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MDEP Design-Specific Common Position CP-EPRWG-06

COMMON POSITION ON EPR BORON DILUTION DURING A SMALL BREAK LOSS OF COOLANT ACCIDENT (SBLOCA)

Participation

Regulators involved in the MDEP working group discussions:	NNSA (China), STUK (Finland), ASN (France), SSM (Sweden), ONR (UK)
Regulators which support the present common position:	NNSA (China), STUK (Finland), ASN (France), SSM (Sweden), ONR (UK)
Regulators with no objection:	AERB (India)
Regulators which disagree:	

PURPOSE OF THE COMMON POSITION

The potential for rapid reactivity insertion due to inherent boron dilution resulting from a Small Break Loss of Coolant Accident (SB-LOCA) is of significant safety importance. The aim of this paper is to represent the common position developed by the participating regulators to ensure consistency in the assessment of this aspect of the design. This will also enable appropriate representation of work carried out by the EPR design supporting the safety submissions to address this issue.

COMMON POSITION

The participating countries consider that the potential rapid reactivity insertion due to inherent boron dilution resulting from a SB-LOCA is of significant safety importance. The analysis of relevant phenomena such as mixing in the reactor downcomer and lower plenum, loop seal clearance and the initiation of natural circulation post LOCA are of importance in predicting the behaviour of core reactivity, and demonstration of an adequate safety margin to re-criticality in such accidents.

The participating countries have therefore performed independent confirmatory analysis to develop a view on the adequacy of the safety justification supporting the EPR design for the relevant phenomena post LOCA.

The regulators consider that the safety submissions supporting the EPR design include adequate substantiation of the claimed safety margins in inherent boron dilution scenario following a LOCA. This is based on calculations performed with thermal-hydraulic systems codes, supported by experimental results from a number of Primär Kreislauf (PKL) tests and additional analysis using 3-D modelling codes to evaluate the extent of mixing.

Given the importance of experimental validation for boron dilution analyses, the participating countries consider that it would be beneficial to perform additional uncertainty evaluation in the light of results from the PKL experiments to demonstrate that the EPR design has adequate safety margin to recriticality in such conditions. However, in Finland and France, further work is not anticipated as sufficient justification has been provided by the licensees.

INTRODUCTION AND BACKGROUND

The EPR reactor coolant system contains boric acid at a concentration that maintains the core subcritical with all but the highest worth control rod inserted in the core, known as the critical boron concentration, following a loss of coolant accident. The required boron concentration varies with time during an operating cycle which is due to changes in the fuel reactivity through the cycle. During an SB-LOCA event, deborated water could accumulate due to the condensation of steam in the Steam Generator (SG) tubes and be transported to the Reactor Pressure Vessel (RPV) and core when natural circulation is restored, potentially causing re-criticality leading to fuel damage. This event is typically referred to as inherent boron dilution.

There is a narrow range of break sizes in the SB-LOCA spectrum which are susceptible to this event. Breaks smaller than this range do not interrupt natural circulation and, therefore, do not lead to the accumulation of deborated water in cross over legs. Those larger than this range depressurise quickly such that the secondary side of the SGs become a heat source to the primary system. Even if heat transfer is re-established to the SGs after they are depressurised, the break is too large for the Low Head Safety Injection (LHSI) to refill the loops and restart natural circulation.

EPR DESIGN APPROACH TO BORON DILUTION

FRAMATOME/AREVA's approach used to analyse an inherent boron dilution transient is based on a three step methodology, complemented by experimental considerations:

1. System code analyses are performed to represent a LOCA boron dilution transient;
2. Corresponding 3D Computational Fluid Dynamics (CFD) thermal-hydraulic simulations are performed, modelling injection of the deborated slug following natural circulation restart. The integral tests are reported to underpin the CFD analysis. Mixing along cold legs, downcomer and lower plenum are represented in 3D; allowing determination of the boron concentration profile at the core inlet. Some modelling choices for key parameters are based on PKL experimental observations of a natural circulation restart sequence; such as choice of loop(s) in which natural circulation occurs, mass flow rate temporal evolution and the deborated slug volume; and
3. Comparison of the risk of the lowest value of the predicted boron concentration and the critical boron concentration, to evaluate potential return to criticality.

DEBORATED WATER SLUGS DISCHARGED SEPARATELY FROM DIFFERENT LOOPS

In the frame of an OECD/NEA Primary Coolant Loop Test Facility international program, the PKL tests have been performed (Appendix A) to evaluate deborated water slug formation and transportation. The results demonstrated the absence of accumulation of highly deborated liquid in the SG inlet plenum, and the transport of boron from the hot side to the cold side of SG-tubes during the refilling phase preceding the restart of natural circulation. On the other hand, the accumulation of deborated water in the SG outlet plenum and cross over leg could lead to the formation of deborated slugs. The refill of the Reactor Coolant System (RCS) results in a phase of intermittent flow followed by the resumption of continuous natural circulation. The risk of potential recriticality is likely to occur following restart of natural circulation, as this transports the deborated water towards the reactor core.

The tests concluded that natural circulation occurs in different loops at different times due to the inherent asymmetries between each SG, and due to the individual refill processes of each loop. Therefore, it is concluded by the designers that only the volume of one loop of deborated water discharge needs to be evaluated.

Moreover, based on PKL test results, the slug volume considered is limited to the volume of the SG outlet plenum and cross over leg. The analysis of temporal evolution of mass flow rate during the restart of natural circulation is scaled from the PKL experimental results to the EPR design.

SUPPORTING SYSTEM ANALYSIS

Thermal-hydraulic aspects of boron dilution, with the exception of the mixing effects, have been analysed using system codes such as CATHARE and S-RELAP5. The CATHARE system analysis code is used to determine the penalising break size and to define boundary and initial conditions for the injection of the deborated slug. AREVA and EDF acknowledge the limitations in the CATHARE modelling, which cannot assess other key parameters of the transient, such as slug size or natural circulation mass flow rate in two phase condition. The detail of analysis supporting the safety submissions of the site specific design is presented in Section 5.

CFD MIXING EVALUATION AND VALIDATION

The transport phase and the mixing that occurs in the cold leg, downcomer, and lower plenum during the transport are evaluated with CFD analyses by AREVA and EDF. CFD analysis tools are increasingly being used as an effective tool for predicting three-dimensional mixing flows, but the applied numerical methods and turbulence models require experimental validation with detailed local resolution of flow and temperature fields. The JULIETTE boron dilution tests provide a database for the qualifying of the CFD model at mock-up scale. The JULIETTE test facility is fully representative of the EPR reactor vessel internals at a 1:5 scale. The EPR CFD model for evaluating the transport of a deborated slug and determining the minimum boron concentration at the core inlet is based on the qualified mock-up scale CFD model.

REGULATORY BASIS AND SUPPORTING ANALYSIS

The regulators consider that in the narrow range of break sizes in the SB-LOCA spectrum which are susceptible to the inherent boron dilution, further investigations are necessary to justify the safety claims and have therefore, where appropriate, conducted independent confirmatory analysis. The following subsections provide the regulatory basis of the participating countries.

China

1. NNSA has issued the Safety Standards on Design Safety of Nuclear Power Plants (HAF 102-2016). In this Guide, Section 6.1.3.4 notes that "*The maximum degree of positive reactivity and its rate of increase by insertion in operational states and accident conditions not involving degradation of the reactor core shall be limited or compensated for, to prevent any resultant failure of the pressure boundary of the reactor coolant systems, to maintain the capability for cooling and to prevent any significant damage to the reactor core.*"

2. Within the Taishan plant design, all the LOCA accidents are calculated by the CATHARE code. This code has been qualified by many tests, and the application of the code for Taishan EPR is accepted in principle.

3. Taishan has submitted the qualification report named "CFD simulation of the Juliette tests model qualification based on flow distribution, velocity fields, pressure fields and temperature distribution". It is noted that the CFD code (STAR-CD V3.2) has been validated against the results from the JULIETTE test facility.

4. For the inherent boron dilution during SIB-LOCA, NNSA/NSC will pay close attention to the conclusions of the assessments from other countries. If necessary, NNSA/NSC will undertake research on this issue.

Finland

1. In STUK's Regulatory Guides on Nuclear Safety (YVL) Guide B.3 there is general requirement (601), that "*In the analyses of anticipated operational occurrences, postulated accidents and design extension conditions, it shall be shown that the reactor can be shut down and maintained in shutdown state, and that the plant can be brought to a controlled state and, thereafter, to a safe state. In addition, it shall be shown that the plant can, in the long term, be brought to a state where fuel removal from the reactor is possible.*"

2. In Guide B.4 a shutdown reactor is defined as: "*Shut down reactor shall refer to a reactor in a subcritical state with an effective multiplication factor, taking uncertainties into consideration, of less than 0.995*".

3. The safety submissions supporting plant performance covering postulated LOCA scenarios in OL3 plant design are calculated with the CATHARE V2.5 and STAR-CD computer codes. To determine the boundary conditions for the CFD analyses, five SB-LOCA cases are analysed using the thermal hydraulic code CATHARE. The resulting initial and boundary conditions were then introduced into the STAR-CD model to calculate the boron mixing after restart of Natural Circulation (NC).

4. Confirmatory analyses have been performed by VTT (APROS code) and by PSI using the STAR-CD CFD code. It is noted that the CFD code (STAR-CD) has been validated against results from the JULIETTE test facility.

5. During review of OL3 operating license application, STUK requested additional justification as to why PKL test experiments can be extended to the EPR plants. On the basis of responses from AREVA/TVO and updated analyses, STUK concluded that inherent boron dilution safety demonstration is achieved for the EPR reactor.

France

1. ASN has issued two letters (both in 2015) to EDF on this aspect of the design, one for the operating reactors and the other for the EPR Flamanville 3 (FA3) project. Both requested EDF to study the consequences on core reactivity and fuel behaviour of a deborated water slug passing through the core and, in the case that these consequences would prove unacceptable;

   a. To study advantages and disadvantages of possible modifications to the plant that could exclude this situation or limit its consequences to an acceptable level for the operating reactors;

   b. To make technical and operating provisions whose performance and reliability shall allow consideration of this type of situation, which result in its exclusion for the EPR design.

2. CATHARE V2.5 thermal-hydraulic system code is used in the AREVA/EDF approach for the EPR FA3 design to evaluate the plant thermal-hydraulic behaviour during the post-LOCA period during which boron dilution can occur, and to determine penalizing break sizes and initial and boundary conditions of the CFD simulation. Generally, the system characteristics (pressure, temperature, flow rates etc.) and the depletion and refill characteristics of the transient are well captured by system codes. However, some models of the code need more validation such as: critical flow rate of the break and modelling of generic EPR SG design. These models are important in AREVA's approach.

3. In addition, the French regulator recognises that the CFD codes are increasingly being used as a tool for calculating 3D mixing flows, but numerical methods and turbulence models require extensive dedicated validation with detailed local instrumentation (for flow and temperature profile prediction). Validation of CFD code (STAR-CD) modelling used for EPR simulation is based on JULIETTE experimental test simulations. For the inherent boron dilution tests, the JULIETTE test loop is modified in order to allow the representation of flow from the safety injection system and the release of a large slug. However, some key phenomena are not represented in these tests; such as density effects introduced by a deborated slug at saturation temperature, injection of the slug in a loop without Emergency Core Cooling System (ECCS) and some modelling choices differ (eg. modelling of the core, mesh refinement, etc.).

4. These limitations raise doubts about the validation of the models used in full scale reactor simulations. Generally speaking, uncertainties of CFD calculations are not quantified. Moreover, the conservatism of the initial conditions (based on CATHARE results), of slug volume and NC restart sequence (based on

a direct transposition of PKL results to the EPR reactor case) is not established. This is why, in the CFD simulation used to derive the boron concentration at the entrance of the core, there is no demonstration that the worst hypothesis have been identified and taken into account.

5. Therefore ASN asked AREVA/EDF to evaluate the potential damage to the reactor core and fuel rods that may be caused by inherent boron dilution, according to key parameter choices. To be conclusive on slug volume and NC restart sequence choices, AREVA/EDF performed additional sensitivities. Following ASN/IRSN request, AREVA/EDF studied simultaneous injection of two 25 m^3 deborated slugs (corresponding to loop seals plus ½ SG volumes) with conservative mass flow for NC restart. CFD evaluation is completed by coupled thermal-hydraulic/neutronic analysis (with best estimate assumptions but considering one control rod out of the reactor core, with sensitivity studies on this parameter to find the most penalizing configuration) and best estimate fuel thermal-mechanics analysis. For this scenario with a large slug volume, prompt criticality occurs but without damage to the fuel, even with these penalizing hypotheses.

6. The main issue was the direct transposition of PKL test results to define modelling choices for key parameters. The recent assessment performed by AREVA/EDF demonstrated that there is no damage on reactor core and fuel assemblies, even assuming penalizing values for key parameters. On that basis, it has been possible to conclude that inherent boron dilution safety demonstration is achieved for the EPR reactor.

Sweden

1. In Swedish Radiation Safety Authority (SSM) Regulatory Code, SSMFS 2008:17 The Swedish Radiation Safety Authority's Regulations concerning the Design and Construction of Nuclear Power Reactors there is a general requirement *"Section 8 It shall be possible in all events up to and including the event class highly improbable events to achieve a stable end state with a water covered core/core melt and established residual heat removal. It shall be possible to cool a molten core over an extended period of time."*

2. The same regulatory code states in Section 18: *"It shall normally be possible to control and monitor the nuclear power reactor from the main control room during all operational states, and it shall be possible to take measures from the main control room to bring the reactor to a safe state and to keep the reactor in this state during all events up to and including the event class improbable events".*

3. Safe State is defined in SSMFS 2008:1 The Swedish Radiation Safety Authority's Regulations concerning Safety in Nuclear Facilities, Chapter 1. Application and definitions: *"safe state: An operating state that minimises the risk of a radiological accident. For a nuclear power reactor, the following normally applies: assured sub-criticality and a temperature below 100 degrees Celsius in the reactor pressure vessel"*.

4. It is to be noted that at this stage, SSM has not reviewed any formal application based on the EPR design. Consideration may be given to performing relevant confirmatory analysis in the future, if appropriate.

UK

1. During the Office for Nuclear Regulation's (ONR) Fault Studies Generic Design Assessment (GDA) of the EPR design, it became apparent that EDF and AREVA had not provided a comprehensive Safety Case for heterogeneous boron dilution faults within the Pre-Construction Safety Report (PCSR). A GDA Issue was therefore raised requiring the designers to provide design basis analysis for external dilution and a safety case for inherent boron dilution faults.

2. In response EDF and AREVA provided a safety case for inherent boron dilution following a LOCA based on calculations performed with the CATHARE 2 thermal-hydraulic systems code supported by experimental results from a number of PKL tests, and additional analyses using the STAR-CD CFD code supported by experimental results from the JULIETTE test rig.

3. In its review of the PKL test data, ONR identified that whilst a number of tests have been performed, it is not clear how prototypic they are for the EPR™. Given the importance of the results, ONR concluded that there is a need for formal Phenomenon Identification and Ranking Table (PIRT) analysis and scaling analysis of the PKL test rig. This is to demonstrate that the results and conclusions from the PKL experiments are applicable to the EPR™ design. For this reason, ONR in its assessment of the EPR™ design raised a number of findings, requesting the Licensee to provide a PIRT and scaling analysis of the PKL test rig to justify the adequacy of the approach. It was also concluded that depending on the results of this analysis there may be a need for further experimental tests to be performed to more accurately represent the EPR™ design.

4. ONR have however concluded that overall results from PKL testing are encouraging; suggesting that, due to stratification in the upper part of the downcomer, significant mixing occurs before the deborated slug enters the core inlet. This is irrespective of whether it is associated with a loop in which the safety injection is assumed to have failed.

5. Further details on PKL are presented in Appendix A.

6. In addition, ONR as part of its assessment of the EDF and AREVA response to this issue, commissioned a review of the CATHARE 2 system code analysis for the SBLOCA case. The ATHLET thermal hydraulic system code was employed for confirmatory analysis to identify the most onerous conditions in terms of break size for an inherent heterogeneous boron dilution fault.

7. The results demonstrate that the thermal hydraulic system codes have difficulty in accurately predicting the size of deborated slugs that can be produced in accident conditions. As such, it was recommended that more weight be placed on the experimental evidence from the PKL test programme.

8. Furthermore, given the complexity of the CFD analysis being used to support the Safety Case for inherent boron dilution following a LOCA, ONR commissioned a set of confirmatory CFD analyses to predict the flow characteristics for the SBLOCA case. The work incorporated refinements in the modelling to reflect the most recent analyses performed by EDF and AREVA.

9. Comparison of the transients demonstrated that the two results were very similar; however, EDF and AREVA simulations showed that less concentrated borated water reached the lower parts of the downcomer than the confirmatory simulations. In the confirmatory analysis, the hot and dilute borated water from the slug temporarily resides in the unaffected cold legs displacing the colder water initially present. This cold water is not displaced in the EDF and AREVA simulations. In view of these differences, an additional Assessment Finding was raised in the close out report relating to this Issue requesting that the Licensee provide further justification and sensitivity assessment of the boundary conditions assumed in the cold leg sections utilised for the CFD modelling of the inherent boron dilution transient analysis studies.

10. The resolution of this finding is the subject of ongoing discussions between UK regulators and the Licensee.

CONCLUSION

During an SB-LOCA event, deborated water can potentially accumulate in the loop seal due to the condensation of steam in the steam generators and be transported to the reactor pressure vessel and core when natural circulation is restored, potentially causing re-criticality which may lead to fuel damage.

The participating countries have therefore performed independent confirmatory analysis to develop a view on the adequacy of the safety justification supporting the EPR design for the relevant phenomena post LOCA.

The regulators consider that the safety submissions supporting the EPR design include adequate substantiation of the claimed safety margins in inherent boron dilution scenario following a LOCA. This is based on calculations performed with a thermal-hydraulic systems code, supported by experimental results from a number of PKL tests and additional analyses using detailed mixing evaluation and CFD codes.

Given the importance of experimental validation for boron dilution analyses, the participating countries consider that it would be beneficial to perform additional uncertainty evaluation in the light of results from the PKL experiments to demonstrate that the EPR design has adequate safety margin in such conditions. However, in Finland and France, further work is not anticipated as sufficient justification has been provided by the licensees.

APPENDIX A

PRIMÄR KREISLAUF (PKL) TEST RESULTS

i. Some major assumptions of the AREVA and EDF approach for inherent boron dilution analysis directly rely upon PKL test results. These cover aspects of plant relating to the absence of accumulation of deborated water in the hot leg or the SG inlet plenum and SG tubes (influencing maximum slug volume), asymmetric restart of natural circulation in different loops (natural circulation restarts first in loops without safety injection), and natural circulation restart mass flow evolution.

ii. PKL is the largest full pressure test facility that may be scaled to model the EPR™. The test facility has been used to simulate LOCA and particularly to study the deborated water slug discharge and boron dilution phenomenon.

iii. The PKL III test rig facility replicates a 1,300 MW Pressurised Water Reactor of the KONVOI design with all elevations scaled 1:1. The scaling factor for diameters is 1:12 and for volumes and power is 1:145. There are differences between the PKL facility and an EPR™ in terms of geometry (scale, height of SG tubes, downcomer, primary pumps etc.). Although the geometry of the KONVOI design is similar to the generic EPR™ design, the capabilities of the safety injection system are not totally prototypic. The KONVOI reactor has a High Head Safety Injection (HHSI) system whereas the EPR™ design has a Medium Head Safety Injection (MHSI) system; and, the injection capacity of the Low Head Safety Injection (LHSI) on the KONVOI is greater than that on the EPR™ design. In addition, the emergency operating procedures for post fault manual cooldown also differ.

This concludes the common position paper "EPR Boron Dilution during a Small Break Loss of Coolant Accident (SBLOCA)" by the participating Regulators.