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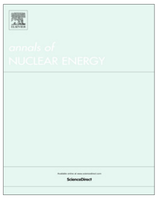

Some considerations to improve the methodology to assess In-Vessel Retention strategy for high-power reactors

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ABSTRACT

The In-Vessel Retention (IVR) strategy for Light Water Reactors (LWR) intends to stabilize and isolate corium and fission products in the reactor pressure vessel and in the primary circuit. This type of Severe Accident Management (SAM) strategy has already been incorporated in the SAM guidance (SAMG) of several operating small size LWR (reactor below 500 MWe (like VVER440)) and is part of the SAMG strategies for some Gen III + PWRs of higher power like the AP1000 or the APR1400. However, for high power reactors, estimations using current level of conservatism show that RPV failure caused by thermo-mechanical rupture takes place in some cases. A better estimation of the residual risk (probability of cases with vessel rupture) requires the use of models with a lower level of conservatism.

In Europe, the IVMR project aims at providing new experimental data and a harmonized methodology for IVR. A synthesis of the methodology applied to demonstrate the efficiency of IVR strategy for VVER-440 in Europe (Finland, Slovakia, Hungary and Czech Republic) was made. It showed very consistent results, following quite comparable methodologies. The main weakness of the demonstration was identified in the evaluation of the heat flux that could be reached in transient situations, e.g. under the “3-layers” configuration, where the “focusing effect” may cause higher heat fluxes than in steady-state (due to transient “thin” metal layer on top). Analyses of various designs of reactors with a power between 900 and 1300 MWe were also made. Different models for the description of the molten pool were used: homogeneous, stratified with fixed configuration, stratified with evolving configuration. The last type of model provides the highest heat fluxes (above 3 MW/m^2) whereas the first type provides the lowest heat fluxes (around 500 MW/m^2) but is not realistic due to the non-miscibility of steel with UO_2. Obviously, there is a need to reach a consensus about best estimate practices for IVR assessment to be used in the major codes for safety analysis, such as ASTEC, MELCOR, SOCRAT, MAAP, ATHLET-CD, SCDAP/RELAP, etc. Despite the model discrepancies, and leaving aside the unrealistic case of homogeneous pool, the average calculated heat fluxes in many cases are well above 1 MW/m^2 which could reduce the residual thickness of the vessel considerably and threaten its integrity. Therefore, it is clear that the safety demonstration of IVR for high power reactors requires a more careful evaluation of the situations which can lead to formation of either a very thin top metal layer provoking focusing effect or significantly overheated metal, e.g. after oxide and metal layer inversion. It also requires an accurate mechanical analysis of the ablated vessel.

The current approach followed by most experts for IVR is a compromise between a deterministic analysis using the significant knowledge gained during the last two decades and a probabilistic analysis to take into account large uncertainties due to the lack of data for some physical phenomena (such as transient effects) and due to excessive simplifications of models. A harmonization of the positions of safety authorities on the IVR strategy is necessary to allow decision making based on shared scientific knowledge. Currently, the acceptance criteria of a safety demonstration for IVR may be differently defined from one country to the other and the differences should be further discussed to reach harmonization on this important topic. This includes the accident scenarios to be considered in the demonstration and the

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modelling of the phenomena in the vessel. Such harmonization is one of the goals of IVMR project. A revised methodology is proposed, where the safety criterion is based not only on a comparison of the heat flux and the Critical Heat Flux (CHF) profiles as in current approaches but also on the minimum vessel thickness reached after ablation and the maximum integral loads that is applied to the vessel during the transient. The main advantage of this revised criterion is in consideration of both steady-state and transient loads on the RPV. Another advantage is that this criterion may be used in both probabilistic and deterministic approaches, whereas the current approaches are mostly deterministic (with deterministic calculations used only for estimates of uncertainty ranges of input parameters).

1. Introduction

The European IVMR project started in June 2015, in the frame of the H2020 program. Gathering 23 partners from 14 European countries, it aims a revisiting the severe accident strategy of In-Vessel Retention (IVR), in particular for reactor of "high-power", i.e. 1000 MWe or more. After the Fukushima accidents, it has become even more important than before to examine all possible strategies to stop the progression of a severe accident and to look at the possibility to implement such strategies in the design of new reactors or as a back-fitting measure for existing reactors, which is, of course, more difficult.

The In-Vessel Retention of molten corium by external cooling of the vessel lower head was introduced about 20 years ago (Henry and Fauske, 1993; Tuomisto and Theofanous, 1994). It was first applied to two designs of reactors: AP600 (Theofanous et al., 1997) and VVER-440 (Kymälainen et al., 1997). The VVER-440 case has led to a practical application at the Loviisa plant (Finland) where IVR is a part of the severe accident management and later in Paks plant (Hungary), Bohunice and Mochovce plants (Slovakia) and Dukovany plant (Czech Republic). The AP600 design was not further developed as it was later replaced by the AP1000 design (Esmaili et al., 1997) keeping the option of IVR. In parallel, other designs involving IVR were examined, such as APR-1400 (Knudson et al., 2004; Rempe et al., 2004; Whang et al., 2017), SWR-1000 (BWR-type, also known as KERENA), VVER-640 (Dombrovskii et al., 2007). The concept is also considered for the recent Chinese designs HPR-1000 and CAP-1400. Studies on reactors of very high power (1800 MWe) were even made (Jin et al., 2015). The concept is very attractive for several reasons:

- It ensures that corium is maintained in the vessel, avoiding the presence of large masses of fuel and non-volatile fission products in the containment and the risks of failure of the containment.
- In principle, external cooling of the vessel appears to be able to extract enough power in most of the situations (following different accident scenarios) and is suitable for long term stabilization of corium
- The practical design, under its simplest form, appears less expensive and can be more easily applied at operating NPPs, e.g. having small reactor pits, than an ex-vessel stabilization measure

In this paper, the VVER-440 is considered as a reference because it is currently the only design where IVR strategy has been extensively discussed and certified by different safety authorities.

This paper looks only at the issue of corium retention within the vessel because it is the minimum requirement for IVR strategy. The issues of containment integrity (including hydrogen risk), fission products release in the atmosphere and recriticality are not addressed. For corium retention, the methodology to demonstrate the feasibility of IVR and to estimate safety margins was well established in the early papers (Theofanous et al., 1997) and was only marginally improved later, by adaptations to the specific features of other reactor designs. Basically, the methodology relies on a probabilistic assessment of the profile of heat flux on the vessel wall due to the presence of the molten corium pool which is compared to the profile of maximum heat flux which may be extracted by external cooling (referred to as CHF). When that methodology is applied to relatively low-power reactors (below 600 MWe), it can be shown that IVR works with sufficient safety margins. When it is applied to high-power reactors (1000 MWe or above), the integrity of the vessel cannot be ensured in all situations as some scenarios or assumptions lead to situations where the local maximum heat flux on the vessel wall exceeds 1.8 MW/m^2, which is considered as a reasonable maximum value for the CHF (although higher values were reached in some ULPU experiments but with very optimized designs). In this paper, we give a review of the scenarios or conditions leading to excessive heat flux. From that analysis, we propose two relevant parameters that can be used to classify reactor designs with respect to the chances of success of IVR strategy. Then we propose a revised methodology to assess the probability of success of IVR strategy. The particular aspect of mechanical behavior of the ablated wall is discussed in more details as it appears to be of fundamental interest for the improvement of the methodology. In addition, different ways of reaching higher CHF are studied in IVMR project and presented in this paper. Finally, perspectives about the necessary experimental data are given and some possible innovations are discussed.

2. First analytical activities: Reactor calculations

Analyses of various designs of reactors with a power between 900 and 1300 MWe were also made. The general synthesis of the calculations performed by each project partner as well as the main conclusions from this work are presented in this section. Details of calculations can be found in (Sangiorgi, 2016). All participants were able to calculate severe accident (SA) scenarios with External Reactor Vessel Cooling (ERVC), for the reactor design and with the code of their choice. However, almost all participants identified needed improvements in order to obtain satisfying simulations. This was an unexpected conclusion: current system codes are not completely up-to-date for the simulation of lower plenum phenomena or they do not provide sufficient guidelines for users to produce reliable results. Although the topic is rather well documented since 20 years, it was striking to see that current SA codes include very diverse descriptions and models for corium and vessel behavior in the lower plenum. Of course, this has consequences on the variability of predictions of maximum heat flux and success of the IVR strategy.

Regarding the choice of SA scenario, the LBLOCA associated with unavailability of active safety injection systems has been identified as the most critical one due to its fast kinetics. However, it should be noticed that several participants evaluated other scenarios like SBO or SBLOCA, and the order of magnitude of steady-state heat