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Related to: EPR Working Group activities

COMMON POSITION ON EPR CONTAINMENT MIXING

Participation

Countries involved in the MDEP working group discussions:	China, France, Finland, the United Kingdom and the United States
Countries which support the present common position	China, France, Finland, the United Kingdom, and the United States
Countries with no objection:	India, Sweden
Countries which disagree	
Compatible with existing IAEA related documents	

Multinational Design Evaluation Program

EPR Working Group

EPR Accidents and Transients, and Severe Accident Technical Experts' Subgroups

COMMON POSITION ON EPR CONTAINMENT MIXING

Purpose

To identify common positions among the regulators reviewing the EPR accidents and transients in order to:

1. Promote understanding of each country's regulatory decisions and basis for the decisions,
2. Enhance communication among the members and with external stakeholders,
3. Identify areas where harmonisation and convergence of regulations, standards, and guidance can be achieved or improved, and
4. Supports standardisation of new reactor designs.

INTRODUCTION

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, the inaccessible areas inside containment experience higher temperatures and radiation than the accessible areas. The EPR design includes a number of features that promotes mixing. Heat transfer to the containment heat sinks is promoted by the CONVECT system.

The CONVECT system consists of rupture foils, convection foils, mixing dampers, and related instrumentation and control equipment. Rupture foils and convection foils are placed in the ceiling of each steam generator compartment. More than half of the foils are convection foils. The mixing dampers are located in the lower part of the containment in the in-containment refuelling water storage tank wall above the water level. There are eight of these. Opening of the foils and dampers is designed to set up circulation patterns in both the accessible and inaccessible areas. The rupture foils are passive components which will burst open if the pressure differential on the foils exceeds a predetermined value. The rupture foils burst in either direction. The convection foils which are passive components, are rupture foils placed in a frame. The frame 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 compartment temperature reaches a certain level.

The mixing dampers open either on a differential pressure signal between the accessible and the inaccessible areas or on a preset containment pressure signal. The containment pressure signal is set just above atmospheric pressure, assuring fast opening of the mixing dampers for most accident scenarios. A solenoid operates each mixing damper. 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. When electric power is restored to the solenoid, it is again available for normal operation. The mixing dampers can be operated from the control room.

SUPPORTING ANALYSIS

The CONVECT system performance has prompted various regulators reviewing the EPR to believe that there was value in sharing, and documenting the conclusions of the reviews of various nuclear authorities.

Evaluation of containment mixing in the EPR is important for two reasons:

- During design basis accidents with high energy release from the RCS, the containment heat sinks (containment wall, internal structures) play a vital role in removing steam from the containment atmosphere. A poorly mixed or stratified containment may prevent steam in the containment atmosphere from coming into contact with the relatively cold heat structures.

- During a severe accident, where hydrogen has been released into the containment, a poorly mixed or stratified containment could allow accumulation of hydrogen in localised areas that may put the containment integrity at risk.

The applicant has conducted extensive analysis of the CONVECT system performance using lumped parameter models and computational fluid dynamics tools. The MDEP EPR technical expert subgroups on Accidents and Transients and Severe Accidents discussed their own confirmatory analyses and applicant's results.

The US NRC has performed confirmatory studies exploring mixing under design basis conditions using various multi-node lumped parameter models. STUK and IRSN have performed studies using both lumped parameter and computational fluid dynamics models for the severe accident scenarios. These studies complement each other in that they explore similar phenomena using different tools and for different events.

Further details of the supporting analyses are presented in appendix 1.

COMMON POSITION

The supporting analyses concluded that the CONVECT system is effective in facilitating general mixing in the containment atmosphere and in preventing the containment design pressure from being exceeded for design basis events. Temperature stratification is possible for steam line breaks that would take place at high elevation in containment. For conditions where temperature stratification was predicted, the design pressure was not exceeded. However, these stratified temperature conditions may lead to challenges in temperature qualification of instrumentation within containment which must operate following a design basis event.

As regards to severe accidents, the results of the analysis performed show that the CONVECT 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 CONVECT system (which is made up of mixing dampers, rupture foils and convection foils) have been confirmed by regulators and their TSOs as well as the applicant and the studies have confirmed that there is sufficient mixing within the EPR containment after an accident to support the design.

This common position may be updated as necessary.

APPENDIX 1

Design Basis Accidents

For US certification, the applicant developed a multi-node GOTHIC model of the U.S. EPR containment with 30 lumped parameter nodes for analysis of design basis events. The dome region was subdivided into a 5 x 5 x 19 mesh. The 30 node representation of the containment permits explicit modeling of the CONVECT system's foils and mixing dampers. The applicant stated that the arrangement of nodes is sufficiently detailed to permit development of natural circulation patterns in the containment. Both local atmosphere and local wall temperatures are calculated by the applicant and are used in heat transfer predictions. The applicant stated that the detailed, three-dimensional representation of the dome region is capable of predicting stratification, should it occur. The applicant provided benchmarks against data from the Heissdampfreaktor (HDR) in ANP-10299, Revision 2. HDR is a decommissioned superheated steam reactor in the Federal Republic of Germany. The HDR test facility is characterized by a steel cylindrical containment consisting of a lower section divided into 70 subcompartments, and a large upper dome section. The applicant, using this model, demonstrates that there was adequate mixing such that all acceptance criteria were met. The two-room containment concept and lack of active containment atmospheric heat removal raised issues which were not studied previously by NRC staff. The main issues raised by the staff were:

- Confirm the two-room containment responds as a single volume during the initial pressure rise.
- Study the effectiveness of the dampers and foils in creating effective circulation patterns within the containment.
- Study the effectiveness of the passive heat sinks to terminate the pressure rise and reduce containment pressure.

On behalf of the NRC, VTT Technical Research Centre of Finland (VTT) performed a set of containment calculations for the U.S. EPR using the APROS computer code. APROS is capable of describing a reactor using a multi-node simulation similar to the GOTHIC code used by the applicant and the MELCOR code used by the staff (reference NUREG/CR-6119, "MELCOR Computer Code Manuals," Version 1.8.3, Volumes 1 and 2). Heat and mass transfer to the containment internal structures is calculated using a realistic simulation based on natural circulation heat transfer correlations and condensation determined from the heat/mass transfer analogy. The APROS realistic approach is similar to the diffusion layer model programmed into the GOTHIC code and to the heat/mass transfer package in the MELCOR code. VTT describes this model as a realistic approach. The APROS realistic approach is similar to the diffusion layer model (DLM) programmed into the GOTHIC code and to the heat/mass transfer package in the MELCOR code. The purpose of the APROS study was development of a computer model that can predict flow distribution, flow mixing, and heat transfer in the containment following design basis accidents. Explicit representation of the CONVECT system in the model was a prerequisite. Sensitivity studies were run to evaluate the effectiveness of the foils and mixing dampers, opening of doors within the containment, the effect of heat transfer assumptions, and the effect of the elevation of the break. Two different APROS nodalization schemes were developed: a single-node model and a 41 cell multi-node model. Two different accident scenarios were analyzed: (1) a large-break LOCA and (2) a main steam line break. The results were measured in terms of peak containment pressure and peak containment temperature. The discussion below, typically, addresses observed changes in containment pressure. It should be understood that similar changes occur in containment temperature.

In the sensitivity analysis, a double-ended break in the cold leg pump suction line was assumed. A number of useful insights were gained from the studies:

- The foils burst in all four steam generator compartments in less than a second, and the mixing dampers opened within a few seconds. 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 100 seconds, the pressures equalized, and local flows subsided. Nevertheless, certain flow patterns continued. The pressurizer compartment (and possibly some equipment compartments) is an exception. Mixing in the pressurizer compartment was limited. There are no foils in the ceiling of the pressurizer compartment. For US certification the applicant has added safety-related vents (doors) to the pressurizer compartment in event of an internal piping rupture which will equalize pressure and promote mixing.

- The beginning of hot leg injection had a very pronounced effect on the containment response. The rising containment pressure and temperature were almost immediately terminated in the APROS calculations. Before the start of hot leg injection, containment pressure and temperature were rising. Containment pressure dropped quickly after hot leg injection.

- The time history of the analyzed LOCA shows two pressure and temperature peaks. The first peak is determined by the energy stored in the primary coolant that blows into the containment during the first 40 seconds. This energy is well defined by stored energy in the RCS. The second peak occurs later, at the time when hot leg safety injection starts. The second peak depends on when hot leg injection is initiated.

- Studies done with additional doors opening showed flow patterns changing and more mixing. Both the first and second pressure peaks were reduced, as well as peak temperatures as compared to the assumption that the doors did not open.

- The APROS calculations indicate that should the dampers fail to open, containment pressure and temperature would increase by approximately 55.2 kPa (8 psi) and 13.9 °C (25 °F), respectively.

The assumed LOCA break location was at a low elevation in the containment. An additional case was run placing the break arbitrarily in the top node of the steam generator compartment. The result was an increase (more than 68.9 kPa (10 psi)) in containment pressure. These results led the staff to examine main steam line breaks (MSLB) which could occur at higher elevations. Thermal stratification was observed in several nodes. It was the most pronounced between the dome and the lower levels of the service space. The higher the break location was, the stronger the stratification became. Accumulation of non-condensables (air, nitrogen gas) was observed in the lower nodes of the service space. The presence of non-condensables reduces condensation on the walls.

Two MSLB confirmatory calculations were performed. A double-ended break was postulated at the highest point of the steam lines within the containment dome. The same 41-node APROS model developed for LOCA analysis was used for the steam line break cases. The CONVECT system was explicitly represented. All doors were assumed to stay closed. The purpose of the APROS MSLB calculations was to gain an understanding of flow distribution, flow mixing, and heat transfer in the containment, to see if thermal stratification would occur, and to evaluate the effectiveness of the CONVECT system.

The following observations were gained:

- The foils ruptured within the first second of the calculations. The mixing dampers were opened in approximately one second.

- During the short term (up to 100 seconds) superheated steam was released into the dome, the warm steam remained in the dome. Some of the air from the dome was pushed down 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 became even stronger later 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 downward into the lower portion of the containment.

- The single-node representation of the dome region in the APROS model prevented both circulation and stratification in the dome. With the dome being a large volume, the expectation is that stratification will occur in the dome. A more detailed modeling of the dome is needed to study this phenomenon. (Such detail for the dome is provided in the applicant's GOTHIC containment model.)

- Containment pressure peaked around 70 seconds, then started to decrease slowly. Later in the transient the structures were heated, condensation decreased, and a second pressure peak was observed, smaller than the initial peak.

- The CONVECT system opened to produce relatively uniform containment pressures. The CONVECT system was less effective in setting up circulation patterns between the containment equipment space and the service area which would act to reduce stratification. Circulation was affected by the elevated location of the steam line break within the Containment Building.

- 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).

Using the input from the VTT 41 node APROS model, the NRC staff developed an equivalent input for use with the MELCOR containment analysis code (reference NUREG/CR-6119). The staff first benchmarked the MELCOR model against the APROS results for the postulated DEG-CLPS. Similar results to those from APROS were obtained. The staff next compared the predictions of the 41 MELCOR model with the applicant's GOTHIC predictions for the same postulated accident. Similar results to those of the applicant were obtained showing the applicant's multi-node GOTHIC model to be conservative in predicting both peak containment temperature and pressure for the postulated DEG-CLPS break. The consistency of results between the applicant's GOTHIC model, and the independently developed APROS and MELCOR models gives confidence in the representative nature of the result and independent of the computer code used.

To investigate possible uncertainty in the prediction of loss coefficients in the applicant's model, the staff repeated the MELCOR MSLB calculation using twice the flow resistance for the dampers determined by the applicant. The increase in flow loss was found to have an insignificant effect on the calculated pressure or temperature. In a similar manner, the staff investigated the effect of flow area into the service space. For the sensitivity analysis, the staff reduced the flow area in the 41-node MELCOR model between the containment dome and the service space by a factor of two. The decrease in flow area was found to have an insignificant effect on the calculated pressure or temperature.

The staff developed a second MELCOR model based on the applicant's 30-node GOTHIC input. Results from this model indicated that the applicant's evaluations using GOTHIC are conservative for the postulated DEG-CLPS large-break LOCA analyses in comparison with the MELCOR prediction. The staff noted that the applicant described the vertical circulation path in the service space using vertical stacks that were only three nodes high. The staff was concerned that additional noding detail would be needed in the service space in order to properly evaluate thermal stratification which might occur following a piping rupture. By studying containment drawings and compartment design information, the staff developed a 42-node MELCOR model with additional noding detail in the middle region of the service space. Basically, the middle service space node was split into four nodes on one side of the containment and into eight nodes on the other side of the containment. The revised model was used to evaluate the DEG-CLPS break. This break was selected, since it provides an elevated long-term steam source to the containment and thus might be more affected by containment atmospheric stratification. The result was that containment peak pressure was little affected by the additional noding. The peak pressure calculated by both the 30- and the 42-node MELCOR models remained below that calculated by the applicant for the U.S. EPR using GOTHIC.

Severe Accidents

Finland

The Finnish Regulatory Authority completed a series of studies that used both computational fluid dynamics and lumped parameter models to evaluate severe accidents. One goal of the studies was to determine efficiency of mixing in the containment and efficiency of recombiners in reducing hydrogen concentration. MELCOR is a lumped parameter code used for reactor and containment analysis. FLUENT is a general purpose CFD-code, which has been modified by VTT to include the physical models needed in containment analysis. Although lumped parameter models can predict mixing, CFD models are much better suited for accurately predicting mixing. The work of STUK permits the comparison of the results from these two tools and provides some very interesting conclusions.

The studies included a small break LOCA on the top of the pressurizer. The accident scenario was a 45.6 cm^2 break at the top of the pressurizer with failure of the emergency core cooling pumps and containment spray, but with successful partial and fast secondary cooldown and emergency feedwater operation. The results indicated that the hydrogen concentration in the different rooms is very similar, which indicates that MELCOR predicts good mixing of the containment atmosphere. The exception is the dead-end (a room with just one opening) spreading room, which has a more stable hydrogen concentration. The results also indicated that the mixing of the containment atmosphere appears to be quite good, when the rupture foils on top of the steam generator room and mixing damper doors between the annular and pool domains operate as planned.

Fluent simulations giving a more detailed spatial distribution of hydrogen suggests that burning in the pressurizer zone might not be possible. The first long prevailing steam release has reduced oxygen concentration practically to zero in the room around the leak at the top of the pressurizer and in the room below that. In the lower parts of pressurizer zone there is still oxygen, but hydrogen does not essentially spread into the bottom of the domain. There is no flow route through those rooms (the doors in this room were not modeled to open). Due to separation of oxygen and hydrogen the recombiners in the pressurizer zone are not effective in this case.

In the steam generator rooms the recombiners at the lower levels start to operate only when recirculation through the hydrogen dampers brings hydrogen to them. This follows from the stratified conditions in the domain. The established recirculation brings cool mixture through the hydrogen dampers before hydrogen is released. Due to stratification, Fluent simulations show higher hydrogen concentration than MELCOR at the top of the steam generator room, between 4 and 8 %, even higher during release peaks. In the lower part the concentration stays mainly below 4%. In the dome area mixing is very efficient due to natural convection caused by cooling structures. In this area the general hydrogen level reaches hardly 4 % in other areas than in the plumes rising from the steam generator rooms. In general, the trends are the same in both simulations showing quite efficient mixing and good recombiner performance. Recombiners seem to reduce the hydrogen level below 4 % within 3 hours in this case.

Another comparison was done with a small break LOCA and a LOOP. The case has been simulated with both recombiners being credited and without the recombiners being credited. In both cases the mixing of the containment atmosphere appears to be quite good, when the rupture foils on top of the steam generator room and mixing damper doors between the annular and pool domains operate as planned. The results show that there are differences in concentrations during release peaks but quite soon the atmosphere is well mixed. Both simulations show that hydrogen released will be mixed quite efficiently around the containment.

USA

The NRC also conducted severe accident confirmatory calculations. The NRC confirmatory analysis was based on MELCOR 1.8.6. Although the scenarios were different and the quantities of hydrogen produced are quite different, the results showed that most compartments are well mixed. For US certification the US EPR AREVA MAAP analysis also shows well mixed hydrogen concentrations. The congruity of results using different tools and studying different events all showed relatively good mixing in containment.

France

In 2009, IRSN performed studies to assess the efficiency of the CONVECT system to mix the containment atmosphere in case of severe accidents. For this purpose, several configurations were considered to investigate the effect of opening failure on gas mixing.

For this evaluation, IRSN used both lumped parameter code (ASTEC/CPA) and CFD code (TONUS). ASTEC/CPA was used during the water/steam release phase to evaluate the pressure, the steam/air distribution and also the wall temperature profiles. Then, these data have been transmitted to TONUS code in order to simulate the H_2 release phase. So, local values have been produced to evaluate the containment atmosphere mixing during H_2 release phase.

Two kinds of scenarios were selected for these studies, small-break LOCA (SB LOCA) in cold leg 2 with and without core reflooding. It was observed by prior assessments that, for transients with low mass and energy released (MER) in the containment such as SB LOCA, only a few rupture foils opened even on the break side. Indeed, upon opening of the first rupture foils, the containment pressure difference might be cancelled and no further rupture foils would open. In consequence, the assumption that all rupture foils remains closed was considered.

The SB LOCA without core reflooding was a 20 cm^2 in cold leg 2 with the failure of the safety injection and containment spray systems. The partial and fast secondary cool down and the emergency feed water system were operating.

During the core degradation phase, hydrogen was almost totally released at the break. In consequence, the following cases were studied:

- Case 1: Normal configuration where convection foils and mixing dampers are assumed to open within the criteria,
- Case 2: All convection foils on the opposite side of the break remain closed. This configuration is considered to evaluate the effect of opening failure of convection foils located in the opposite side,
- Case 3: Case 2 + all mixing dampers on the opposite side of the break remain closed. This configuration is considered to evaluate the effect of opening failure of convection foils and mixing dampers located in the opposite side,
- Case 4: All rupture foils are simulated to behave like convection foils. This configuration is considered to evaluate the benefit of substituting rupture foils by convection foils.

The SB LOCA with core reflooding was a 20 cm^2 break in cold leg 2 with the failure of the safety injection and containment spray systems. The partial secondary cool down (no fast secondary cool down) and the emergency feed-water system were operating. The opening of the dedicated depressurization valve was delayed, leading to accumulators discharge on damaged core.
During the core degradation phase, hydrogen was released at three different locations: the break and the lower part of pump rooms 2 and 3 by the pressurizer relief tank (PRT). In consequence, the following cases were studied:

- Case 1: Normal configuration where convection foils and mixing dampers are assumed to open within the criteria,
- Case 2: All mixing dampers on the opposite side of the break remain closed,
- Case 3: All rupture foils are simulated to behave like convection foils,
- Case 4: Opening of 180 m^2 at the top of the steam generators (SG) compartments. This configuration is considered to evaluate the impact of the two-room concept.

For this scenario, the convection foils failure is very unlikely in comparison with the previous scenario due to the various locations of steam and hydrogen release.

According to ASTEC calculations, hydrogen release begins about 40 h after the start of the accident for the SBLOCA without reflooding and 2 h after the start of the accident for the SBLOCA with reflooding. The total hydrogen mass released in the containment for both scenarios is close to 980 kg for the scenario without reflooding and to 870 kg for the scenario with reflooding. But the kinetic of the hydrogen release is much faster for the scenario with reflooding, 1000 s versus 10000 s. Therefore, for the scenario with reflooding, the impact of recombiners is less significant and the hydrogen mass in the containment is instantaneously more important.

There were different containment release stages:

- water and steam releases at the beginning of the accident (high MER),
- steam release between the beginning of the accident and the beginning of the core uncovering (low MER),

- hydrogen and steam releases at the beginning of the severe accident (high MER),
- steam release after the hydrogen release (low MER).

The opening of the mixing dampers and the convection foils leads to some effective convection flows within the containment. The difference of the release locations for both scenarios and the different CONVECT system failures considered have an impact on these flow patterns.

Convection flows for both scenarios:

- from SG1 and SG2 compartments (break side) to the dome;
- from the dome to the lower part of the equipment rooms through the mixing dampers,
- from SG3 and SG4 compartments (opposite side of the break) to the dome during low MER in the containment (between the beginning of the accident and the beginning of the core uncovering and after the hydrogen release).

Convection flows for the scenario SBLOCA without reflooding:

- from the dome to SG3 and SG4 compartments (opposite side of the break) during high MER in the containment. This local convection flow in cases 2 and 3 does not exist because of unavailability of the convection foils in SG3 and SG4 compartments;

Convection flows for the scenario SBLOCA with reflooding:

- from SG3 and SG4 compartments (opposite side of the break) to the dome during high MER in the containment, except at the beginning of the severe accident in case 4, One room containment design, where these convection flow paths are different, from the dome to SG4 compartment and from SG3 compartment to the dome.

TONUS showed hydrogen stratification for both equipment rooms and accessible rooms:

- hydrogen concentrations are higher at the top of the steam generator rooms than at the lower parts;
- hydrogen concentrations are higher in the dome than at the lower levels of the accessible area.

For the scenario SB LOCA without core reflooding, there is a good mixing of the containment atmosphere for all cases, even if for the cases 2 and 3 considering postulated partial failures of the CONVECT system, the hydrogen local concentrations are slightly higher. In addition, the kinetic of the hydrogen release of this scenario is not very high, so the recombiners are efficient. Furthermore, the local hydrogen concentrations would not lead to a risk of flame acceleration.

For the scenario SB LOCA with reflooding, the kinetic of the hydrogen release is very high. Despite of a good mixing in the containment, the assessment results show that high hydrogen local concentrations at the top of the steam generator compartments and in the dome during a short period of time, between 5 and 10 minutes are observed. So, during this short period of time, the analysis shows that there is a risk of flame acceleration. The CONVECT system has no influence on this phase because even in the case 4 with an opening of 180 m^2 at the top of the SG compartments, there is a risk of flame acceleration.

In conclusion, for both scenarios and in spite of postulated partial failures taking into account, IRSN deems the CONVECT system effective.