Multinational Design Evaluation Programme (MDEP) Design-Specific Common Position

CP-HPR1000WG-03

HPR1000 Working Group

Common Position addressing In-Vessel Retention strategy for HPR1000

Participation

Regulators involved in the MDEP working group discussions:	ARN (Argentina), NNSA (China), NNR (South Africa), ONR (UK)
Regulators which support the present common position:	ARN (Argentina), NNSA (China), NNR (South Africa), ONR (UK)
Regulators with no objection:	none
Regulators which disagree:	none

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1. Introduction

Pressurised Water Reactors (PWRs) nuclear power plant designs include safety measures with the aim of returning the plant to a safe state following an accident and preventing the escalation to a severe accident and core melt scenario. In the low probability occurrence of a core melt scenario with loss of the heat removal function, there is potential for the molten core to relocate to lower head and melt through the Reactor Pressure Vessel (RPV). When the RPV fails, the molten corium can then fall into the reactor cavity, and the corium can erode the containment basemat. This may continue until melt through is reached, which may lead to a radioactive release to the environment. In addition, if there is water present in the reactor cavity at the time of failure of the RPV, there is potential for the molten core to interact with the water and result in large steam explosions that may challenge the containment structures.

Basically, in order to ensure the heat removal as well as confinement function in severe accidents, there are two types of melt retention strategies based on the planned location of the stabilisation of the corium: In-Vessel melt Retention (IVR) and Ex-Vessel melt Retention (EVR). Both the two strategies are used in different types of advanced PWRs, respectively. The IVR strategy is adopted by the designer in HPR1000, which uses water to cool the RPV outer surface and retain the molten core within the RPV. This strategy is designed to prevent RPV failure during severe accidents and the consequential severe accident phenomena so that the integrity of the containment is maintained.

Regarding HPR1000 IVR, which is an important severe accident management strategy, this Common Position (CP) is developed by the MDEP HPR1000 Working Group (HPR1000 WG) members, consisting of regulators from Argentina, People's Republic of China, South Africa and the United Kingdom. The national regulatory requirements of member countries regarding the IVR are of general nature, and detailed regulatory requirements are not given. The purpose of this CP is to present an acceptable approach to IVR design and safety assessment strategy for the HPR1000. A Technical Report (TR) on the regulatory requirements and practices of severe accidents, as well as a questionnaire and clarification of HPR1000 IVR design assessment, has been completed as part of other MDEP activities. These efforts have provided the basis for the production of this CP.

Firstly, this CP introduces the main design features and assessment strategy of HPR1000 IVR, and then, an acceptable approach to HPR1000 IVR design and assessment is presented in Section 3.

2. Main design features and assessment of HPR1000 IVR

In order to achieve IVR after a severe accident, relevant design features have been adopted in HPR1000 design, and common practices have been adopted in the assessment of the effectiveness of the IVR strategy. In order to understand the details of IVR relevant design and assessment, regulators from the WG members put forward a questionnaire with 34 questions to the HPR1000 designer. The questionnaire covered the system design, analysis and safety assessment, Critical Heat Flux (CHF) testing, etc. Based on the detailed response of the HPR1000 designer an overview of the design and the analysis which supports the safety justification of the IVR strategy are summarised below.

2.1 Design feature

According to the HPR1000 designer, the following design features are of importance for achieving the IVR strategy:

- The combination of active and passive injection measures, including gravity injection from the elevated passive water tank in the containment, and active injection driven by pump;
- A special flow channel and its inlet and outlet are designed between the RPV and the insulation layer, which are optimised to ensure efficient heat transfer;
- The pressuriser is equipped with two trains of the Severe Accident Dedicated Valve (SADV) for severe accidents to achieve full depressurisation of the RPV;
- Related equipment is equipped with diverse power sources, including offsite power source, emergency diesel generator, Station Black Out (SBO) diesel generator, mobile diesel generator, etc. The instruments and valves can also be powered by the severe accident battery;
- The control initiation of passive measures can be carried out on Severe Accident I&C System to ensure that the IVR strategy can be started in case of total loss of AC power;
- Startup of the IVR strategy needs to be manually operated by the operator after a severe accident occurs, and the control of injection flow is realised by the self-adaptive pumps, valves and pipeline, without the need of active adjustment;
- In order to avoid the impact on the normal operation, measures to prevent spurious injection are considered in the design;
- Operating parameters, such as water level, flow rate and temperature, are monitored to inform operators of the status of IVR function.

2.2 Safety Assessment

According to the HPR1000 designer, the effectiveness of IVR shall be guaranteed only when both thermal as well as structural criterion is satisfied. The IVR effectiveness assessment work carried out by the HPR1000 designer includes:

Thermal analysis: A 1:1 two-dimensional IVR CHF test facility was established, and the CHF correlation along the outer wall of RPV was obtained. Based on representative severe accident scenarios, deterministic analysis was carried out to determine whether IVR is effective in those representative scenarios. In addition, based on the Risk Oriented Accident Analysis Method (ROAAM), a sampling analysis on heat flux from molten pool to RPV wall was carried out taking consideration of the uncertainties of parameters of molten pool, including steel mass, zirconium oxidation fraction and decay heat of molten pool, informed by the deterministic analysis. The assumption of steady state of the two-layer molten pool was adopted in the sampling analysis. The HPR1000 designer claims that it is proved that the heat flux from molten pool to RPV wall was less than the CHF obtained from the test, and there is sufficient margin.

Mechanical analysis: The designer claims that the Finite Element Analysis (FEA) shows that the pressurised thermal shock of spurious injection under normal operation or the pressurised thermal shock at the moment of water injection under accident conditions will not threaten the integrity of RPV; the static analysis proves that the RPV residual wall thickness and its maximum tensile stress can maintain the integrity of the RPV; and the finite element analysis shows that the RPV can still maintain its integrity under the influence of long-term creep and other factors.

3. Common Position

High level requirements/expectations are set by the regulators related to ensuring heat removal and confinement safety functions during accident conditions. For severe accident scenarios, this means it is an expectation that adequate heat removal from the molten core is provided such that the confinement of radioactivity is maintained. In HPR1000, IVR is adopted to perform the heat removal function during severe accidents. Since there are no specific requirements on this strategy, the WG members consider the following common position can be an acceptable approach to IVR design and assessment of HPR1000.

Scenario Identification

The melting process of different severe accidents should be analysed to identify the representative severe accident scenario(s) for IVR verification. Whilst it is generally realised that the LB LOCA severe accident presents the most challenging scenario for IVR based on the engineering judgement and accident sequence analysis, the choice of representative scenarios should be justified by the designer due to the uncertainties of severe accident progression and phenomena.

Corium Configuration

The stratification behaviour of the molten pool after the melt is relocated to the lower head has a direct impact on the effectiveness of IVR. The behaviour of molten pool stratification is complicated. Large uncertainties in the corium degradation and relocation process mean that the geometry and composition of the corium pool cannot be known. Simplifications are therefore applied in deterministic modelling of the corium pool. There is currently no international consensus on how the pool should be modelled; however, one internationally established method is to model the pool as two layers consisting of a light metal layer and an oxidised layer. Special attention should be paid to the thermal focusing effect caused by the stronger convective heat transfer from the light metal layer to the side wall. In addition, the core melt transient process and interaction should also be paid attention to due to uncertainty in the corium behaviour.

Effectiveness Assessment

- In order to ensure that the decay heat in the RPV can be continuously removed in the IVR configuration during severe accidents, it should be adequately proved that the heat flux between the outer wall of the RPV and the water should be lower than the local Critical Heat Flux of the outer wall of the RPV. The CHF along the outer wall of the RPV should reflect the real nuclear power plant design and typical severe accident conditions.
- Influence of pressurised thermal shock on RPV structure integrity should be analysed under the condition of spurious injection in normal operation.
- Influence of pressurised thermal shock on RPV structure integrity at the moment of water injection under typical severe accident scenarios should be analysed.
- The inner wall of the RPV will be heated and ablated after corium relocation. It should be proved by mechanical analysis that the residual wall thickness after ablation has sufficient mechanical strength to bear the weight of the melt pool and the lower head and a certain internal pressure, so as to maintain the integrity of RPV.

System Design

- IVR system design should be able to bring the system to a stable state and to maintain residual heat removal continuously after a severe accident.
- The safety features related to the water inlet, the flow path between RPV and insulation layer, and the outlet should be designed to an appropriate level of reliability.
- The design of the IVR flow channel should take into the consideration the potential deformation of RPV lower head caused by heating and ablation, and potential debris in the containment that enter IVR cooling channel after accident, such that sufficient flow is maintained to provide adequate cooling to the RPV.
- The nuclear power plant design should be equipped with appropriate supporting systems that enable IVR to perform its safety functions and allow for monitoring of related parameters. These supporting systems include instrumentation and control, water sources and power supplies. These should be designed to an appropriate reliability and should be designed such that IVR can be implemented and monitored during a potential complete loss of AC power event.
- The reliability of the startup of the IVR system should be ensured. At the same time, the spurious startup of the IVR may affect the normal operation and RPV performance. Therefore, measures to prevent the spurious startup of the IVR should be considered in the design.

ABBREVIATIONS

AC	Alternating Current
CHF	Critical Heat Flux
CP	Common Position
EVR	Ex-Vessel melt Retention
FEA	Finite Element Analysis
HPR1000 WG	MDEP HPR1000 Working Group
IVR	In-Vessel melt Retention
I&C	Instrument and Control
LB LOCA	Large Break Loss of Coolant Accident
MDEP	Multinational Design Evaluation Programme
NPPs	Nuclear Power Plants
PWR	Pressurised Water Reactor
RPV	Reactor Pressure Vessel
ROAAM	Risk Oriented Accident Analysis Method
SADV	Severe Accident Dedicated Valve
SBO	Station Black Out
TR	Technical Report

References

[1] HPR1000 MDEP – Severe Accidents TESG In-Vessel Retention questionnaire.

[2] HPR1000 MDEP – Technical Report on Regulatory Requirements and Practices for Severe Accidents.