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ASTEC application to in-vessel corium retention

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Summary

This paper aims at showing the capability of the ASTEC code to simulate In-Vessel corium Retention (IVR). First, the DIVA module of ASTEC code is briefly introduced. This module treats the core degradation and corium thermal behaviour, when relocated in the reactor lower head. Former ASTEC V1.2 version assumed a predefined stratified molten pool configuration with a metallic layer on the top of the volumetrically heated oxide pool. In order to reflect the results of the MASCA project, improved models that enable modelling of more general corium pool configurations, were implemented recently by the CEA into the DIVA module of the ASTEC V1.3 code.

In parallel, the CEA is working on ASTEC modelling of the External Reactor Vessel Cooling (ERVC). The CESAR capability to simulate the ERVC was tested. The conclusions were that the CESAR module is capable of simulating this system although some numerical and physical instabilities can occur. Developments were then made on the coupling between the DIVA module and the CESAR module. In specific conditions, code oscillations remain and an analysis was made to reduce the numerical part of these oscillations. A comparison of the results with the SULTAN experiments is presented.

The ASTEC V1.2 code version was applied to IVR simulation for VVER-440/V213 reactors assuming defined corium mass, composition and decay heat. The external cooling of reactor wall was simulated by applying imposed coolant temperature and heat transfer coefficient (HTC). The obtained results (pool temperatures, heat flux distribution, reactor wall ablation) were compared with available predictions of other codes.

A Introduction

In the case of a hypothetical severe accident (SA) in a Light Water Reactor, the loss of fuel coolant can lead to the melting of part of the core. In this event, pieces of the molten core, a mixture of oxides and metals, commonly called corium, might drop into the RPV bottom head. The mitigation strategy of SA consequences, relies on two different concepts:

- Ex-vessel corium retention and spreading,
- In-Vessel Retention (IVR).

For the first concept, which is the basic option chosen for the European Pressurized Reactor (EPR) design, a core catcher (spreading surface) is placed behind the vessel (Ref [1]). For the second concept, the corium retention is achieved by an ERVC system based on the flooding of the cavity. This concept has been adopted for advanced PWRs such as the AP600/AP1000 and the APR1400 (in combination with an in-vessel core catcher) as well as for older VVER-440/V213 reactors. The success of the IVR depends on the thermal margins: the difference between the thermal loading (by the melt natural convections) on the inside and the limits of coolability (due to boiling crisis) on the outside of the reactor pressure vessel. The avoidance of a heat-transfer crisis on external reactor surface and thus effective cooling in the above-mentioned medium and higher-powered advanced designs is assured by coolant flow streamlining alongside the curved reactor surface (installation of flow baffles) and by optimising the IVR cooling loop design. Water chemistry and reactor surface morphology are other promising factors for enhancement of the critical heat flux (Ref. [2]).

Contrary to the above-mentioned advanced designs, the VVER-440/V213 reactors were designed and built a long time ago, when the possibility of core melting was not accounted for in the design stage of these low-powered reactors. Thus the possibility of additional implementation of technical modifications, which are necessary for the creation of an IVR-cooling loop, is rather limited. However, this is compensated with significantly lower maximum heat fluxes than expected for higher-powered reactors.

Within the framework of SARNET project, as well as within national projects, the ASTEC code was for the 1st time used for IVR applications. In parallel model improvements and adaptations of the ASTEC code version V1.2 were carried out in order to describe more precisely the main phenomena relevant to an IVR situation: corium thermal behaviour in the lower head of the vessel and thermal-hydraulic behaviour of the ERVC.

The objectives of this paper are, on the one hand, to present the code developments and adaptations that were carried out and to demonstrate the code capability at simulating the IVR situation. On the other hand, the results of the IVR situation obtained for the simulation of a modified VVER-440/V213 reactor are presented and analysed.

B CORIUM BEHAVIOR IN THE VESSEL LOWER HEAD OF THE ASTEC V1.3 VERSION

In the ASTEC code system, the DIVA module is in charge of the description of core degradation from its initial state up to its behaviour when re-located in the lower vessel head. In the former ASTEC version, namely the V1.2 version, it was assumed that the corium was stratified in three different layers (from bottom to top): an oxidic pool, a metallic layer and a debris bed. In order to take into account some MASCA findings (Ref. [3]) which highlighted a heavy metal layer below the oxide layer, the CEA developed a brand new modelling for corium thermal behaviour when located in the lower vessel head.

This new modelling, in the DIVA module, implemented in the newer ASTEC version V1.3, was devoted to:

- **Corium configuration**. Arbitrary corium layer arrangement can be made by the user. Moreover, the thermodynamic equilibrium between a metal layer and an oxide layer can be simulated.
- **Thermal exchanges**. The heat transfer laws between the layers and between the layers and the vessel were massively rewritten. The proposed laws take into account major recent findings from experimental programs such as BALI (Ref. [4]) or COPO/ACOPO. Obviously, heat transfer laws are also configuration dependant.

The main models are presented hereunder.

Corium stratification.

Once the corium flows from the core to the lower vessel head, the liquid metal and the liquid oxide can be separated in two non-miscible liquid pools. Depending on the corium oxidation level (basically the fraction of oxidized zirconium) and on the temperature of the liquids, and according to thermodynamic equilibrium, the liquid metal may be heavier than the oxidic pool.

From a formal point of view, the actual corium configuration should be computed with a thermodynamic tool, which at present, is not available in the ASTEC code. Therefore the corium stratification has to be specified by the user.

In the V1.3 ASTEC code version, the DIVA module can handle arbitrary corium configurations limited to a nine layer case. The two major corium configurations are summarized in Figure 1 below.

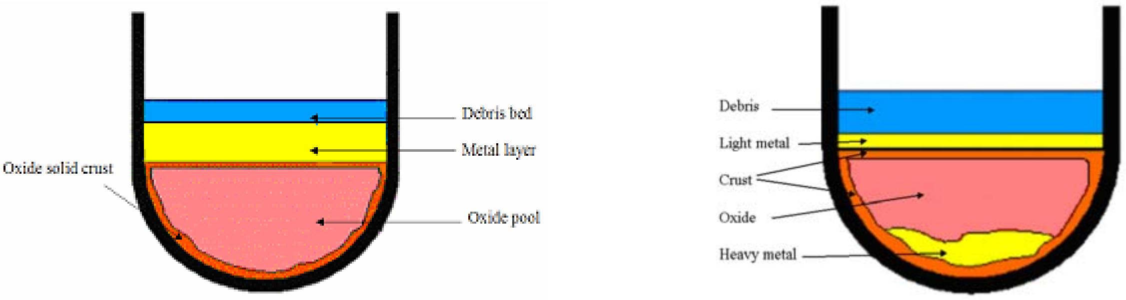

Figure 1 : Typical corium configurations in the DIVA module

The configuration on the left represents the former case as dealt in the ASTEC V1.2 code. On the right, the so-called MASCA configuration is represented. Since the heavy metal layer and the oxide layer are in thermodynamic equilibrium, they are surrounded by a crust whose temperature is the oxide phase liquidus temperature. Moreover, there is no crust between these two layers.

Heat exchanges

The basic assumption of the heat exchanges between two different layers or between a corium layer and the vessel is summarized in Figure 2 below. The main assumption that is made is that the fluxes are equal. This implies that a steady state situation is reached.

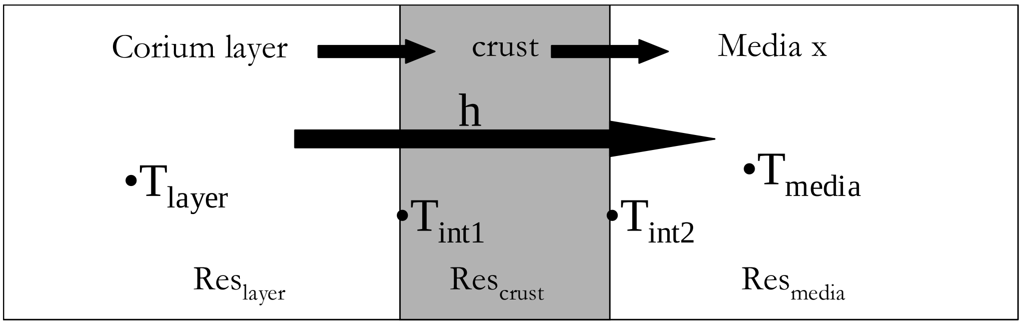

Figure 2: DIVA basic heat transfer modelling

The heat flux that is exchanged between the corium layer and Media x (that can be either a corium layer or the vessel wall), is determined by the following relation: Q=h *(Tcorium-Tmedia), where the global heat transfer coefficient, h, is related to the local heat resistances by the relation: $\frac{1}{h} = Res_{layer} + Res_{crust} + Resi_{mediax}$

In the ASTEC V1.3 code version, the determination of the local heat transfer resistance of a considered corium layer depends on the following parameters:

- Internal power due to fission products
- Convection pattern leading to laminar or turbulent convection

- Surrounding medium that implies or not convection movements
- Thermodynamic equilibrium

According to these parameters, the corresponding Nusselt number is determined thanks to relevant correlations (Refs. [5], [6], [7]).

A postulate PWR application

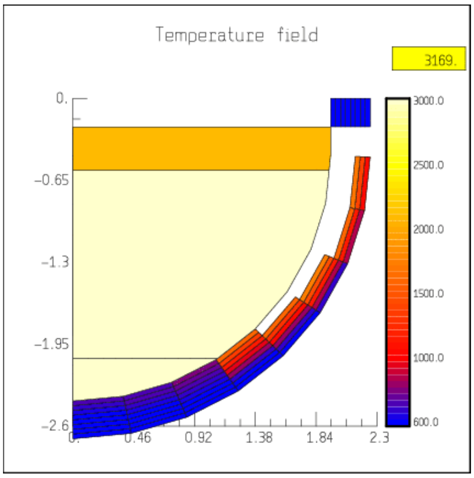

Figure 3: Corium and vessel temperature of a postulate PWR accident – ASTEC V1.3 results

Figure 3 represents the temperature of the corium and of the vessel at vessel rupture time. This results from an ASTEC V1.3 code version simulation of a postulated PWR accident. At time t= 0s, the bottom head of the vessel is filled with 120 tons of oxide (mixture of UO_2 and ZrO_2) above 5 tons of heavy metal in thermodynamic equilibrium. Above that, a 5 ton metallic light layer has settled.

The results obtained demonstrate that the vessel is melted in its whole thickness just near the light metallic layer which acts as a thermal bridge: the heat coming from the oxide pool is focused by the light metal layer to the vessel wall. It has to be noted, that according to the assumption of flux equality, the meshing of the vessel has to be refined in its thickness in order to catch a focusing effect.

Conclusion

The DIVA modelling of the corium when located in the lower vessel head has been largely rewritten. The major code modifications aim at:

- Allowing the code to deal with arbitrary corium stratification
- Improving the heat transfer based on recent findings.

The first results of the new modelling are encouraging. The next step will be to compare the code results with experimental data obtained on relevant tests such as those obtained in the LIVE or SIMECO (Ref. [8]) facilities. Part of this qualification work is to be performed within SARNET.

C MODELLING OF ERVC USING THE CESAR MODULE

The IVR analyses for VVER-440/V213 reactors, described in the next chapter, were performed using imposed boundary conditions (BC) on the external reactor area. These BCs are generally described using a constant heat transfer coefficient combined with a coolant temperature. However, in actual IVR-cooling loop arrangement, this constant quantity depends on the external condition of the two-phase flow in natural circulation. Furthermore, flow instabilities can be expected. This may result in significant changes in heat transfer on the external reactor surface.

The description and the model of the IVR-cooling loop is necessary to get the local two phase flow conditions, for example, the pressure, the void fraction, the flow rate.

Among the ASTEC modules, the modelling of the vessel external cooling with water in natural convection seems to be possible with CESAR. The 5 equation model used in CESAR, considering the approximations made in the physical modelling of the core degradation of the core, seems sufficient for the required level of relevance. A test depicted on Figure 4 shows that the behaviour of a heated channel in forced convection when the power dissipated in the wall is increased to values which correspond to the order of magnitude of the heat flux encountered in the In Vessel Retention situation (1MW/m^2 for advanced PWRs).

In Figure 4a, the results of standard CESAR calculations show strong oscillations for the void fraction at several elevations in the channel. These oscillations lead to the crash of the CESAR calculations. This kind of two-phase flow with a pressure close to the atmospheric pressure is difficult to model with a code due to the large density difference between liquid and steam. A specific study was performed to reduce numerical oscillations. One of the detected phenomena responsible of the oscillations is the transition between the flow regimes for the heat transfer coefficient calculations. In Figure 4b, the heat transfer coefficient laws have been smoothed and the calculation continues until the end of the injected power increase.

This study is ongoing for the natural convection flows which are very complex. Indeed in experiments using this mode of flow strong oscillations are observed and it is important to filter the numerical oscillations and to keep the physical ones.

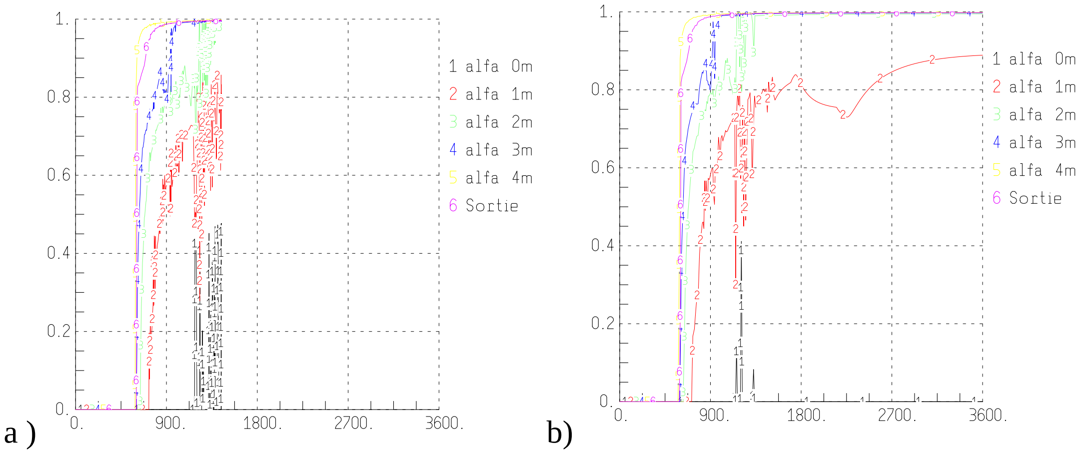

Figure 4: a) void fraction with standard CESAR calculation, b) void fraction with modified heat transfer CESAR calculation – ASTEC V1.2 results

The ERVC CESAR circuit along the vessel will have to be interfaced with the vessel described by the DIVA module and with the reactor containment described with the CPA module to take into account the steam release toward the containment where it will condense partially and the water returns in the reactor pit. The interface with the CPA can be managed without any new developments.

The interface between the DIVA and the CESAR modules required a special development to explicitly link the two ASTEC modules. Indeed, in the lower head (and also at core level), part of the steel vessel belongs to the two code models: CESAR deduces from the vessel temperature (calculated by DIVA) and the two phase flow heat transfer coefficients, the heat flux exchanged between the water and the vessel. This heat flux (vapour and liquid) will be a BC for DIVA, corresponding to the external vessel flux.

The code coupling highlights restrictions in the use of ASTEC. The restrictions are:

- To avoid the averaging of the heat flux between the corium layer and the lower head cells, an axial refined mesh is necessary in the zone where the heat flux is maximum.
- With the IVR strategy, the residual thickness of the vessel wall in case of severe accidents can be very low compared to its initial value. The meshing along the radial direction must be set to its maximum in the zone where the heat flux is maximum.
- The maximum cell number of the vessel in the lower head of DIVA is about 90. Thus, the meshing of the vessel is set to 5 rings in the radial direction and 17 rings in the axial direction.
- Each vessel cell of DIVA can be connected to only one cell of a CESAR volume.

An automatic procedure using the SIGAL tool has been written to prepare the data for the external cooling loop. The user must specify the rest of the geometry of the loop.

The first qualification for the new tools is the calculation of the SULTAN experiment (Ref [9]). This experiment which was performed in the CEA-Grenoble allows the study, in channels, of the critical heat flux depending on the local two phase flow condition.

The comparison in **Figure 5 depict**s **the behaviour of the pressure difference between the bottom and the top of the heating part of the SULTAN channel when the inlet flow rate increases. For this calculation, the channel thickness is 15cm, the channel is vertical and the injected power is 0.5MW/m^2. The pressure differences computed with CESAR are in agreement with the experimental data and with the CATHARE code results.**

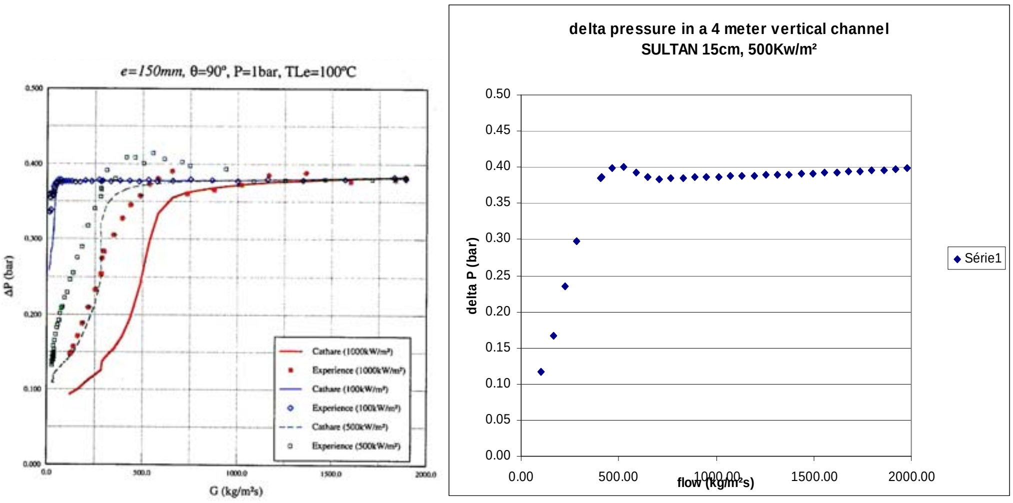

Figure 5: Comparison for the pressure drop in the SULTAN channel as a function of the flow rate between experiment and Cathare calculations (left) and CESAR calculations (right) (Ps=0.1MPa, vertical channel 15cm, 0.5MW/m^2).

In parallel, the first calculation of the coupled tool on a postulated VVER-440 geometry was performed, assuming forced convection in the IVR-cooling loop. The flow rate is injected using a source (20kg/s) in a pipe before the external cooling part of the circuit. The steam is extracted using a break on top of the cooling loop. The main results are depicted in Figure 6.

In the lower head, there are 3 layers (on the bottom, the heavy metallic layer in equilibrium with the oxide layer and above a light metal layer). The inlet flow is liquid and due to heat transfer from the corium pool, steam appears in the channel along the lower head wall and the void fraction increases. In the upper part of the channel, the static pressure is highly reduced because of the presence of the steam.

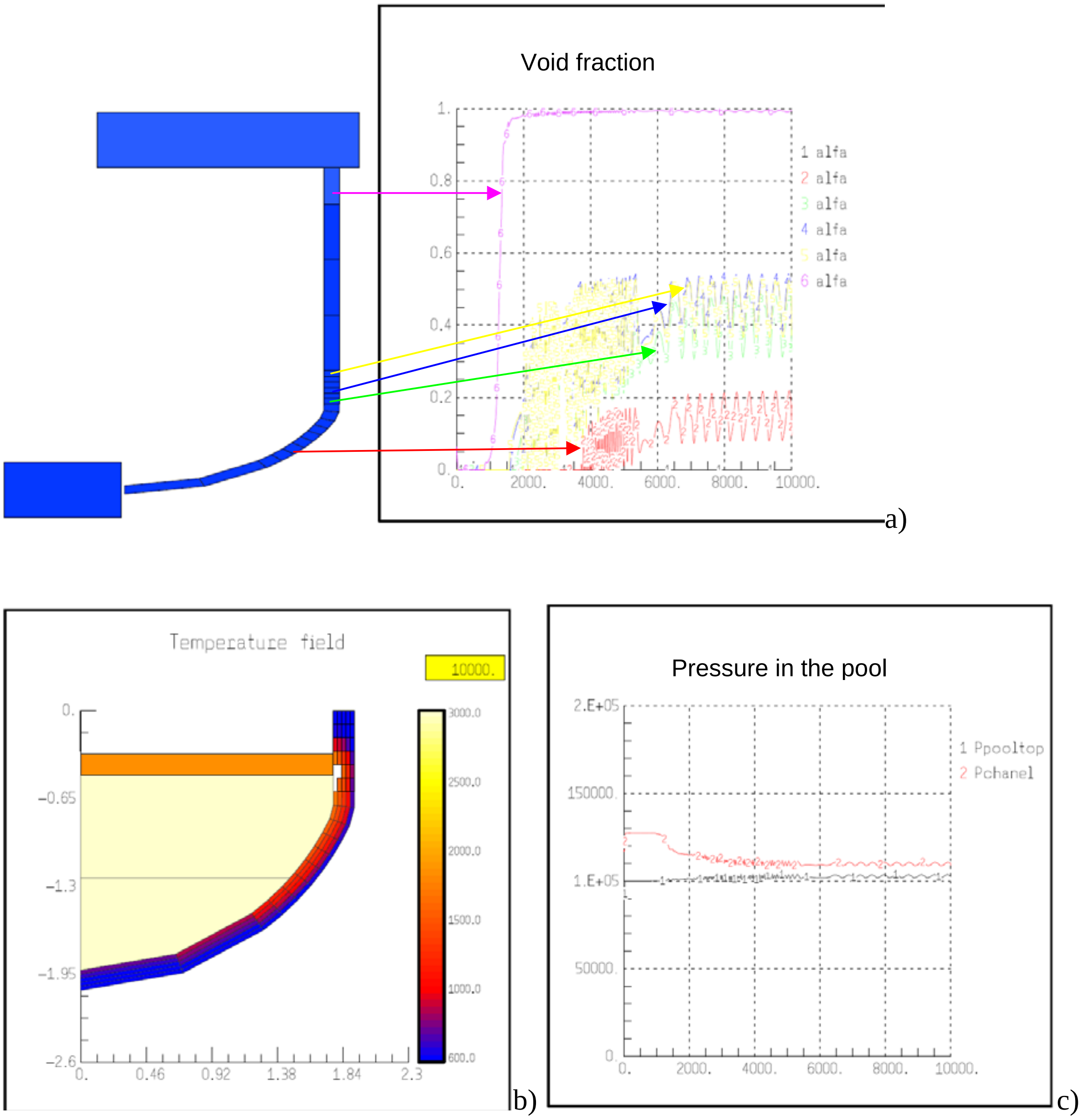

Figure 6: for a VVER440 geometry, diagram of the EVRC loop and void fraction in the loop a), lower head component temperature b) pressure in the upper pool and in the middle of channel along the lower head.

Oscillations in the calculation are probably due to a diameter too small for the break. The first results obtained with the coupling between DIVA and CESAR are encouraging and must be continued. The next step will concern the stability studies with natural convection and a first qualification of the tools on LIVE experiments (single liquid phase flow).

D APPLICATION OF ASTEC V1.2 IVR ON VVER-440/V213 REACTORS

The most important design features in favour of for the adoption of the IVR concept to VVER-440/V213 reactors are as follows:

- Low core power;
- Large water volumes on both primary and secondary sides (long elapsed time before the onset of core melting);
- No penetrations in the RPV lower head ;
- High RPV and thus high driving head for natural circulation in IVR cooling loop.

As main obstacles for the effective cooling of an external RPV surface were identified a massive thermal and biological shield of the RPV elliptical bottom, which prevents free access of water from the flooded cavity to the RPV surface. Pioneering work in the field of IVR adoption for VVER-440/V213 reactors was performed by Finnish experts for Loviisa NPP (Ref. [10]). This NPP, equipped with two VVER-440/V213 reactors, is currently the only one operating NPP in the world where the IVR was adopted and approved by the regulatory authority as a SAM measure. However, due to some differences between the Loviisa confinement (equipped with an ice condenser) and standard VVER-440/V213 units (equipped with a bubbler condenser) the application of the Finish experience is not straightforward. Feasibility studies for IVR adoption for standard VVER-440/V213 units were performed within the framework of VERSAFE (Refs. [11], [12]) and ARVI projects (5th FW Programme EU) as well as within national projects performed for Slovak and Hungarian NPPs. Technical modifications for the adoption of the IVR concept were proposed and analysed, together with corresponding SAM strategies within both national projects. The ASTEC code was widely used to estimate the front-end thermal-hydraulic and core degradation phase (e.g. estimation of time-margins and corium compositions) as well as for the modelling of the response of the confinement equipped with a bubbler condenser.

In this paper, we focus on the results obtained with the DIVA module of the ASTEC V1.2 code within the SARNET project (Ref. [13]). Attention was paid to heat transfer in volumetrically heated molten pools in the lower head and heat transfer through RPV walls assuming imposed boundary conditions (constant HTC and coolant temperature) on the external RPV surface. The most limiting condition regarding the thermal loading of RPV occurs when the corium in the lower head is fully molten (except for the crust on the boundary of the oxidic layer) and no decay heat is consumed in melting or heating up the debris or the vessel internals. Such a bounding case may not occur in a SA, but is usually chosen for licensing considerations. The analyses were performed for the defined corium composition and decay heat of the molten corium pool assuming that 100% of UO_2 was relocated from the core into the lower head; only the fraction of decay heat which corresponds to volatile fission products was subtracted.

The results obtained with ASTEC V1.2 rev.1 were compared with the available results obtained by the MVITA code in the ARVI project as well as with the Finish results obtained for Loviisa NPP. For this purpose, the boundary conditions were harmonised:

- Two different initial corium pool configurations (mass and compositions of the corium, decay power) in the lower plenum were considered. These configurations are further referred to as “ARVI” and “Loviisa” configurations – see Table I.
- Primary pressure set at 0.15 MPa (RPV depressurization was considered);
- External coolant temperature set at 120 °C (~saturation value);
- External heat transfer coefficient set at 10 $kW/m^2/K$;

Table I. Analysed cases – initial corium configurations

Configuration		**“Loviisa”**	**“ARVI”**
Power [MW]		9	9.334
Composition and masses of the materials [t] Remark: Marking and composition of the materials correspond to the materials used in the ASTEC code	**UO_2**	42.7	47.6
	ZrO_2	9.8	1.9
	Zr	0	7.7
	Steel	0	0.8
	Fe	46	15.2

The main difference between the two configurations is in total steel/Fe content. Based on the simple quantitative analysis of stainless steel vessel internals, which are present in the lower plenum and core region of VVER-440/V213, the steel mass used in the “Loviisa” configuration seems to be much more realistic than in the “ARVI” configuration, which is significantly underestimated. As can be seen from Figure 7, for the “Loviisa” configuration there is a thick metallic layer on the top of the corium pool, which results in relatively low maximum heat fluxes in this region (~ 550 kW/m^2) and consequently relatively low wall ablation. The maximum heat flux predicted by Finnish experts in [10] is about 420 kW/m^2. The shape and depth of ablation coincides well for both calculations. Material ablated from the RPV wall in the DIVA calculation is added to the metallic layer, which slightly increases the corium level in the lower head. This means, the empty space created due to wall ablation is not taken into account in the DIVA calculation. However, this inaccuracy has only a minor impact on the results of the analysis.

The comparison of the DIVA and the MVITA (Ref. [3]) prediction for thin metallic layers (corresponding to “ARVI” configuration) is shown in Figure 8. In this case the maximum heat flux predicted by the MVITA code (~ 900 kW/m^2) is significantly higher than the DIVA prediction (~ 600 kW/m^2).

E CONCLUSIONS

The evaluation of the corium In Vessel Retention concept has been an important subject for both the CEA and IVS institutes under the auspice of the SARNET project. This paper summarizes their activities over the last years.

On the one hand, the CEA is involved in the extension of the ASTEC code capability to IVR situations. This work aims at improving corium modelling, described by the DIVA module, based on recent findings on both corium layer stratification and thermal heat exchanges between layers and the vessel. This work also aims at demonstrating that the CESAR module, without major modifications, is capable of simulating the ERVC system.

On the other hand, the IVS is deeply involved in the computation of the corium In Vessel Retention situation using the ASTEC code for VVER440/213 reactor type. This work started with the use of the ASTEC V1.2 version, in which lacks in modelling were identified, and continued with the use of the latest ASTEC release, namely the V1.3 version.

The CEA and IVS studies, here summarized, demonstrate that the ASTEC code has the capability to analyse IVR situations using an ERVC system. Nevertheless, some qualification work has to be performed on both corium thermal behaviour when located in the vessel head and on the two phase flow modelling of the CESAR module when used as the ERVC. A large part of the work is planned within the next SARNET Joint Programme of Activity.

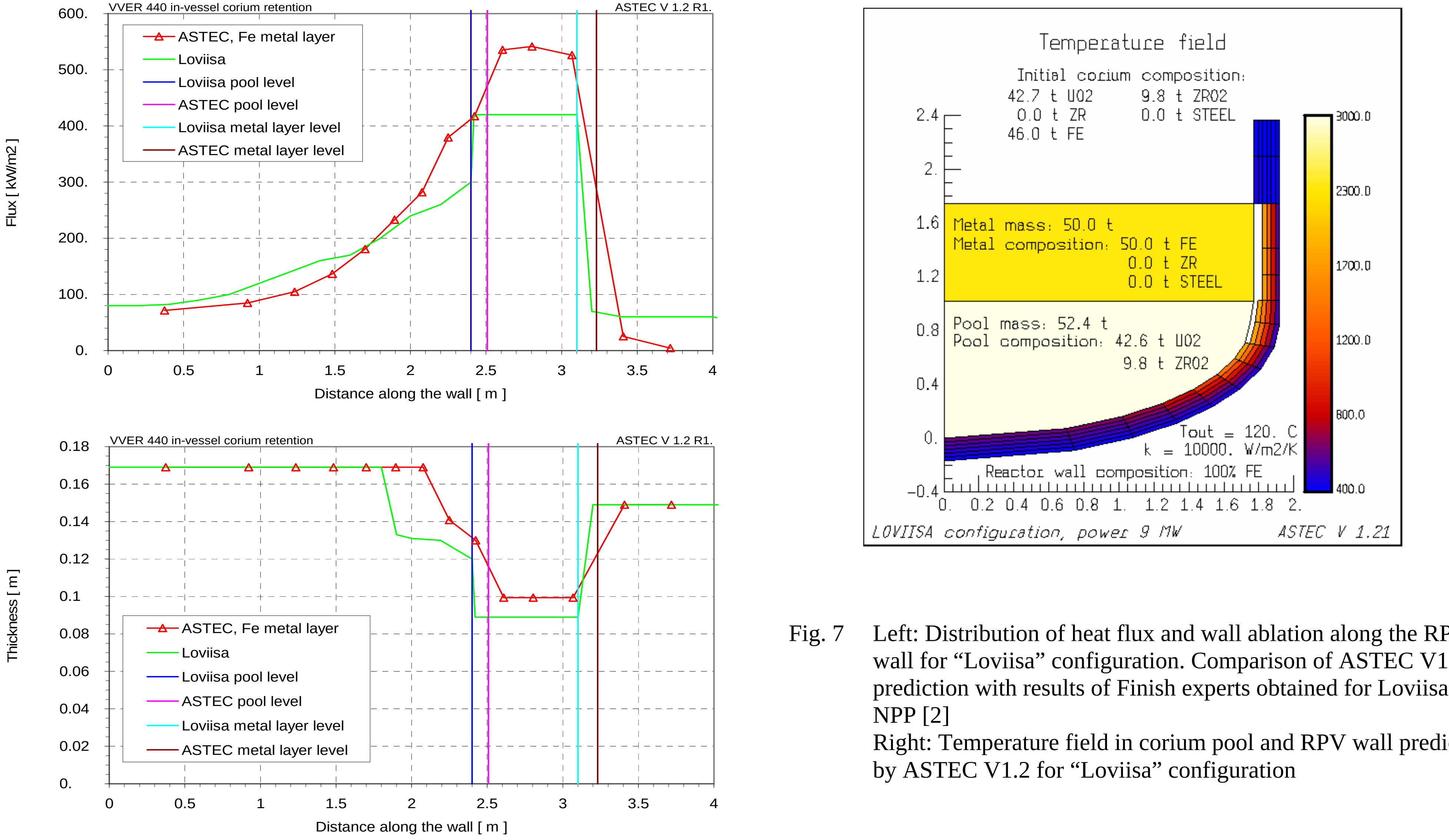

Fig. 7 Left: Distribution of heat flux and wall ablation along the RPV wall for “Loviisa” configuration. Comparison of ASTEC V1.2 prediction with results of Finish experts obtained for Loviisa NPP [2]
Right: Temperature field in corium pool and RPV wall predicted by ASTEC V1.2 for “Loviisa” configuration

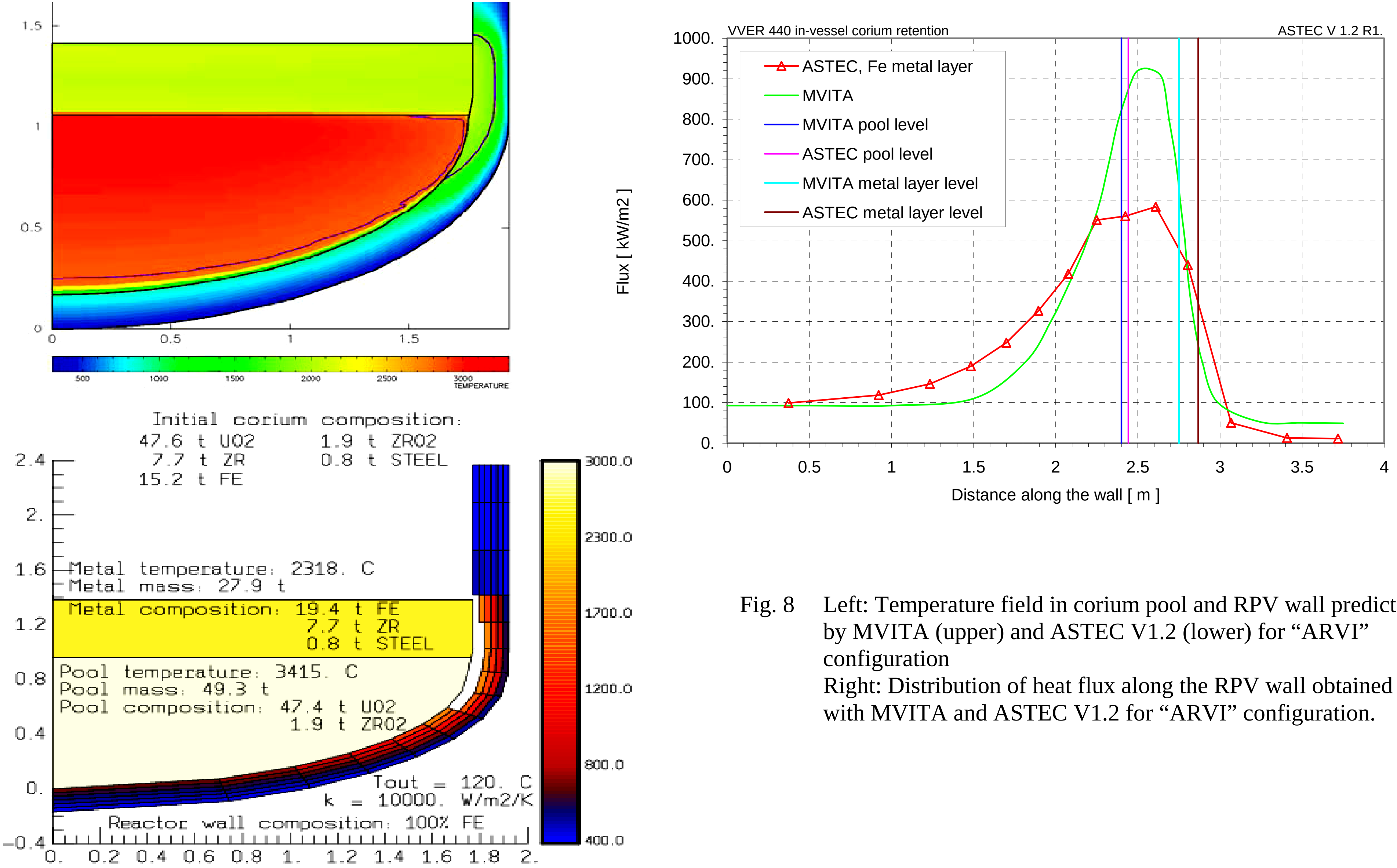

Fig. 8 Left: Temperature field in corium pool and RPV wall predicted by MVITA (upper) and ASTEC V1.2 (lower) for “ARVI” configuration
Right: Distribution of heat flux along the RPV wall obtained with MVITA and ASTEC V1.2 for “ARVI” configuration.

Glossary

ERVC	External Reactor Vessel Cooling
HTC	Heat Transfer Coefficient
IVR	In-Vessel Retention
NPP	Nuclear Power Plant
RPV	Reactor Pressure Vessel
SA	Severe Accident
SAM	Severe Accident Management

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