Multinational Design Evaluation Programme
Design-Specific Technical Report
TR-EPRWG-06

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MDEP Design-Specific Technical Report TR-EPRWG-06

EPR Severe Accidents Technical Expert Subgroup

Technical Report on hydrogen management for EPR

Participation

Regulators/TSOs involved in the MDEP working group discussions:	IRSN (France), STUK (Finland), ONR (UK), NNSA (China)
Regulators which support the present technical report:	IRSN (France), STUK (Finland), ONR (UK), NNSA (China)
Regulators with no objection:	AERB (India)
Regulators which disagree:	none

Multinational Design Evaluation Program

EPR Working Group

EPR Severe Accidents Technical Expert Subgroup

TECHNICAL PAPER ON HYDROGEN MANAGEMENT FOR EPR

1. AIMS OF THE PROGRAMME

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

   1.1. Promote understanding of each country's regulatory decisions and the basis for these decisions;

   1.2. Enhance communication among members and with external stakeholders; and

   1.3. Identify areas where harmonization and convergence of regulations, standards, and guidance can be achieved or improved.

2. INTRODUCTION

2. During the course of a severe accident (SA) in a light water nuclear reactor (LWR), such as the EPR design, large amounts of hydrogen could be generated and released into the containment during reactor core degradation. The released hydrogen may combust or potentially detonate, which could challenge the integrity of containment and could potentially lead to large radioactive release. Additional combustible gases (hydrogen and carbon monoxide) may be released into the containment in case of molten corium/concrete interaction. As observed during the Fukushima Dai-ichi accidents, hydrogen combustion could cause high pressure peaks challenging the reactor containments and potentially leading to the failure of surrounding buildings.

3. Hydrogen combustion may also be a safety concern in case of fuel degradation in spent fuel storage areas, where flammable conditions may be reached if adequate ventilation is not provided. In such areas, the hydrogen combustion may lead to the dispersion of radioactive substances into the environment.

4. In a mixture known to be flammable, hydrogen combustion may be triggered by an energy source of less than a millijoule. Consequently, in the presence of electrical power sources or hot surfaces, it is probable that ignition would occur rapidly once the gas mixture enters the flammability domain.

5. In contrast, a much larger energy source (at least several kilojoules) is required to trigger direct (blast) detonation. This explains why direct detonation may be ruled out for practical purposes and the mechanism considered most likely to initiate a detonation is flame

acceleration and the deflagration-to-detonation transition (DDT). Theorised to be due to hydrodynamic instabilities and turbulence (primarily caused by obstacles in the path of the flame front), an initially laminar deflagration (with a subsonic flame velocity) may accelerate. Rapid combustion conditions may also develop, involving rapid deflagration, DDT and detonation. These explosive phenomena pose the biggest threat to the mechanical integrity of the containment and safety components, as they can produce very large, localized dynamic loads.

6. To study the global pressure loads, the Adiabatic Isochoric Complete Combustion (AICC) pressure is considered, and to check the potential for flame acceleration and DDT, experimentally derived criteria are typically used, such as the sigma criterion, which compares the rate of expansion (gas density before non-isochoric combustion divided by the density after this same combustion) with a limiting value derived from a range of experiments.

3. OBJECTIVE OF THIS PAPER

7. The objective of this paper is to identify what is common and what is different between the EPR design proposed in France (Flamanville 3: FA3), Finland (Olkiluoto 3: OL3), UK (Hinkley Point C: HPC) and China (Taishan: TSN) related to hydrogen management, focusing mainly on Hydrogen Passive Autocatalytic Recombiners (PARs). In that goal, IRSN (for EPR FA3), STUK (for EPR OL3), ONR (for EPR HPC) and NNSA (for EPR TSN) have answered the following questions:

    1. What are the regulatory requirements / expectations for hydrogen management?
    2. How many PARs available and how many of those are necessary for EPR safety report calculation?
    3. What is the rationale for PARs implementation?
    4. What is the rationale for Qualification Test?
    5. What is PARs Safety Classification?
    6. Do you use PARs with igniters? If yes, rationale for igniter's location?
    7. Do you consider Hydrogen ignition by PARs in the safety calculation?
    8. What kind of hydrogen monitoring during severe accident?
    9. How is the availability of PARs ensured during the life of the plant (periodic test, inspections, operating limiting conditions)?
    10. What are the protected measures for PARs during plant outage, if any, and what are the checks before restart?
    11. Do the safety calculations take into account availability of PARs during shutdown events?

12. Are there PARs in the spent fuel building? Rationale for having them or not?

8. A summary of the answers is presented below.

4. EPR HYDROGEN MANAGEMENT

9. Regarding the regulatory expectations for hydrogen management, even if formulated differently according to the different safety authorities, all EPR designs have the same objectives: to prevent deflagration or detonation loads that could challenge the integrity of the containment or the operability of the components needed for severe accident management. It has to be pointed out that Finland and China have an additional specific requirement regarding the amount of hydrogen expected to be generated in the containment: it should be estimated on the basis of the assumption of total oxidation of the fuel cladding in China and total oxidation of the “easily oxidising reactor core materials” in Finland when analysing the containment leak tightness. In France, the amount of hydrogen expected to be generated in the containment is predicted by analysis of different severe accident scenarios chosen to design the hydrogen mitigation system: representative scenarios (severe accident discharge valve is opened without delay when core exit temperature reaches 650°C) and extreme scenarios (severe accident discharge valve is opened with delay after reaching core exit temperature of 650°C). In the UK, the amount of hydrogen expected to be generated in the containment is predicted by analysis of different severe accident scenarios chosen to design the hydrogen mitigation system for a worst case scenario. The approaches on the amount of hydrogen expected to be generated in the containment are different between the different countries but ultimately allow all EPR designs to answer the safety objectives described previously.

10. To mitigate the consequences of hydrogen combustion in the containment and to reduce the risk of flame acceleration that could endanger the containment integrity and the safety components operability during a severe accident, the hydrogen risk management on the EPR design utilises Passive Autocatalytic Recombiners (PARs) and the CONVECT system designed to promote gas mixing inside the EPR large free containment volume following accident scenarios.

5. CONVECT SYSTEM

11. 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 the CONVECT system to promote mixing and heat transfer to the containment heat sinks in case of design basis accident and severe accident.

12. 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.

13. 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.

14. 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.

15. 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.

16. According to the MDEP Common Position CP-EPRWG-03 (“Common position on EPR containment mixing” - 16 March 2015), the effectiveness of these features 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. Consequently, the following of this paper will focus on PARs.

6. PASSIVE HYDROGEN AUTOCATALYTIC RECOMBINERS (PARS)

17. Currently only PARs are used, no igniters are included in the design. Igniters are typically active systems needing electricity and in case of active igniter malfunction a delayed spark could be produced when hydrogen is accumulated with high concentration (in a single technology approach). R&D has shown that PARs may also act as igniters over a relatively small area in the hydrogen-air-steam ternary diagram. The recent R&D reviewed PAR behaviour under low oxygen content in prolonged accident conditions, and concluded that PARs will remain operational in such conditions, with reduced efficiency. For the generic EPR design, in safety analysis of hydrogen risk the ignition of hydrogen is assumed to happen at the most penalizing time when the maximum amount of hydrogen is present in the containment or the potential for flame acceleration is highest with the intention of maximising the potential consequences due to fast deflagration. The ignition locations are therefore not typically aligned with the PAR locations, and ignition by PARs is not directly calculated. The effect of increased local thermal loads due to slow hydrogen deflagrations ignited by PARs on the behaviour of equipment and instrumentation needed to manage a severe accident should be considered within the safety case.

18. All the EPR designs include 41 large and 6 small PARs installed in the accessible areas (main operation floor and annular rooms) as well as in the non-accessible areas (steam generator compartments and other equipment rooms). The PARs are distributed throughout the containment to reduce both local concentrations and the global mass of hydrogen and to support atmospheric mixing. The PARs arrangement is supported by various lumped parameters and 3D-code analyses for severe accident scenarios in an iterative way:

- starting with an arrangement based on engineering judgement,
- assessing modification to the arrangement (distribution between equipment cells, dome and annular rooms),
- selecting the best arrangement, and
- performing calculations, both with lumped parameters codes and Computational Fluid Dynamics (CFD) codes for this arrangement to justify the hydrogen mitigation system.

19. Among the principles followed in deciding the locations of PARs are the need to establish good in- and outflow conditions of the PARs (to avoid any decrease of the PARs efficiency) and to be located away from any safety relevant equipment used in severe accident (for example electrical cable trays), such that damage caused by the hot gas from the PARs can be avoided. As an example, qualitative principles followed in deciding the locations of PARs for FA3 are the followings:

- there is no obstacle to gas entrance into PARs nor to gas exit from PARs within a certain distance under a PAR and over a PAR. Typical distance is in the order of the hydraulic diameter of the PAR,
- there is no “easily flammable equipment” within a certain distance from PAR,
- there is no equipment used for SA management within some meters from PARs (except hydrogen monitoring using thermocouples located on PAR).

20. There are currently no PARs proposed for installation within the spent fuel building for the EPR design. The rationale for not including PARs is that fuel melting in spent fuel pool (SFP) is considered as a very low frequency event and preventative measures are included in the design to reduce the risk of fuel uncovery. The EPR design includes a number of features to introduce additional water into the SFP should a loss of water inventory accident occur to prevent fuel uncovery.

21. For EPR FA3 in France and presently EPR HPC in UK, six PARs are each equipped with a single thermocouple located downstream of the PAR outlet. In the Operating Strategies for Severe Accidents (OSSA) (the EPR Severe Accident Management Guide), the temperature of these thermocouples is used to provide only a qualitative indication whether hydrogen recombination is taking place. In contrast, EPR OL3 in Finland and EPR TSN in China have specific hydrogen (and steam) monitoring system designed for severe

accident in different parts of the containment. This system automatically withdraws a micro sample from containment space and analyses its gas composition outside containment. This hydrogen and steam measurement system for severe accident provides indicative information about quantity of released hydrogen, hydrogen concentrations in different containment rooms, and efficiency of the PARs and the CONVECT system. In the OSSA, the hydrogen concentration is taken into account in predicting the potential challenge to the containment integrity. The instrumentations are different between some countries but ultimately allow all EPR designs to answer the main safety objectives.

22. PARs are passive equipment and their effectiveness and availability should be considered in all reactor states where hydrogen is released, including shutdown states. Calculations supporting the safety case using lumped parameter and CFD codes are presented for severe accidents occurring only during power operation and for the generic EPR design and they are performed assuming that all PARs are efficient. For the generic designs, this implies that the majority of PARs are expected to be available during shutdown conditions.

23. However the requirement for the provision of temporary protective measures for PARs during plant outages (such as coverings) and procedures to ensure that these protective measures are removed before restart are not presently known for the different EPR designs. The technical specifications of the plant should then include the unavailability of some PARs in outage states consistently with safety justifications based on complementary calculations.

24. For all EPR designs, PARs have the relevant safety classification for all systems designed for severe accident management (safety class F2 for FA3 and TSN, safety class 3 for OL3 and HPC) and are seismically classified.

25. Each outage, a specific number of PARs are subject to periodic tests to ensure that they retain the required performance characteristics. All the PARs are tested after a given number of years: for instance in a cycle of 4 years (for FA3) or 5 years (for OL3). The periodic test is the following:

- a visual inspection of all the plates of the selected PARs,
- testing the normal start up and operation of 3 catalytic sheets.

26. For HPC it is proposed that PARs will be checked for deterioration in performance at maintenance intervals in accordance with the maintenance schedule but the details are not presently known.

27. As regards to R&D, before implementing PARs inside the reactor containment, extensive qualification tests campaigns were performed by the manufacturers of the PARs used in the different EPR designs with the objective of complying with the major design requirements outlined in: E. Bachellerie & al, Generic approach for designing and implementing a passive autocatalytic recombiner PAR-system in nuclear power plant containments, Nuclear Engineering and Design 221 (2003) 151–165. Moreover, the OECD/NEA report entitled “Status Report on Hydrogen Management and Related Computer Codes” [NEA/CSNI/R(2014)8] indicates the recent investigation regarding PARs performance.

7. CONCLUSIONS

28. To mitigate the consequences of hydrogen combustion in the containment and to reduce the risk of flame acceleration that could endanger the containment integrity and the safety components operability during a severe accident, the hydrogen risk management on the EPR design utilises Passive Autocatalytic Recombiners (PARs) and the CONVECT system designed to promote gas mixing inside the EPR large free containment volume following accident scenarios.

29. 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.

30. PARs are passive equipment and have been subject to extensive qualification tests campaigns and, for all EPR designs. PARs have the relevant safety classification for all systems designed for severe accident management and are seismically classified.

31. Effectiveness and availability of PARs should be considered in all reactor states where hydrogen is released, including shutdown states. It is acknowledged the main purpose of periodic testing of the PARs during EPR outages is to ensure that the PARs retain the required performance characteristics, and it is important to ensure the availability of the PARs by removal of any temporary protective measures.

32. The main differences regarding hydrogen management in the different EPR designs is the hydrogen monitoring system during a severe accident. The instrumentations are different between some countries but ultimately allow all EPR designs to answer the main safety objectives.