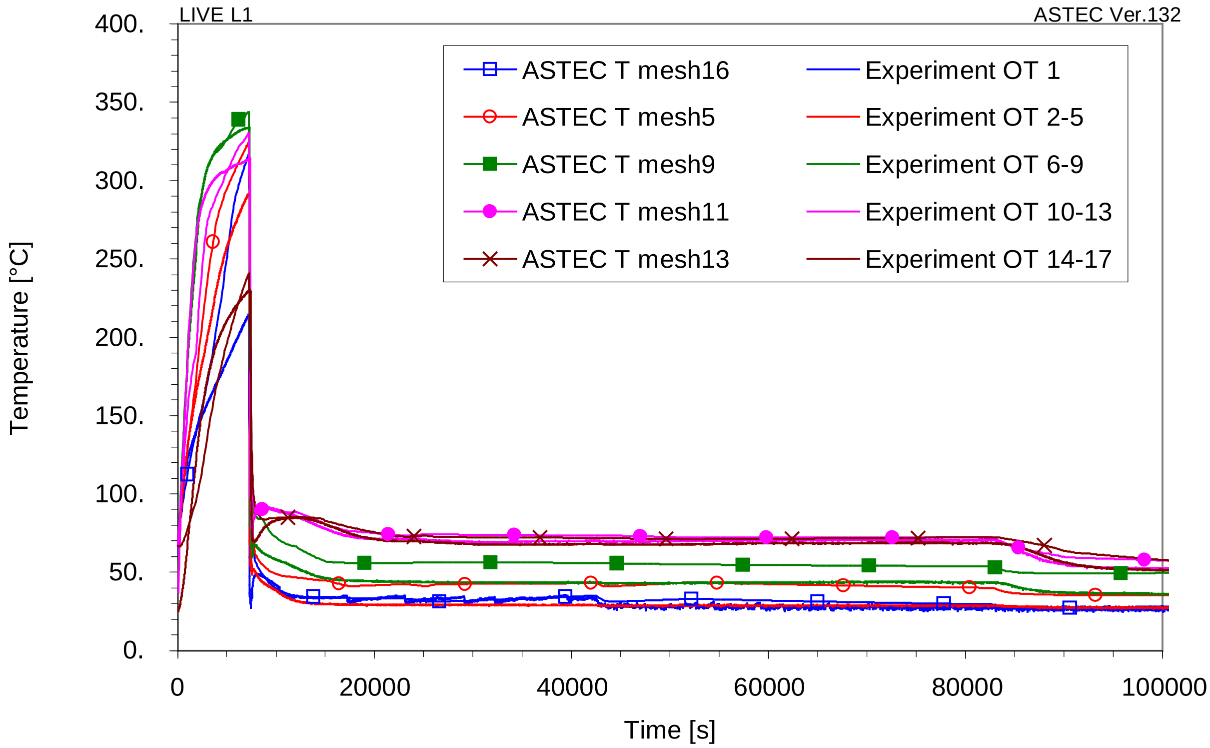

Figure 5: The outer temperatures of the wall

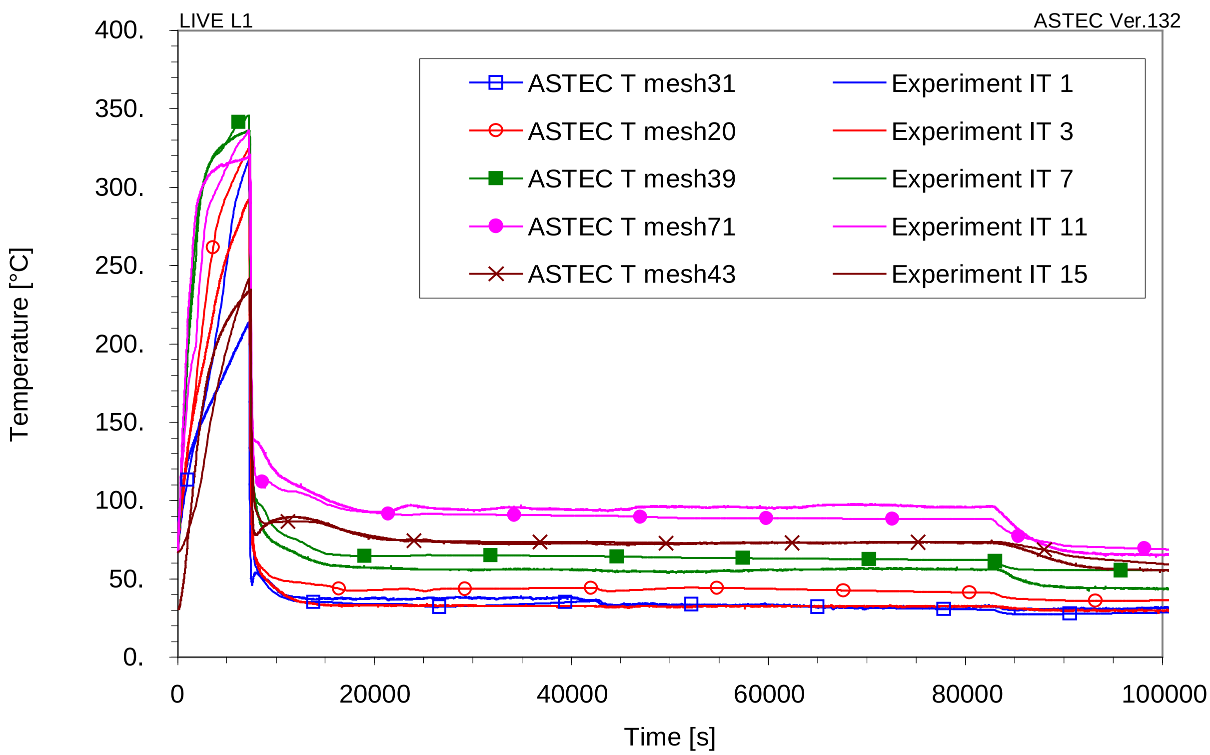

Figure 6: The inner temperatures of the wall

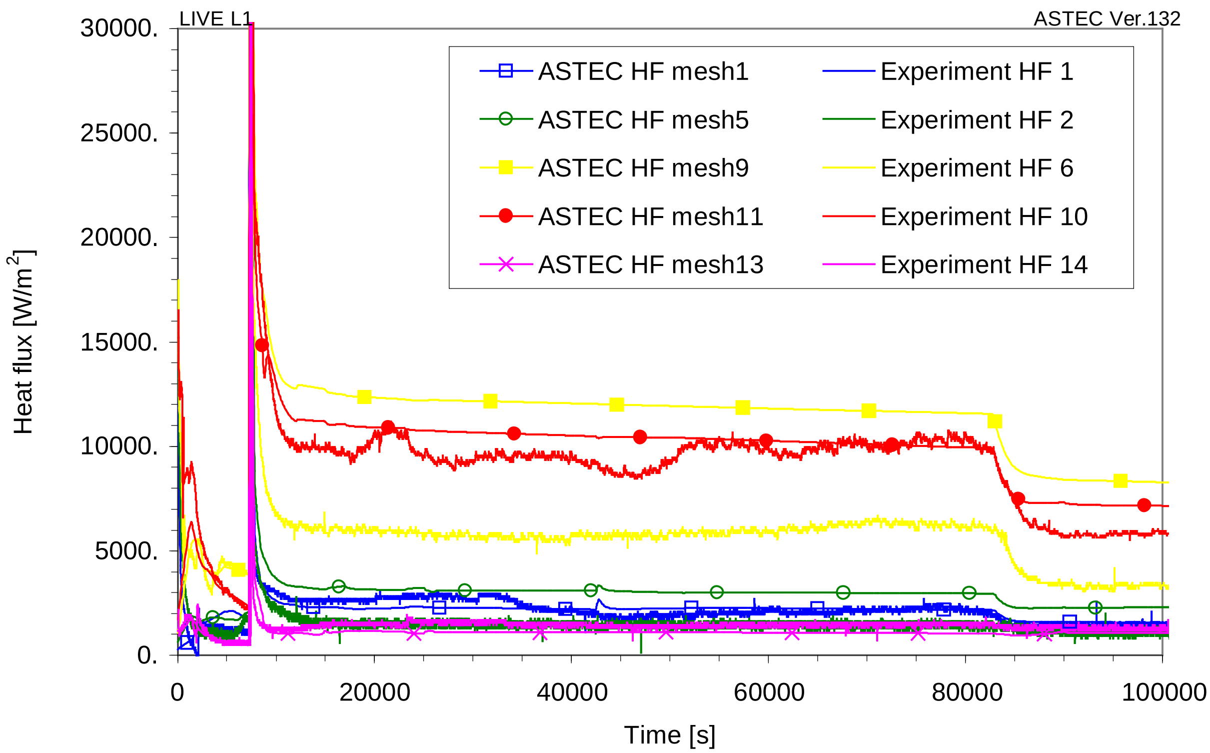

Figure 7: The heat flux distribution through the wall

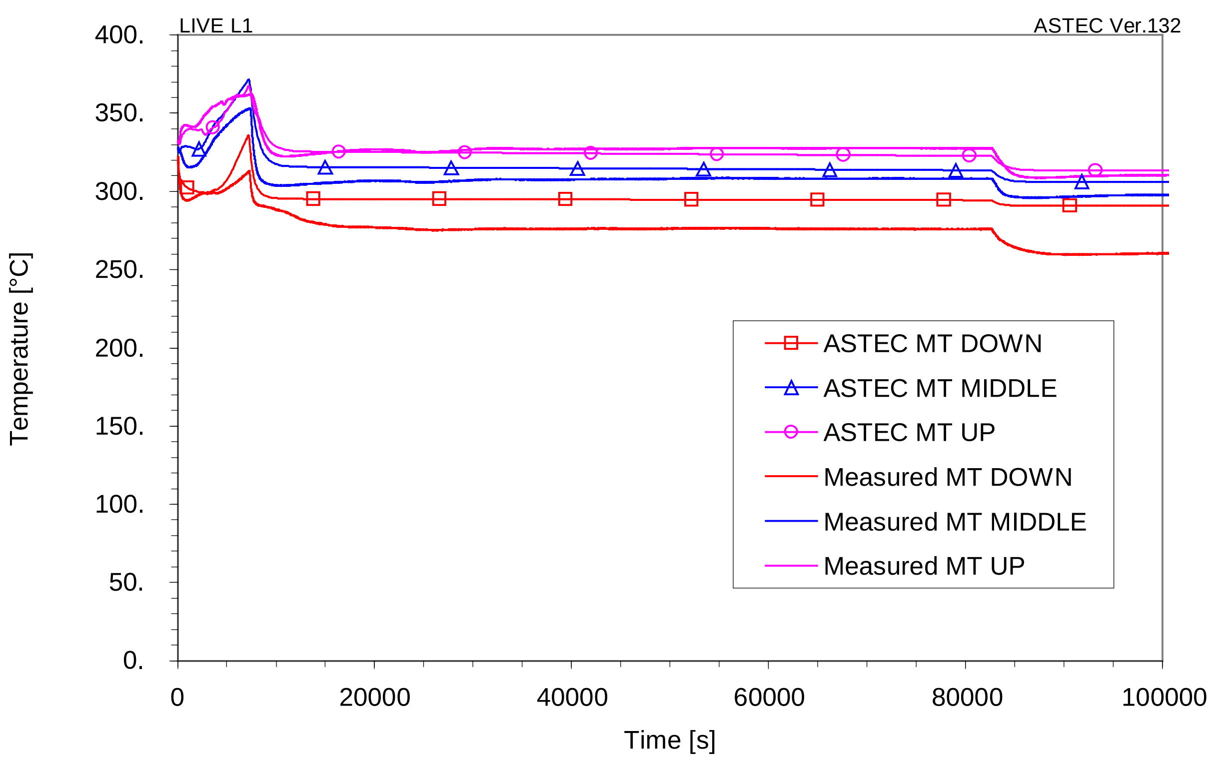

Figure 8: The temperature of the melt

3.3 The crust thickness

Because of the continued development of ASTEC code, new physical correlations are still being implemented into the new versions of the code. Many scientists from member groups of SARNET are working on validation of ASTEC physical models and reactor applications. The theory of each module of ASTEC code is relatively well described. The code users can follow the physical equations and the implementation of numerical solution in the source of ASTEC. The comments and suggestions from the ASTEC users are implemented in each new version of ASTEC code.
One of the physical variables that became important during the LIVE-L1 modeling was the thickness of the crust. The value of the crust thickness is not yet implemented to DIVA's modeling. On the other hand, the theory about the crust thickness between the corium layer and the vessel wall is well described in the manual [6]. A crust is modeled between a corium layer *x* and the vessel mesh *k*. We assume that there is no residual power in the crust. Using the assumption of the steady state and a linear temperature distribution through the crust, the following equation can be written:

$$q_1 = q_2 = q_3$$

$$h_{xl,vk}^{ext}(T_{xl}^{melt} - T_{xl}) = \frac{e_{cr}}{\lambda_{cr}}(T_{vk}^{\mathrm{int}} - T_{xl}^{mel}) = \frac{e_{vk}}{2\lambda_{vk}}(T_{vk} - T_{vk}^{\mathrm{int}}) \quad (1)$$

When we eliminate T_{vk}^{int} from the equation (1), the crust between the vessel wall and the corium layer is as follows:

$$e_{cr} = \left[\frac{1}{h_{xl,vk}^{ext}} \frac{T_{vk} - T_{xl}^{mel}}{T_{xl}^{mel} - T_{xl}} - \frac{e_{vk}}{2\lambda_{vk}}\right].\lambda_{cr} \quad (2)$$

The description of the equation and its variables is shown on *Figure 9*. Thanks to DIVA's post processing possibilities, the value of the crust thickness was implemented directly to its results. The equation (2) was written to the special file and there has been given a way to reach all-important variables. The first results of equation (2) are seen on *Figure 11*.

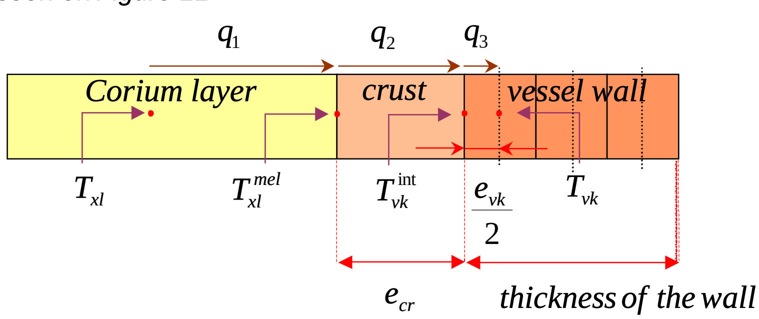

Figure 9: Representation of heat transfer

The problem seemed to be in the value of heat transfer coefficient h_{vk}^{ext} and in the value of thermal conductivity of the crust λ_{cr}. The computation of these variables is not directly implemented to DIVA's results.
The *heat transfer coefficients with vessel meshes* consider the meshes inclination and are characterized by two angles: φ, which is specific of the top of the layer, and θ, which is associated to the vessel mesh (*Figure 6*). At first, the heat transfer coefficient was computed for different positions at the vessel wall as follows:

$$h_{xl,vk}^{ext} = h_{xl}^{ext} \cdot \left(0,25 + \frac{8.(1-0,25).(1-\sin\varphi_{xl}).\cos^3\bar{\theta}_{vk}}{3.(\frac{\pi}{2} - \varphi_{xl} - \cos\varphi_{xl}.\sin\varphi_{xl}) + 2.\sin^3\varphi_{xl}.\cos\varphi_{xl}} \right) \quad (3)$$

$$\bar{\theta}_{vk} = \frac{\theta_{vk+1} + \theta_{vk}}{2}$$

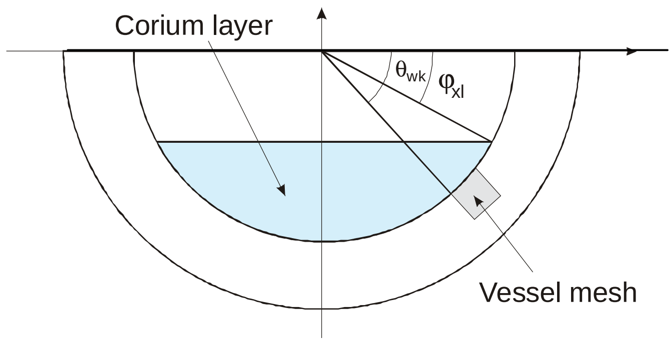

Figure 10: Spherical configuration of the lower plenum

Secondly, a thermal conductivity of the crust was studied. Concerning LIVE-L1 calculation, the thermal conductivity of the crust can be revealed. The thermal conductivity of the corium layer can be found in [5]. The crust is formed from the same material as the corium layer. Moreover, the crust has a lower temperature than the corium layer.

The temperature of the crust was taken from the experimental results. The temperature of the crust was measured belong to the Wall 5, Wall 9 and Wall 11 (see *Figure 4*). For these temperatures (416 K, 432 K, 471 K), the thermal conductivity of the material is 0.446 W/mK (for temperature <553K).

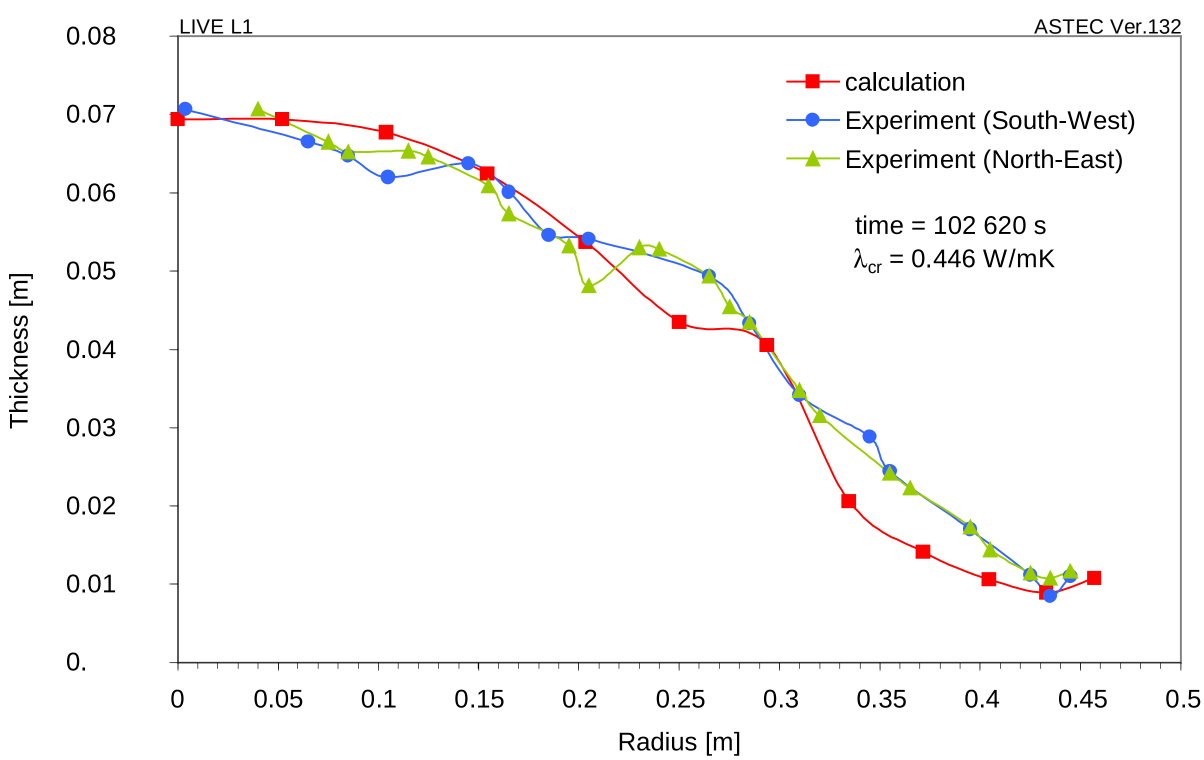

Figure 11: The crust thickness

4 CONCLUSIONS

In this paper the results of simulation of LIVE-L1 experiment with code ASTEC (module DIVA) were presented. At first, the all-important characteristics of the LIVE-L1 experiment were summarized. The results of LIVE experiment enhanced the database of the transient processes during core melting; melt relocation and accumulation. Secondly, an input deck for the model of LIVE-L1 has been created in the code ASTEC (module DIVA). One of the important steps in ASTEC development in the area of in-vessel retention of corium is its validation with LIVE-L1 experimental results.

The results of DIVA calculations are presented in a Section 3.2 and compared with the experimental results. The discrepancy in temperature distribution during the Phase 2 may be caused due to the failure of two heating planes. The temperature distribution during the later Phases is fair.

During the simulation of LIVE-L1 experiment, a crust thickness became important. Because of the continued development of ASTEC code, new physical correlations are still being implemented into the new versions of the code. The calculation of the crust thickness is well described in manual, but is not yet implemented to DIVA's outputs. In a Section 3.3, the first results of additional computing of the crust in DIVA are presented.

Finally, it is important to note, that the simulation of LIVE-L1 experiment represented a simulation of transient processes (air at the beginning, than water cooling). Concerning these transient processes, the correctness of the calculations depends on the number of boundary conditions.

When we want to apply module DIVA to simulations of in-vessel retention at a real nuclear power plant, some approximations have to be done. During an accident at real NPP, there will be limited information about the boundary conditions on the reactor outer surface *during transient processes*. We should assume, that the cavity would be flooded by water *before* the corium relocates to the lower head. Consequently, the DIVA simulations of this case might be fair.

When we want to model the transient processes in DIVA module it is necessary to couple this module with CESAR (module of ASTEC). The module CESAR will compute the heat transfer coefficient as a boundary condition for DIVA at each instant. The simulations of DIVA-CESAR coupled model represent a next step in ASTEC validation. The results of DIVA-CESAR calculations of LIVE-L1 experiment can be expected in a near future.

ACKNOWLEDGEMENTS

I would like to thank Dr. Alexei Miassoedov who gave the permission on LIVE-L1 experimental results to CEA and to CTU. I am also especially grateful to Laurence Godin- Jacqmin (CEA, Cadarache) who has always been available to help and answer my questions during my stay at CEA Cadarache.

REFERENCES

[1] Bachrata. In-vessel retention via external reactor cooling, Bachelor thesis, Czech technical university in Prague, June 2007

[2] Miassoedov, Laurence Godin-Jacqmin et al. Application of the ASTEC V1 code to the LIVE-L1 experiment, Proceedings at ICAPP´08, June 8-12 2008, Anaheim, CA USA

[3] sarnet.grs.de, 28.10.2007

[4] Miassoedov et al. Results of the LIVE-L1 experiment on melt behaviour in RPV lower head performed within the LACOMERA project at the Forschungszentrum Karlsruhe, Proceendings of the ICONE, April 2007, Japan

[5] Sehgal, Yang. Ex-vessel core melt stabilization research, SAM-ECOSTAR-D26, January 2002

[6] G. Guillard et al. Astec-V1/DOC/06-17, ASTEC V1 code, DIVA physical modeling, SEMCA-2006-234, pp. 53-68