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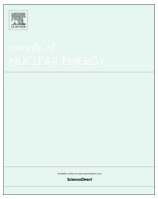

Modelling issues related to molten pool behaviour in case of In-Vessel Retention strategy

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ABSTRACT

The In-Vessel Retention (IVR) strategy for Light Water Reactors (LWR) intends to stabilize and retain the core melt in the reactor pressure vessel. This type of Severe Accident Management (SAM) strategy has already been incorporated in the SAM guidance (SAMG) of several operating small size LWR (reactors below 500MWe, like VVER440) and is part of the SAMG strategies for some Gen III+ PWRs of higher power like the AP1000.

The demonstration of IVR feasibility for high power reactors requires using less conservative models as the margins are reduced.

In this paper modelling issues related to molten pool behaviour in case of IVR are highlighted based on sensitivity studies performed with the severe accident integral code ASTEC (Accident Source Term Evaluation Code) for a typical PWR reactor. In particular, the following physical processes are addressed:

- Heat transfer coefficients in thin light metal layer and in heavy metal layer.
- Kinetics of corium stratification and thermal exchanges between oxide and metal phases during inversion of stratification.
- Relocation of steel coming from ablated vessel wall.
- Characteristics of oxide crust.

Analyses based on a simple configuration of corium in the lower head allow identifying potential impact of each modelling assumption on the heat flux distribution along the vessel wall, especially in transient situations. Based on this study, the most critical areas where the knowledge is too limited or where the current analytical methods should be improved are identified as being (i) the duration of situations with thin metal layer on the top of the oxide, associated to the knowledge of the kinetics of corium stratification and (ii) the possible super-heat of the metal layer at stratification inversion coupled with the risk of oxide crust failure.

This work is performed in the frame of the European project IVMR (In-Vessel Melt Retention) coordinated by IRSN. This project has been launched in 2015 and gathers 27 organizations. Its main objective is the evaluation of feasibility of IVR strategy for LWR (PWR, VVER, BWR) of total power 1000 MWe or higher.

1. Introduction

During a severe accident in Light Water Reactor (LWR), the lack of fuel cooling in the reactor vessel leads to core heat up and then melting of materials. The melt flows down to the lower plenum of the vessel. Consequently, the main part of the power generated by the fuel is not produced in the core zone anymore but at the bottom of the reactor pressure vessel (RPV). In this situation, a strategy of external cooling of the vessel wall (ERVC) to maintain the integrity of the vessel and to stabilize the corium inside the RPV may be used. This would reduce significantly the threats to the last barrier (the containment) and therefore reduce the risk of large release of low-volatile radioactive products to the environment. In order to demonstrate the feasibility of such a strategy and to assess the vessel integrity, one of the main difficulties lies in the evaluation of the thermal loads applied on the vessel wall.

In current methodologies, both bounding case and probabilistic approaches are used based on stabilized corium configurations. This is the case, for example, in the demonstration performed for VVER440 reactor of Loviisa power plant (Kymäläinen et al., 1997), for AP1000 reactor design (Esmaili and Khatib-Rahbar,

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Nomenclature

Latin letters

D	Diffusion coefficient [m^2/s]
F	Heat flux [W/m^2]
H	Layer height [m]
R	Vessel radius [m]

Dimensionless numbers

Ra_i	Internal Rayleigh number [-], $Ra_i = (g.\beta.\omega.\rho.H^5)/(\alpha.\lambda.\mu)$
With g	Standard gravity [m/s^2]

α	Thermal diffusivity [m^2/s]
β	Thermal expansion coefficient [K^{-1}]
ω	Volumetric power [W/m^3]
λ	Thermal conductivity [W/m/K]
μ	Dynamic viscosity [Pa.s]

Subscripts, superscripts

ox	Oxide layer
met	Metal layer

2005) or for new Korean reactor design APR1400 (Jung et al., 2015). Complex phenomena involved during transient situations, due mainly to thermo-chemistry in the quaternary system U-O-Zr-Fe which leads to metal and oxide phases separation, are not considered in these evaluations. Up to now, there is a lack of experimental data, due to the difficulties associated to the use of UO_2 at large scale, which prevents complete understanding of all the processes involved and their impact on heat flux distribution to the vessel wall. In a recent past, the shortcomings of in-vessel corium modelling and the need for transient models were pointed out (Fisher et al., 2011; Le Tellier et al., 2015; Fichot and Carénini, 2015; Jin et al., 2015).

In this paper, modelling issues related to molten pool behaviour in the lower head are investigated using the integral severe accident code ASTEC. After presenting the main features of the models implemented in ASTEC code for corium behaviour in the lower head of the RPV, stabilized corium configurations are first considered. Then, the main issues associated to transient situations and their deterministic evaluations are discussed.

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2. Modelling of corium behaviour in the lower head of ASTEC code

The vessel lower head is modelled in ASTEC code using a 2 dimensional meshing axially and radially. It is made of truncated cones allowing any shape of reactor vessel lower head to be modelled (see Fig. 1). It is worth noting that the chosen axial and radial meshing can be non-regular in order to have a refinement of the meshing in the top part of the lower head, where focusing effect is expected and in the outer part of the vessel wall, expected to remain unmolten in IVR configuration.

In ASTEC code, corium relocates from the core down to the lower head, only when it is molten. The melt jets interact with water and may be totally or partially fragmented depending on the level of water inside the vessel. The code evaluates the jet break-up length and deduces the fragmentation rate and the associated water vaporization. Accurate evaluation of this steam production is important in order to be able to predict the associated pressurisation, as well as corium cooling and remaining mass of water in the vessel. If the melt jet is totally fragmented, a debris bed is created at the bottom in the lower head. In the opposite, if it is only partially fragmented, a corium layer is formed covered by the debris bed (see Fig. 2). Debris and corium layers are considered homogeneous, with an average composition and temperature (0D modelling). Models are implemented to take into account the possible melting of the debris layers, which then feed the corium layers, and the sinking of debris into corium layers or inversely, depending on their respective density and viscosity. Then, ASTEC evaluates the separation of non-miscible liquid oxide and metal phases (Salay and Fichot, 2005) and the stratification of those phases up to 3 corium layers. This stratification process is very important and a key point in the evaluation of the heat flux profiles applied by the corium to the vessel wall. Indeed, formation of a metal layer on top of the oxide pool may lead to concentrate the heat flux to the vessel wall at this elevation (so called focusing effect). Heat transfers are evaluated between all the layers in the lower plenum as well as between corium and the vessel wall and the internal structures based on correlations (see paragraph 3). When the vessel wall heats up, its mechanical deformation and progressive melting are calculated until its possible failure.

It is worth noting that crusts around the oxide pool are not modelled as a specific component but are considered in the heat fluxes evaluation as thermal resistances. Thus, the crusts inertia is neglected and their thicknesses at each interface are evaluated

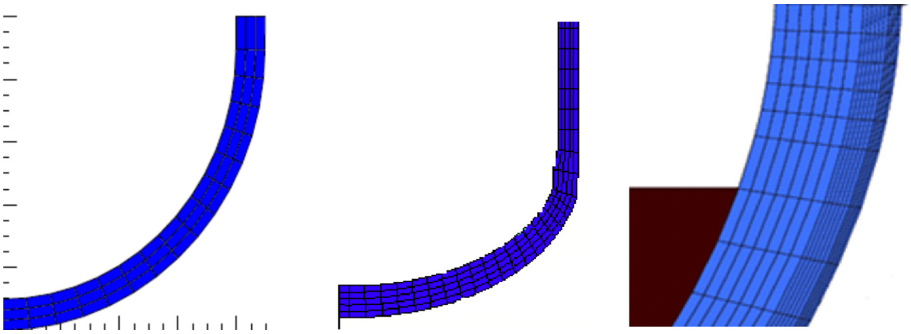

Fig. 1. Examples of lower head geometries (axisymmetric) and meshing with ASTEC code (left: hemispherical; centre: semi-elliptical; right: non-regular axial and radial meshing).