TSO Perspectives to Review a Reactor Concept based on In-Vessel melt Retention (IVR) Strategy for Severe Accident Management

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Abstract

In-Vessel melt Retention (IVR) is a Severe Accident (SA) mitigation measure applied in some Pressurized Water Reactors (PWRs) in order to cool down molten fuel (corium) inside the Reactor Pressure Vessel (RPV) by flooding the reactor cavity and cooling the RPV external surface with water. The safety demonstration provided to a national safety authority to support a reactor concept crediting the IVR strategy to enhance safety of an existing plant or to license a new generation design can be based on both deterministic and Probabilistic Risk Assessment (PRA). Experimental data can be used to support analyses or to validate models implemented in computer codes. This paper provides Technical Safety Organisations (TSOs) perspectives to review IVR as SA mitigation measure applied in NPP. The paper is structured as it is advised in the European Technical Safety Organisations Network (ETSON) Technical Safety Assessment Guide ETSON/2013-003.

1. Introduction

In-Vessel melt Retention (IVR) is a Severe Accident (SA) mitigation measure applied in some Pressurized Water Reactors (PWRs) in order to cool down molten fuel (corium) inside the Reactor Pressure Vessel (RPV) by flooding the reactor cavity and cooling the RPV external surface with water. As well, the IVR strategy can also be supported by cooling the corium inside the RPV by direct injection of water onto degraded core. Heat extracted from RPV is transferred to water in the containment, then heat removal from containment needs to be ensured by other means. Sufficient amount of water is required to warrant long term RPV external cooling.

The idea of IVR originated from the back-fitting of the Generation II reactor Loviisa VVER-440 in Finland in order to cope with the core-melt risk [1]. The IVR strategy was then employed in new reactor designs such as Westinghouse AP600 [2] and AP1000 [3], the Korean APR1400 [4] as well as Chinese advanced PWR designs HPR1000 [5] and CAP1400 [6]. The IVR strategy was meanwhile adopted in other operating VVER-440 reactors and the strategy is under discussion or implementation for VVER-1000 or other reactors of the same power rating ([7] to [11]).

Depending on the intended strategy, IVR requires that whole or a part of the decay heat of the melt pool is removed by coolant flow outside of the RPV. The lower the decay heat, the better are the chances for successful IVR. The Critical Heat Flux (CHF) at all points of the outside surface of the RPV lower head is limiting for the external RPV cooling, so that a boiling crisis is prevented. Consequently, IVR chances of success can be increased significantly if, for instance, the efficiency of the external heat removal is enhanced by a special design of water flow channels, or if the reactor is a low-power one or if the reactor is designed with sufficient passive water capacities (accumulators or some other system, or even using the secondary circuit). Indeed, in this last case, in case of Loss Of Coolant Accident (LOCA), the time before core uncover is rather long, thus decay heat decreases nicely before any core degradation. In addition to these characteristics, in order to avoid any core melt at high primary circuit pressure and to allow in-vessel coolant injection, it is vital for the IVR strategy that the reactor includes a reliable depressurization system of the Reactor Coolant System (RCS) allowing primary circuit pressure relief at elevated reactor core temperatures. The capacity of the depressurization system shall be sufficient to guarantee limitation of primary circuit pressure increase including in case of delayed in-vessel coolant injection. Moreover, during the process of removing the decay heat from corium by external coolant flow, the RPV lower head wall is ablated from the inner side by the melt pool as long as the heat removal is insufficient. As a result, minimum remaining RPV lower head wall thickness is reached if stable heat removal regime is finally established; otherwise the RPV lower head fails.

The most important issues for the IVR strategy are:

- pressure level evolution inside of RPV;
- in-vessel core melt evolution and the consequent heat fluxes imposed on the RPV lower head by the molten core (impact of transient evolutions of oxide and metal layers on the heat flux such as the "focusing effect", when a significantly higher heat flux is present in some limited region of the RPV wall, causing larger ablation of the RPV wall);
- the external cooling of the RPV: heat flux and its margin to the CHF and the stability of water/steam circulation (considering curvature and dimensions of both the RPV lower head and the water channel outside of the RPV lower head);
- the long-term mechanical behavior/stability of the remaining, partly ablated load-bearing RPV wall.

The safety demonstration provided to a national safety authority to support a reactor concept crediting the IVR strategy for SA management can be based on both deterministic and Probabilistic Risk Assessment (PRA). Experimental data can be used to support analyses or to validate models implemented in computer codes. Differences may exist between the case of reviewing IVR concept where the success of the IVR strategy "is guaranteed" per design feature implying that the success probability is very high, and the case where the reactor concept takes credit of the IVR strategy with "non negligible" probability of RPV lower head failure. In the first case, one should pay more attention to the evidence of the safety demonstration of the success of the IVR strategy including the PRA; in the second case, the attention should be more focused on the deterministic studies related to the consequences of RPV lower head failure with a (partly) flooded vessel cavity i.e. Direct Containment Heating, Fuel-Coolant Interactions and Corium-Concrete Interactions taking into account steam relief paths out of the vessel cavity and the overall reduction of the residual risk of the NPP.
This paper provides Technical Safety Organisations (TSOs) perspectives to review IVR as SA mitigation measure applied in NPP. The paper is structured as it is advised in the European Technical Safety Organisations Network (ETSON) Technical Safety Assessment Guide [12]. Namely, although all the research on IVR is in principle motivated by nuclear safety, many aspects of that research are not directly relevant for TSOs (such as, for instance, flow pattern within the melt or detailed heat flux distribution on the RPV outside wall). Although physical phenomena occurring on a lower scale definitely determine the success or failure of IVR, the TSOs perspective is to look into the implicit consequences of these phenomena and not at their detailed mechanisms.
The items to investigate from the TSOs perspective are the following:

- Identification of the safety objectives to be respected
- Analysis methodology, computer codes used and their validation for the safety issue
- Appropriate use of plant specific details, "key" input data and assumptions in the SA analysis
- Correctness, completeness and compliance with the state-of-the-art of the SA calculations and results
- Compliance with the safety objectives

2. Identification of the safety objectives to be respected

For the safety issue associated to the IVR strategy, safety objectives and criteria to be fulfilled should be clearly identified. As said previously, a safety objective could be to get a very high success probability of the IVR strategy (IVR success "is guaranteed"). In any case, attention should be paid to the main safety objectives to maintain containment integrity and/or to reduce radioactive releases. This is particularly related to reactor concepts based on the IVR strategy with the risk of RPV lower head failure being "non negligible".
The following criteria should be respected during the short-term and long-term phases of SA:

- minimum cooling heat flow necessary to ensure removal of the decay heat (together with other heat removal mechanisms);
- minimum remaining RPV lower head wall thickness in order to avoid mechanical failure due to loads to the RPV wall.

During the review, these criteria should be analysed with particular attention paid to:

- the eventual occurrence of CHF (the margins to the departure from nucleate boiling at each angular position on the RPV lower head should be ensured) and the recirculation of cooling water. Appropriate heat removal from the containment should be provided as well;

- the level of uncertainty associated to the material composition of the RPV lower head and its mechanical properties and the loads coming from the melt under possible primary circuit pressure transients (from rapid evaporation caused e.g. by delayed water injection into the RPV / lower head) or as a result of the limited rate of primary circuit depressurization;
- any impact of long-term SA on these criteria (recirculation of water containing debris, RPV wall corrosion, boric acid concentration in the reactor cavity…).

3. Analysis methodology, computer codes used and their validation for the safety issue

In the IVR strategy, as in other SA strategies, modelling of phenomena is often subject to large uncertainties, such as core melting and material relocation into the RPV lower head for instance, because of the difficulty to validate codes due to limitations of available experiments to represent the prototypical reactor case. Consequently, one should pay attention to the available experimental data supporting the IVR strategy and its representativeness for the case being reviewed. Moreover, one should pay attention that adequate safety margins are maintained in order to avoid underestimating potential detrimental consequences. This particularly applies to the way heat removal from the RPV lower head and from the containment is calculated and to the method used to determine the minimum remaining RPV lower head thickness.

If, for some aspects, sound engineering judgement or expert advice is used, particular attention should be paid to the expert elicitation process and its documentation and justification.

4. Appropriate use of plant specific details, "key" input data and assumptions in the SA analysis

The RPV lower head geometry, the number of welds in the area that can potentially be "weak spots" during core degradation, the possible presence of penetrations at the RPV bottom, the vessel thermal insulation, the vessel cavity layouts and the external vessel cooling system layout (water capacities, water inlet and evacuation of the generated steam) are plant specific details of interest.

"Key" input data and assumptions necessary for the efficiency of the IVR strategy may be obtained by identifying if, in the safety report, it is foreseen to demonstrate successful IVR crediting ex-vessel cooling only or crediting both ex-vessel cooling and in-vessel water injection.

Particular attention should be then paid to how ex-vessel cooling is achieved (e.g. through flooding of the cavity or by spraying the lower plenum outer surface), how produced steam is properly released into the reactor containment, how this heat is removed from the containment, and how in-vessel water injection is achieved, if needed.

Finally, particular interest should be given to the adequacy of hardware provisions and the feasibility of SA management actions credited for the successful achievement of IVR, including the procedures regarding the operation of the RCS depressurization (also in case of station blackout) and activation of any systems to delay the beginning of core uncover if needed. Particular attention should be paid to the possible local radioactive or other environmental conditions that may be adverse to the effective operation of water injection means that are credited, in particular if local operator actions are required.

If active water recirculation is required for the IVR strategy, special interest should be given to the presence of debris driven into sump water during SA. The concerns are the debris impact on the recirculation pump (cavitation risk due to clogging of the sump filter) as well as the impact of recirculating heavily contaminated water on possibly radiation sensitive components of the recirculation circuit.

Once the "key" input data are identified, the uncertainties, if any, regarding these input data should be addressed carefully to check that they are properly taken into account, with identification of any so-called "cliff-edge effects", by means of sensitivity studies for instance.

As an example, some of the "key" input data to be given particular attention could include (list non limited):

- the possible delay due to human factors to bring the RCS depressurization into operation;
- the necessary time delay to effectively bring the credited means into operation for water injection, in particular if local operator actions are required;
- the achievable flow rates with pumps and water reserves, possibly depending on RCS pressure (if in-vessel injection is credited for IVR) or on containment pressure (for external RPV cooling), for injection of cooling water in SA conditions;
- the target water height (if any) to be achieved in the vessel cavity in order to allow for external cooling of the RPV wall;
- although flow patterns within the melt in the vessel are not directly relevant for TSOs, the mass of molten steel in the lower head, at the time when the minimum acceptable RPV lower head thickness is reached, appears from the EC H2020 IVMR project as a main parameter for which the analysis should be cautious;
- the creep and tensile mechanical properties of the RPV lower head steel wall.

5. Correctness, completeness and compliance with the state-of-the-art of the SA calculations and results

Correctness, completeness and compliance with the state-of-the-art of SA calculations and results could be achieved through a comparison of the IVR strategy results presented in the safety analysis report to the state-of-the-art approaches as applied in the framework of e.g. the EC H2020 IVMR project [13]. Specifically, the core melt may be described on the local scale (using Computational Fluid Dynamics codes) or on the volume-average scale (using Lumped-Parameter codes). Also, the time-dependent behaviour or the time-averaged behaviour may be observed. R&D results are necessary, in particular to confirm the CHF values on the RPV lower head surface.

Moreover, attention should be paid to existing IVR demonstrations for similar plants where the IVR strategy has been implemented (if such information exists and reviewers have access to it).

Particular interest should be given as to whether:

- SA scenarios used in the safety report are adequately chosen in order to cover a wide spectrum of situations. They should be sufficiently described, especially the initial conditions at SA onset, the SA management actions to be credited as well as their timing and the SA long-term period. As a matter of fact, sequences that could lead to fast core melting, typically Large Break LOCA, are the ones leading to RPV failure, but they have in general a low frequency in the PRA. On the contrary, IVR could be predicted as successful for more slowly evolving sequences, which have in general the highest frequency in PRA;
- the use of some systems outside their qualification range is foreseen: this should be clearly stated in the analysis.

Sound engineering judgement or expert advice and also checks by hand calculations (for instance, assuming a stratified core melt with two uniform temperatures) could be performed by a reviewer to check that the results are within the expected boundaries. Nevertheless, on the IVR demonstration, as previously outlined, modelling of phenomena is subject to large uncertainties. Consequently, it is of particular interest for reviewers to independently make their own counter-calculations, after independently developing the input data deck and selecting the appropriate modelling for key phenomena.

Due to significant uncertainties in modelling, the reviewer should be careful to verify that the design margins are able to accommodate modelling uncertainties. Attention should be paid to check that key results (maximum heat flux from melt to RPV wall, cooling heat flux on RPV outside surface, RPV wall thickness after ablation), for which large uncertainties may be expected, have been the subject of a sensitivity analysis. If the impact of uncertainties on the IVR demonstration has been found to be substantial, it is of interest to check that a proper method to incorporate uncertainties through the demonstration has been used.

6. Compliance with the safety objectives

Finally, it will have to be verified that safety objectives and related criteria to be respected, as identified previously, have been met. Particular attention will be given to the available margins relative to uncertainties. Sufficient safety margins regarding main safety objectives mentioned in section 2, that is, to maintain containment integrity and/or to reduce radioactive releases, should anyway be kept. This item should be checked, especially when so-called "best-estimate" calculation results are provided.

For instance, regarding the RPV lower head mechanical failure, for the VVER-440, where the IVR strategy is usually accepted, the RPV lower head wall thickness can be reduced to 6 cm due to melting. Moreover a part of the remaining wall thickness is at such a high temperature that the load bearing capability of the wall material in this part is severely impaired. In the EC H2020 IVMR project, it was found that, for a 1000 MWe reactor "well designed for IVR", the RPV lower head wall thickness would be reduced to approximately 2 cm in the worst case. From a mechanical point of view, even if theoretically there could still be margin to RPV lower head failure, it is difficult to keep a "good enough" safety margin when such a low value of reduced RPV lower head thickness is found. This difficulty likely prevails even if all aspects of SA and uncertainties on the mechanical properties of the RPV lower head are taken into account. Similar misgivings (that is, due to uncertainties in the heat transfer from the RPV to the cooling water) may also be present when considering a "good enough" safety margin concerning the cooling heat flow.

One also has to keep in mind the source of uncertainties coming from the extrapolation when applying the results of R&D (for prototypic conditions and geometry) to a real plant.

7. Conclusion

IVR is a SA mitigation strategy applied in some PWRs in order to cool down molten fuel inside the RPV by flooding the reactor cavity and cooling the RPV external surface with water. The safety demonstration of a reactor crediting the IVR strategy, to enhance safety of an existing plant or to license a new generation design, can be based on both deterministic and probabilistic risk assessment. Experimental data should be used to support analyses or at least to validate models implemented in computer codes. TSOs perspectives to review the IVR strategy as SA mitigation measure applied in NPP have been presented according to the following items of investigation:

- Identification of the safety objectives to be respected
- Analysis methodology, computer codes used and their validation for the safety issue
- Appropriate use of plant specific details, "key" input data and assumptions in the SA analysis
- Correctness, completeness and compliance with the state-of-the-art of the SA calculations and results
- Compliance with the safety objectives

In the IVR demonstration, as in other SA strategies, modelling of phenomena is often subject to large uncertainties, such as core melting and material relocation into the RPV lower head for instance, because of the difficulty to validate codes due to limitations of available experiments to represent the prototypical reactor case. Consequently, one should pay attention to the available experimental data supporting the IVR strategy and its representativeness for the case being reviewed. Moreover, it is of particular interest for reviewers to independently make their own counter-calculations, after independently developing the input data deck taking into account plant specific details of interest and selecting appropriate modelling for key phenomena, in order to check that adequate safety margins are maintained and are able to accommodate modelling uncertainties. This principle is crucial in order to evaluate heat removal from RPV lower head and minimum remaining RPV lower head thickness.

The attention should be kept on all aspects of SA (adequacy of hardware provisions and feasibility of all SA management actions credited for the successful achievement of the IVR strategy, including the long term period of SA) and, if deemed necessary, the attention should also be focused on deterministic studies related to the consequences of an hypothetic RPV lower head failure with a (partly) flooded vessel cavity.

At the end, sufficient safety margins regarding the main safety objectives, that is, to maintain containment integrity and/or to reduce radioactive releases, should anyway be kept.

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Abbreviations

CHF	Critical Heat Flux
IVR	In-Vessel melt Retention
LOCA	Loss Of Coolant Accident
NPP	Nuclear Power Plant
RCS	Reactor Coolant System
RPV	Reactor Pressure Vessel
PWR	Pressurized Water Reactor
SA	Severe Accident
ETSON	European Technical Safety Organisations Network