MIXING OF THE ATMOSPHERE WITHIN THE EPR DESIGN CONTAINMENT IN DESIGN BASIS & SEVERE ACCIDENT CONDITIONS
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Abstract

This paper presents the outcome of regulatory assessment of the generic EPR design relating to the performance of the atmospheric mixing measures within the containment during design basis and severe accidents. The EPR containment differs from many typical PWRs in that it uses a two room design concept. Equipment rooms immediately surrounding the reactor coolant system are isolated from the rest of the containment. Beyond this inner region, personnel access can be provided during certain maintenance tasks. The EPR design includes features that promote mixing within the containment during accident scenarios. Heat transfer to the containment heat sinks is facilitated by the “CONVEXT system”, consisting of passive rupture and convection foils, active mixing dampers, and related instrumentation and control equipment. Opening of the foils and dampers is designed to set up circulation patterns in both the accessible and inaccessible areas to increase the heat transfer surface areas in design basis accidents, and promote mixing of hydrogen released into the containment during a severe accident. The performance of the CONVEXT system has been the subject of independent confirmatory analyses by participating regulators and their technical support organisations using lumped parameter codes and detailed CFD computer codes. For severe accidents scenarios which remain on the predicted accident progression path, the CONVEXT system enables hydrogen released to be mixed efficiently within the containment. Despite some temporary high local hydrogen concentration in some accident scenarios, the containment integrity is not expected to be threatened. This paper has been facilitated by the Multinational Design Evaluation Programme, an NEA initiative set up to enhance standardization of safety assessment of new reactor designs by the national regulatory and safety authorities.

1. INTRODUCTION

1.1. MDEP Objectives

The Multinational Design Evaluation Programme (MDEP) is an OECD NEA initiative set up to enhance standardisation of safety assessment of new reactor designs by the national regulatory authorities in order to:

— Promote understanding of participating countries’ regulatory decisions and basis for these decisions;
— Enhance communication among the members and with external stakeholders;
— Identify common positions among regulators reviewing new reactor designs (including EPR);
— Achieve or improve harmonisation and convergence of regulations, standards, and guidance.

1.2. Background

The EPR containment is a new design, different from many typical Pressurised Water Reactor (PWR) containments in that it uses a two room design concept. Equipment rooms immediately surrounding the Reactor Coolant System (RCS) are isolated from the rest of the containment. Beyond this inner region, personnel access can be provided during certain maintenance tasks. Separation is provided by structures and closed portals to minimise radiation exposure in the accessible space areas. During power operation, inaccessible areas inside the containment experience higher temperatures and radiation than accessible areas. The EPR design includes a number of features that promote mixing of the environment within the containment in accident conditions.

The CONVEXT system consists of rupture foils, convection foils, mixing dampers, and the related instrumentation and control equipment. Rupture foils and convection foils are placed in the ceiling of each Steam Generator (SG) compartment. There are eight mixing dampers located in the lower part of the containment in the In-containment Refuelling Water Storage Tank (IRWST) wall above the water level.
Opening of the foils and dampers is designed to set up circulation patterns in both the accessible and inaccessible areas to increase the heat transfer surface areas in design basis accidents, and promote mixing of hydrogen released into the containment during a severe accident. The rupture foils are passive components which will burst open if the pressure differential on the foils exceeds a predetermined value. The rupture foils can burst in either direction. The passive convection foils are rupture foils placed in a frame, which is kept in the closed position by a fusible link. Should temperature rise to a set level, the link will melt with a short delay, and the frame will swing open by gravity. The result is that a convection foil will open on a pressure differential and will also open if the local compartment temperature reaches a certain level.

The mixing dampers are either opened manually from the main control room or are automatically activated on an absolute containment pressure signal set just above atmospheric, providing early opening of the mixing dampers for most accident scenarios. When closed, the mixing damper is held in position by an electromagnet against a compressed spring. In case of a power failure to the solenoid of the electromagnet, the spring will drive the mixing damper open.

The performance of the CONVECT system has been the subject of independent confirmatory analyses by a number of participating regulators and their technical support organisations using a variety of analytical tools such as lumped parameter codes and detailed Computational Fluid Dynamics (CFD) codes.

These analyses examined the effectiveness of the CONVECT system in facilitating general mixing in the containment atmosphere and in preventing the containment design pressure from being exceeded for design basis events. The outcome of this work has been shared amongst the participating regulators wishing to assess this feature of the EPR design, leading to improved understanding of its performance in accident conditions.

This paper presents the outcome of the regulatory assessment of the generic EPR design relating to the performance of the atmospheric mixing measures within the containment during design basis and severe accident conditions, which has been the subject of a common position paper.

2. SUPPORTING ANALYSIS

2.1. General

The CONVECT system performance has been independently assessed by a number of regulators reviewing the EPR design to evaluate containment mixing in the EPR for two key accident types:

- **Design Basis Accidents**: during which high energy water and steam is released from the RCS where the containment heat sinks (containment wall, internal structures) play a vital role in removing steam from the containment atmosphere. This supporting analysis is primarily to investigate the extent of any potential stratification within the containment which could prevent steam in the containment atmosphere from coming into contact with the relatively cold structures;

- **Severe Accidents**: during which, in addition to two phase flow, hydrogen is also released into the containment. A poorly mixed or stratified containment could allow accumulation of hydrogen in localised areas, detonation of which may put the containment integrity at risk.

The regulators note that the plant designers have conducted extensive analysis of the CONVECT system performance using lumped parameter models and CFD tools. This analysis has been used to demonstrate the role of natural circulation in temperature evolution and profile, evaluate pressure trends and calculate hydrogen concentration and distribution within the containment.

A number of regulators have performed confirmatory studies exploring mixing under design basis conditions using multi-node lumped parameter codes. Whereas, some others have performed studies using both lumped parameter and CFD models for the severe accident scenarios. These studies complement each other in that they explore similar phenomena using different tools and for different scenarios.

These confirmatory analyses and the EPR designer’s results have been discussed at the MDEP EPR technical expert subgroups on Accidents and Transients and Severe Accidents.

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2.2. Design Basis Accidents

The EPR designer has developed a model of the EPR containment using lumped parameter codes for analysis of design basis events. The model represents the different compartments, dome region and includes explicit modelling of the CONVECT system’s foils and mixing dampers. The supporting justification argued that the nodalisation approach is sufficiently detailed to permit development of natural circulation patterns in the containment. Both local atmosphere and local wall temperatures are calculated and used in heat transfer predictions. Whilst the design analysis appeared to demonstrate adequate mixing, the two-room containment concept and lack of active containment atmospheric heat removal raised novel issues not studied previously:

- Two-room concept responding as a single volume during the initial pressure rise in accident conditions;
- Effectiveness of open dampers and foils in creating circulation patterns within the containment;
- Effectiveness of passive heat sinks in limiting, and subsequently reducing, containment pressure.

A set of confirmatory calculations were performed using a multi-node APROS model. Heat and mass transfer to the containment internal structures is calculated using natural circulation heat transfer correlations and condensation determined from the heat/mass transfer analogy. The APROS approach is similar to the “Diffusion Layer Model” programmed into GOTHIC and to the heat/mass transfer package in MELCOR.

The APROS study developed a model that included explicit representation of the CONVECT system to predict flow distribution, flow mixing, and heat transfer in the containment following design basis accidents. Sensitivity studies were carried out to evaluate; effectiveness of the foils and dampers, heat transfer assumptions, and the effect of break elevation. A single-node and a 41 cell multi-node model were developed to analyse Large-break Loss of Coolant Accident (LOCA) and Main Steam Line Break (MSLB) accident scenarios and predict peak containment pressure and temperature (P & T).

The sensitivity studies assumed a double-ended guillotine break in the cold leg pump suction line (2A CLB), providing the following useful insights:

- Foils burst in all four SG compartments, and mixing dampers opened within a few seconds of the postulated event. The entire free volume of the containment participated in the initial pressure rise. The first pressure peak was reached within 30 to 40 seconds;
- There was good mixing in most parts of the containment during the first hundred seconds of the accident. After which, the pressures equalised, and most local flows subsided. Mixing was limited in the pressuriser (PRZ) compartment which does not have ceiling foils, and in some equipment rooms;
- The start of safety injection had a very pronounced effect, almost immediately terminating the rise in containment pressure and temperature, followed by a rapid fall in pressure;
- The time history of the analysed LOCA shows two pressure and temperature peaks. The first is determined by the energy stored in the RCS that releases into the containment during the first 40 seconds. The second peak occurs later, dependent on the time at which safety injection starts;
- Should dampers fail to open, peak containment P & T were observed to increase by 55 kPa and 14°C.

The postulated break location for the main analysis was at a low elevation. An additional case was run placing the break in the top node of the SG compartment. The result was an increase of 68.9 kPa in peak containment pressure. This result led to the selection of the MSLB for analysis, as these could occur at higher elevations. Thermal stratification was observed to depend upon the break elevation and was most pronounced between the dome and the lower volumes. Accumulation of non-condensable gases (air, nitrogen) was observed to reduce the rate of condensation on the walls.

Two MSLB confirmatory calculations were performed with the 41-node model. A double-ended break was postulated at the highest point of the steam lines within the containment dome. The purpose of the MSLB calculations was to gain an understanding of flow distribution and mixing, heat transfer in the containment, thermal stratification, and the effectiveness of the CONVECT system. The following points were observed:

- Foils ruptured and mixing dampers opened in the first few seconds of the postulated transient;
- During the first 100s of superheated steam release, warm steam remained in the dome. Some of the air from the dome was displaced into the lower part of the containment through vertical flow paths;
- A clear vertical stratification formed during the short term between the dome and lower parts of the annular region. The stratification subsequently became stronger and lasted for more than 24 hours;
— Over the long term, a circulation pattern formed in the upper part of the containment; however, due to large temperature differences between the upper and lower part of the containment, the buoyancy effect inhibited gas flow into the lower parts of the containment;
— The single-node representation of the dome region prevented the expected circulation and stratification. A more detailed model of the dome would be needed to study this phenomenon;
— Containment pressure peaked around 70 seconds then decreased slowly. Following heating of structures a reduction in the condensation rate, and a second smaller pressure peak, were observed;
— Operation of the CONVECT system produced relatively uniform containment pressure, however it was less effective in setting up circulation patterns between the containment equipment space and the service area which would act to reduce stratification;
— Gas temperatures in the upper regions of the containment were significantly higher for the MSLB than for LOCAs. The difference existed for the duration of the calculation (24 hours).

A MELCOR model was developed based upon the 41-node APROS model, and the predications of this model were compared against results from the APROS and GOTHIC models for the postulated 2A CLB. Similar results to those from both models were obtained, with the EPR designer’s multi-node GOTHIC model shown to be conservative in predicting peak containment P & T. The consistency of results between the reactor designer’s GOTHIC model, and the independently developed APROS and MELCOR models gives confidence in the representative nature of the predictions.

Confirmatory sensitivity studies were performed on the damper flow resistance and flow area, by varying these parameters. In addition, sensitivity studies were carried out to examine the impact of the nodalisation on the recirculation patterns between different volumes. The results indicated that additional nodes and flow parameter changes each had a minimal effect on the peak containment P & T which remained below that calculated by the EPR designer using GOTHIC.

2.3. Severe Accidents

A series of independent confirmatory studies using both CFD and lumped parameter models have been undertaken by the regulators using the MELCOR, ASTEC/CPA, TONUS and FLUENT codes, to evaluate severe accidents. One of the main objectives of the studies was to evaluate the efficiency of hydrogen mixing measures in the containment and efficiency of recombiners in reducing hydrogen concentrations.

2.3.1. Pressuriser SB-LOCA

This study considered a SB-LOCA on top of the PRZ using MELCOR, with failure of the emergency core cooling and containment spray, but with successful partial and fast secondary cooldown and emergency feedwater operation. The results showed similar H₂ concentrations in different rooms, indicating good mixing of the containment atmosphere, when the rupture foils and mixing dampers operate as intended. The exception is the spreading room, which has a single opening, and exhibits a more stable H₂ concentration.

FLUENT simulations giving a more detailed spatial H₂ distribution suggest that burning in the PRZ volume is unlikely. The first prevailing steam release reduces O₂ concentration in the room around the leak and the room below. In the lower parts of PRZ volume there is still oxygen, but H₂ does not spread into this lower region. Due to separation of O₂ and H₂ the recombiners in the PRZ zone are not effective in this case.

Noting that both codes exhibit similar trends, FLUENT simulations predicted higher H₂ concentration than MELCOR at the top of the SG room due to stratification; between 4 - 8%, higher during release peaks. In the dome and lower volumes, the concentration remained below 4%, excluding the plumes rising from the SG rooms. In the dome area mixing is very efficient due to the natural convection caused by cooling structures.

A series of sensitivity studies were performed with a small break LOCA and Loss of Offsite Power. The case has been simulated both with and without the recombiners being credited. Both simulations show that hydrogen released will be mixed quite efficiently around the containment and provided an indication of recombiner performance, which reduced the hydrogen level below 4% within 3 hours in this case.

In summary, the results showed well mixed hydrogen concentrations in most compartments, in agreement with the EPR designer’s numerical predictions. The agreement in the outcome of the postulated scenarios using different tools provides confidence in this aspect of the EPR design.
2.3.2. Cold Leg SB-LOCA

This study considered a SB-LOCA in the cold leg, postulating failure of safety injection and containment spray systems using a lumped parameter code (ASTEC/CPA) for the early phase to evaluate the pressure, steam/air distribution and the wall temperature profiles, and a CFD code (TONUS) to simulate the H₂ release phase. Local values have been produced to evaluate the containment atmosphere mixing during this latter phase.

Two kinds of scenarios were selected for these studies: with and without core reflooding. In previous studies, it was observed that, for transients with low Mass and Energy Release (MER) in the containment such as SB-LOCA, only a few rupture foils opened even on the break side as this balances the containment pressure. As a result, the assumption that all rupture foils remain closed was considered.

A number of sensitivity studies were therefore carried out to examine performance of the CONV ECT system with different configuration of dampers and foils failing to operate as per the design intent.

Scenarios without core reflooding assumed the partial and fast secondary cool down and the emergency feed water system were operational, unlike those with core reflooding which also assumed unavailability of fast secondary cool down. The opening of the primary depressurisation valve was simulated as delayed for the core reflooding scenario, leading to discharge of the accumulators onto the damaged core.

During the core degradation phase, H₂ was released at three different locations: the break and the lower part of two pump rooms via the Pressurizer Relief Tank. A series of sensitivity cases were therefore studied to examine the performance of convection foils in different scenarios for various locations of steam and H₂ release.

Whilst the total mass of H₂ released is similar for both cases, the release rate is much faster for the scenarios with reflooding. Therefore, for the scenario with reflooding, the impact of recombiners is less significant and the hydrogen mass in the containment is more important.

For the scenario without core reflooding, the rate of hydrogen release is not very high, so the recombiners are effective, and local hydrogen concentrations are unlikely to lead to a risk of flame acceleration.

For the scenario with reflooding, the rate of H₂ release is high. Despite good mixing, the results show high H₂ local levels at the top of the SG compartments and in the dome for a short period. The CONV ECT system has no influence on this phase because even with a large opening at the top of these compartments there is a potential risk of flame acceleration; although the risk from flame acceleration in such infrequent scenarios has been analysed by the EPR designer to demonstrate that the containment integrity would not be threatened.

3. CONCLUSIONS

The independent confirmatory analyses commissioned by the regulators concluded that the CONV ECT system is effective in facilitating mixing in the containment atmosphere and preventing the design pressure from being exceeded for design basis events. Temperature stratification is possible for steam line breaks occurring at high elevation in the containment, the occurrence of which does not challenge the design pressure. However, the uncertainties relating to stratified conditions may potentially lead to challenges in temperature qualification of instrumentation within the containment, which must operate following a design basis event.

With regards to severe accidents, the results of the independent confirmatory analysis performed show that for scenarios which remain on the predicted accident progression path, the CONV ECT system enables hydrogen released to be mixed efficiently within the containment. Despite some temporary high local hydrogen concentration, the containment integrity would not be threatened.

Overall, the effectiveness of CONV ECT system has been confirmed by regulators and their TSOs as well as the EPR designer, and the studies have confirmed that there is sufficient mixing within the EPR containment after an accident to provide mitigation against design basis and severe accidents.

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