Multinational Design Evaluation Programme (MDEP)
Technical Report
TR-VVERWG-05

Related to: **VVER** TESG SA Activities

Technical Report on Hydrogen Recombiners

Participation

Regulators involved in the MDEP working group discussions:	HAEA (Hungary), AERB (India), NNSA (CPR), Rostechnadzor (RF), NDK (Turkey), STUK (Finland)
Regulators which support the present report	HAEA (Hungary), AERB (India), NNSA (CPR), Rostechnadzor (RF), NDK (Turkey), STUK (Finland)
Compatible with existing IAEA related documents:	Yes

1. Introduction

During the process of severe accident in VVER of AES-91 and AES-2006 design, a large amount of hydrogen may be generated by the steam-metal oxidation reaction in the reactor core, and much less amount also by the reactions between molten corium and sacrificial material (MCSMI). The released hydrogen may combust or potentially detonate, which may threaten the integrity of containment and could potentially lead to large radioactive release. Additionally, other kinds of combustible gas, carbon monoxide for example, may also be released in MCSMI.

2. Objective of this paper

The objective of this paper is to identify what is common and what is different in regulatory requirements and utility practice in approach to using PARs in new VVER design. The main topics covered in this paper include:

- Rationale for PARs
- Rationale for location and number of PARs
- Justification of performance
- Safety classification

3. Summary of findings

a. Rationale for PARs

The safety goal of the PARs is to keep the concentration of hydrogen released from the degraded core low enough to prevent any possibility of combustion that would threaten containment integrity. Containment failure due to hydrogen explosion is one of the events that shall be practically eliminated. PARs also prevent failures to the equipment located inside the containment, which might be caused by fast combustion of gaseous hydrogen. As it is mentioned in the IAEA NS-G 1.10, Design of Reactor Containment Systems for Nuclear Power Plants, possible provisions in the design for achieving this goal are, for example, an enhanced natural mixing capability of the containment atmosphere coupled with a sufficiently large free volume, recombiners and igniters suitably distributed in the containment, and inerting (making the atmosphere non-flammable).

b. Rationale for Location and number of PARs

To achieve the mentioned safety goal, the number of the PARs has been derived and verified by an iterative analysis using a severe accident analysis computer code. In some countries there are additional requirements for increasing safety margin, for example considering specified minimal amount of zirconium oxidation in the analyses. All PARs are assumed to be operable in safety analysis calculations, because PARs are passive components and qualified in the severe accident conditions. Additionally, uncertainty calculation is expected to be made in safety analysis, where it is assumed that some PARs are not operable or hydrogen depletion rate reduced during the accident. In practice, the number of PARs depends on the plant design and determined by the designer, and the failure of some PARs are also taken into account.

The PAR locations in the containment are designed based on assessing the mixing of the containment atmosphere. This is done by using computational tools verified and validated for this purpose. In practice, detailed CFD (computational fluid dynamics) models are applied to calculate the local hydrogen concentrations and to verify the adequacy of PARs placement.

The general approach in the new VVER design provides the location of the PARs based on the following aspects:

- proper distribution of the PARs in the containment should be considered in the design,

- locate the PARs in the area where the hydrogen concentration is higher (according to accident analysis),
- the failure of the normal operational systems cannot lead to the failure of the PARs,
- the PARs shall be protected against flying objects/missiles and from the effects of high energy large breaks,
- the PARs shall not have negative effect on other systems located in the localizing area,
- the PARs shall be accessible for maintenance.

As the spent fuel pool in VVER design is located inside the containment, the PARs in the containments are intended for the hydrogen management in the case of severe accident in SFP as well.

c. PAR performance

- The PAR should pass the qualification test to prove the functionality of the PARs at environmental conditions expected in a severe accident.
- The performance of PARs and containment integrity in case of hydrogen and other flammable gases release during the severe accident shall be justified in SAR. The detailed requirements for the justification are varied in member countries.

d. Safety classification

The requirements for PARs safety classification are varied in member countries, however, in practice in all Member States PARs are safety classified at least class 3.

4. Conclusions

In all Member States PARs are used to mitigate the threats from hydrogen and other flammable gas combustion and detonation. All Member States have established requirements for PARs and hydrogen management, and while such requirements differ in some details between Member States, general approach can be considered the same among all Member States. Most notable differences are protecting measures during plant outage, requirements for safety assessment for the shutdown events with limited PARs availability, and requirements for consideration of hydrogen ignition by PARs in safety calculations.

Appendix
Regulatory answers to PAR Questionnaire

1. How many PARs available and how many of those are necessary for safety report calculation?

The number of PARs depends on the plant design, and the technical details are specified by the designer. In practice, for safety analysis the failure of some PARs is taken into account, but it is not mandatory.

Regulatory Criteria, if any

In Finland: The objective of the hydrogen management system is provided in YVL B.6., requirement 341: “The containment structure and systems used for managing accidents shall prevent such gas burns, gas explosions or other energetic phenomena that may jeopardise containment integrity or leaktightness, or the operability of the components needed for accident management.” The next requirement (YVL B.6, 342) elaborates what is required of the system type: they shall be primarily passive and located inside the containment.

In Hungary: 3a.2.2.7400. During design, the accident management functions and the pressure reduction and hydrogen removal systems performing such functions during accidents shall be determined to such an extent that high-pressure processes in events causing fuel melting and early damage to the containment can be avoided.

In Russia: PARs should be able to fulfil their function under severe accident conditions.

In India: [AERB/NPP-LWR/SC/D (SAFETY CODE ON DESIGN OF LIGHT WATER REACTOR BASED NUCLEAR POWER PLANTS)'

"The plant shall be designed so that it can be brought into a controlled state and the containment function can be maintained, with the result that significant radioactive releases would be practically eliminated."

"Containment system shall include features for management and removal of fission products, hydrogen, oxygen, and other substances that may be released into the containment atmosphere."

"The design shall consider containment response for pressure and temperature build-up expected during postulated design extension conditions with core melt. Consideration shall be given to potential for generation and behaviour of inflammable gases like hydrogen."

"Necessary design features shall be provided to control the concentrations of hydrogen, oxygen and other substances in the containment atmosphere in accident conditions so as to prevent deflagration or detonation loads that could challenge the integrity of the containment."

In Turkey: The requirements on PARs are based on the IAEA Guides (NS-G 1.9, 1.10, 2.15 and SSR-2/1) and RF requirements.

In China, general regulatory requirements are in HAF 102 2016 "Safety of nuclear power plants: design" and HAD 102/06 "Design of Reactor Containment Systems". Detail regulatory requirements for the hydrogen assessment are as follows (General Technical Requirements on post-Fukushima Nuclear Accident Improvement Measures for NPPs (Tentative)):

- The hydrogen monitoring system should have the ability to monitor the hydrogen concentration over the whole range under severe accidents and corresponding alarms should be set, so as to confirm the status of the nuclear power plant and provide information as possible as practicable for decision making during the accident management.
- The hydrogen concentration should be less than 10%(V/V), assuming the hydrogen generated from the metal-water reaction involving 100% of the fuel cladding metal in the active fuel region and distributed uniformly in the containment;
- The damage of the integrity of containment by combustion or exploration due to local accumulation of hydrogen should be avoided, and the impact on the functions of severe accident mitigation systems or equipment should be minimized;
- The hydrogen concentration monitoring and controlling measures should be included in severe accident management guide or relevant procedures.

2. Safety Classification, if any

In India: PAR is categorized as Safety Class 3 (AERB Safety Guide on Safety Classification of SSCs is under revision).

In Russia and Turkey: PAR shall be categorized at least safety class 3 and seismic class 2, but in practice in new VVER design it is categorized as safety class 2 and seismic class 1.

In Finland: The safety class of the PARs is 3. The systems designed for severe accident management are assigned to class 3 as provided in YVL Guide B.2, requirement 313, item 2:

"Safety Class 3 shall include systems accomplishing safety functions that…… are designed for severe reactor accident management".

In Hungary: The safety class of the PARs is 3. Additionally, seismic safety class 1.

In China, there are no specific requirements for the safety classification for PARs.

On practice at Tianwan NPPs, the PARs are safety classified as safety class II, and seismic class I.

3. Rationale for Qualification Test, if any

In all Member States the rationale for qualification test is to prove the functionality of the PARs at environmental conditions expected in a severe accident.

Additionally, India has detailed requirements for qualification of recombiners, which are mentioned at the end of the document.

4. Do you use PARs with igniters? If yes, rationale for igniter's location?

In Finland at Loviisa NPP, igniters (glow plugs) are used in addition to PARs. The igniters are located in the steam generator rooms where the hydrogen concentration might increase rapidly in case of water injection into the degrading core. In such conditions, it may be necessary to remove the hydrogen faster (by controlled combustion) than what would be achievable using PARs. Igniters are located in such a geometry that conditions for DDT (deflagration-to-detonation transition) are not possible due to lack of inadequate flame acceleration distance. However, passive systems are the primary means for hydrogen removal in new build power plants.

Igniters are prohibited to use at NPP in Russia (p. 3.4 NP-040-02).

In China, India, Hungary, Turkey and Russia the new VVER units are equipped only by PARs and no igniters foreseen.

5. Do you consider Hydrogen ignition by PARs in the safety calculation?

In Finland according to YVL B.6 requirement 311, the leak-tightness of the containment in severe reactor accidents shall be demonstrated by increasing the maximum gauge pressure in the safety calculations by a 50% margin that takes into account the uncertainty in the calculation, and adding the calculated AICC combustion pressure to this maximum pressure. This result for the maximum pressure during combustion accounts for slow combustion processes inside the containment, and it is usually not required to calculate different scenarios that assume a deflagration caused by a PAR, or some other ignition source. In some calculations evaluating flame acceleration, different assumptions about the point of ignition may be made.

In Russia and Turkey there are no explicit requirements, but there are general requirements (p. 3.1 NP-040-02, for Russia and Turkey and p. 12.2.3.2.5 NP-006-16 and p. 97 NP-010-16 for Russia) to determine mechanical and thermal loads to the containment and other systems caused by hydrogen burn, which assumes inclusion of the hydrogen ignition by PARs.

In China it was not considered up to now. In the future it will be decided on the basis of results received in new experimental program.

In Hungary it is considered, but only in the design extension conditions.

In India although it is not explicitly mentioned in the regulatory requirements, two cases were considered for analysis by the utility; (a) only catalytic recombination to occur and (b) recombination and ignition of hydrogen-steam-air mixture to occur whenever it enters the deflagration region. Also during the review process, utility was asked to perform AICC pressure estimations.

6. How do you get information about Hydrogen concentration in containment?

By using a separate measurement system, which consists of hydrogen detectors in different parts of the containment.

In Finland the measurement system shall be independent, safety classified and tolerant to single failures.

In China (Tianwan NPPs), India and Russia, the hydrogen monitor system has two channels, hydrogen and oxygen concentration can be provided, and relevant equipment is qualified for severe accident conditions.

7. How is the availability of PARs ensured during the life of the plant? (periodic test, inspections, operating limiting conditions)

The periodic tests of PARs are specified in the Operational Limits and Conditions (OLC) by the license applicant / license holder.

In Hungary in VVER-440 and Russia, some of PARs are checked during outage, and based on this test the cleaning and regenerating of the PARs is executed.

In Finland the Operational Limits and Conditions (OLC) include limiting conditions pertaining to the operability of PARs.

8. What are the protected measures for PARs during plant outage, if any, and what are the checks before restart?

The PARs are protected by shielding that prevents the possible impurities in the containment atmosphere from getting into contact with the catalytic plates. License holder is responsible for installing and removing the shielding, as well as checking the PARs operability using appropriate instructions.

In China, there are not special protective measures for PARs during NPP outage.

9. Do the safety calculations take into account availability of PARs during shutdown events?

In Finland the limited availability of PARs and their restoring times are taken into account in the calculation of accident scenarios during shutdown. This is considered important for evaluating containment integrity.

In Russia in practice it is considered only for tight containment.

In Hungary and Turkey there are no requirements regarding to this specific area.

In India safety calculations take into account PARs availability during shutdown events as the time available for restoring the PARs is large enough.

In China Tianwan NPPs, the availability of PARs can be considered since there are no protective measures.

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

The spent fuel pool in new VVERs is part of the containment. Therefore, PARs placed in the containment mitigate the consequences that arise from the spent fuel pool accidents.

List of requirements:

Finland

The containment is required to maintain its leak-tightness in case of 100% oxidation of the easily oxidized materials in the core, and the resulting hydrogen production.

STUK regulation Y/1/2018, Section 10, requires that the containment shall be designed to maintain its integrity during anticipated operational occurrences and, with a high degree of certainty, during all accident conditions, and that combustible gases are considered in its design (among other issues potentially endangering the containment).

Requirements pertaining to hydrogen management are given in

- YVL Guide B.6: requirements 309, 341, 342
- YVL Guide B.3, requirement 427

Requirements concerning severe accident monitoring, power supply and I&C systems are given in YVL Guide B.1 (requirements 5219, 5235a, 5235b, 5235b, 5415, 5426b, 5427a, 5444).

The OLC are reviewed by STUK. A general provision requiring periodic testing programmes of NPP systems, structures and components is given in YVL Guide A.6, requirement 508.

Requirements concerning the cooling of the SFP and the provisions that should be made against external events that might threaten the SFP cooling are given in the Finnish regulations (YVL Guide D.3 requirements 423, 426, 427).

Russia

System used for BDBA management during first 72 hours after the accident shall be categorized at least safety class 3 (p. 2.5, 2.6 NP-001-15), Safety class 3 systems shall be categorized at least seismic class 2 (p. 2.6.2 NP-031-01).

Mechanical and thermal loads to the containment caused by hydrogen burn and measures for the protection of the containment from such loads shall be justified in the SAR (p. 12.2.3.2 NP-006-16)

Mechanical and thermal loads to the containment caused by hydrogen burn shall be justified in the design (p.87 NP-010-16)

Mechanical and thermal loads to the containment caused by hydrogen burn shall be justified in the design (p.3.1 NP-040-02)

There shall be technical measures preventing hydrogen ignition (p. 3.4 NP-040-02)

There shall be measurement system for the hydrogen mixture parameters (p. 3.7 NP-040-02)

Turkey

IAEA NS-G 2.15 Severe Accident Management Programmes for Nuclear Power Plants

3.22. In the mitigatory domain, strategies should be developed to enable:

- Terminating the progress of core damage once it has started;
- Maintaining the integrity of the containment as long as possible;
- Minimizing releases of radioactive material;
- Achieving a long term stable state.

Strategies may be derived from ‘candidate high level actions’, examples of which are given in Appendix II of Ref. [12] (Implementation of Accident Management Programmes in Nuclear Power Plants, Safety Reports Series No. 32, IAEA). Examples of mitigatory strategies are: filling the secondary side of the steam generator to prevent creep rupture of the steam generator tubes; depressurizing the reactor circuit to prevent high pressure reactor vessel failure and direct containment heating; flooding the reactor cavity to prevent or delay vessel failure and subsequent basemat failure; **mitigating the hydrogen concentration**; and depressurizing the containment to prevent its failure by excess pressure or to prevent basemat failure under elevated containment pressure.

IAEA NS-G 1.10, Design of Reactor Containment Systems for Nuclear Power Plants

6.5. For new plants, possible severe accidents should be considered at the design stage of the containment systems. The consideration of severe accidents should be aimed at practically eliminating the following conditions:

- Severe accident conditions that could damage the containment in an early phase as a result of direct containment heating, steam explosion or hydrogen detonation;
- Severe accident conditions that could damage the containment in a late phase as a result of basemat melt-through or containment overpressurization;
- Severe accident conditions with an open containment — notably in shutdown states;
- Severe accident conditions with containment bypass, such as conditions relating to the rupture of a steam generator tube or an interfacing system LOCA.

6.10. For new plants, the integrity and leaktightness of the containment structure should be ensured for those severe accidents that cannot be practically eliminated (para. 6.5). The long term pressurization of the containment should be limited to a pressure below the value corresponding to Level II for structural integrity.

6.22. In a severe accident, a large amount of hydrogen might be released to the atmosphere of the containment, possibly exceeding the ignition limit and jeopardizing the integrity of the containment. In the event of interactions between molten core material and concrete, carbon monoxide might also be released, contributing to the hazard. To assess the need to install special features to control combustible gases, an assessment of the threats to the containment posed by such gases should be made for selected severe accident sequences. The assessment should cover the generation, transport and mixing of combustible gases in the containment, combustion phenomena (diffusion flames, deflagrations and detonations) and the consequent thermal and mechanical loads, and the efficiency of systems for the prevention of accidents and the mitigation of their consequences.

6.23. Uncertainties remain concerning the production of hydrogen during severe accident sequences; these uncertainties are essentially linked to such phenomena as flooding of a partially damaged core at high temperatures, the late phase of core degradation, the slumping of molten core material into residual water in the lower head of the reactor pressure vessel, and the long term interactions between molten core material and concrete. For new plants, these uncertainties should be taken into account in the design and layout of the means of mitigation of the consequences of the combustion or deflagration of hydrogen, and in the design of the containment.

6.24. The efficiency of the means of mitigation of the consequences of combustion or deflagration should be such that the concentrations of hydrogen in the compartments of the containment would at all times be low enough to preclude fast global deflagration or detonation. Possible provisions in the design for achieving this goal are, for example, an enhanced natural mixing capability of the containment atmosphere coupled with a sufficiently large free volume, passive autocatalytic recombiners and/or igniters suitably distributed in the containment, and inerting. For new plants the amount of hydrogen expected to be generated should be estimated on the basis of the assumption of total oxidation of the fuel cladding.

6.25. The leaktightness of the containment for the most representative accident sequences should be ensured with sufficient margins to accommodate severe dynamic phenomena such as a fast local deflagration, if these phenomena cannot be excluded.

6.26. Even in an inerted containment, the concentrations of hydrogen and oxygen generated over a long period of time by water radiolysis may eventually exceed the ignition limit. If this is a possible threat, a hydrogen control system, passive hydrogen recombines or other appropriate systems for mitigation and monitoring (e.g. systems for oxygen control and measurement) should be installed.

6.27. Provision should be made for hydrogen monitoring or sampling. The concentrations of other combustible gases and oxygen should also be monitored.

6.29. During and following a severe accident, in order to follow the general conditions in the containment and to facilitate the use of guidelines for the management of severe accidents, essential parameters for the containment such as pressures, temperatures, hydrogen concentrations, water levels and radiation dose rates should be monitored.

> III–12. The generation and combustion of large volumes of hydrogen and carbon monoxide are severe accident phenomena that can threaten the integrity of the containment. The major cause of the generation of hydrogen is the oxidation of zirconium metal and, to a lesser extent, the interaction of steel or any other metallic component with steam when the metal reaches temperatures well above normal operating temperatures.
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> III–13. In addition, ex-vessel hydrogen generation needs to be considered. Such hydrogen is produced mainly as a result of the reactions of ex-vessel metallic core debris with steam, and in the long term by molten core–concrete interactions (para. III–17) and by the extended radiolysis of sump water.
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> III–15. Under severe accident conditions, significant hydrogen concentrations could be reached locally in a short time (of the order of some minutes to an hour, depending on the containment design, the scenario and the location) and globally in a longer period of time.
>
> III–16. When the ignition limit is exceeded, combustion of hydrogen is possible and can take different forms, depending on the concentrations, the atmospheric conditions in the containment and the geometry: diffusion flames (which are mainly responsible for thermal loads), slow deflagrations (which are mainly responsible for quasi-static pressure loads), fast deflagrations (for which dynamic effects become important) and detonations (for which the velocity of the flame front exceeds the speed of sound in the unburnt gas, giving rise to extremely severe dynamic effects). Depending on the mode of combustion, the integrity of the containment may be threatened by stresses beyond the structural design limits.

IAEA NS-G-1.9 Design of the Reactor Coolant System and Associated Systems in Nuclear Power Plants Safety Guide

3.47. Hydrogen and oxygen generated by the decomposition of H_2O (or D_2O) in the core can dissolve in the water and steam and be carried to any part of the RCS and connected systems. Gases dissolved in steam piping can easily accumulate when steam in a closed off section of piping cools down and condenses into water. A local accumulation of hydrogen gas in the RCS could give rise to the potential for an explosion that could result in severe damage. The design should be such that the possibility of combustible gas accumulation can be excluded.

IAEA SSR-2/1 Safety of Nuclear Power Plants Design

6.29. Design features to control fission products, hydrogen, oxygen and other substances that might be released into the containment shall be provided as necessary:

a) To reduce the amounts of fission products that could be released to the environment in accident conditions;

b) To control the concentrations of hydrogen, oxygen and other substances in the containment atmosphere in accident conditions so as to prevent deflagration or detonation loads that could challenge the integrity of the containment.

IAEA SSR-2/1 Safety of Nuclear Power Plants: Design

Requirement 2: Management system for plant design

The design organization shall establish and implement a management system for ensuring that all safety requirements established for the design of the plant are considered and implemented in all phases of the design process and that they are met in the final design.

3.2. The management system shall include provision for ensuring the quality of the design of each structure, system and component, as well as of the overall design of the nuclear power plant, at all times. This includes the means for identifying and correcting design deficiencies, for checking the adequacy of the design and for controlling design changes.

Requirement 7: Application of defence in depth

The design of a nuclear power plant shall incorporate defence in depth. The levels of defence in depth shall be independent as far as is practicable.

4.11. The design:

(e) Shall provide for systems, structures and components and procedures to control the course of and, as far as practicable, to limit the consequences of failures and deviations from normal operation that exceed the capability of safety systems;

Requirement 16: Postulated initiating events

The design for the nuclear power plant shall apply a systematic approach to identifying a comprehensive set of postulated initiating events such that all foreseeable events with the potential for serious consequences and all foreseeable events with a significant frequency of occurrence are anticipated and are considered in the design.

5.6. The postulated initiating events shall include all foreseeable failures of structures, systems and components of the plant, as well as operating errors and possible failures arising from internal and external hazards, whether in full power, low power or shutdown states.

Requirement 68: Emergency power supply

The emergency power supply at the nuclear power plant shall be capable of supplying the necessary power in anticipated operational occurrences and accident conditions, in the event of the loss of off-site power.

6.43. In the design basis for the emergency power supply at the nuclear power plant, due account shall be taken of the postulated initiating events and the associated safety functions to be performed, to determine the requirements for capability, availability, duration of the required power supply, capacity and continuity.

6.44. The combined means to provide emergency power (such as water, steam or gas turbines, diesel engines or batteries) shall have a reliability and type that are consistent with all the requirements of the safety systems to be supplied with power, and their functional capability shall be testable.

6.45. The design basis for any diesel engine or other prime mover12 that provides an emergency power supply to items important to safety shall include:

a) The capability of the associated fuel oil storage and supply systems to satisfy the demand within the specified time period;

b) The capability of the prime mover to start and to function successfully under all specified conditions and at the required time;

c) Auxiliary systems of the prime mover, such as coolant systems.

Hungary

3a.2.2.8900. It shall be ensured by the appropriate design that:

c) in electric power supply:

ca) independence from external supply shall be ensured for at least 72 hours in the case of DBC1-4 and DEC plant states,

cb) in DBC2-4 the batteries fulfilling a F1 safety function shall fulfil the safety function for at least 2 hours without recharging

cc) in station blackout plant states (DEC1) the batteries fulfilling a F1 safety function, independently of the batteries designed to fulfil a F1 safety function in DBC2-4, shall fulfil the safety function for at least 6 hours without recharging.

India

AERB/NPP-PHWR/SM/D-2

The suitable recombiner device based on platinum/palladium catalyst shall be considered for installation in the plant only after satisfactory demonstration of its efficacy in safe manner in a separate experimental set-up under suitably simulated containment environment conditions arising out of an accident. The recombiner devices shall be qualified as per the following criteria. Based on the functional requirements of the recombiners and the technology available for conducting the experiments, following qualification parameters are worked out.

a. Qualification under inert atmosphere

    - Hydrogen concentration: up to 4% v/v (in dry air medium), up to 30% v/v (in inert steam environment)

- Steam concentration: As per Shapiro-Moffette diagram to ensure inert conditions.

b. Qualification under non-inert (deflagrable) atmosphere: The safe operational behaviour of recombiners shall be demonstrated for gas mixture compositions within the deflagrable region.

During these tests, it shall be suitably demonstrated that any local ignition within or in the vicinity of recombiners does not lead to any sustained ignition as depicted by rapid and sustained pressure, temperature and concentration transients. These qualification tests should be performed in a graded risk manner (starting from least deflagrable compositions). The following range of gas concentrations shall be considered for qualifying the recombiners.

i. Hydrogen concentration: Up to 10% v/v (in steam environment)
ii. Steam concentration: 10-50 % v/v

c. The catalyst shall be demonstrated to be free from spallation phenomena up to a catalyst temperature of 1000 oC in separate-effect tests (or otherwise) in air for different heat up and cooling down cycles. These test conditions should be decided based on the data collected during the performance evaluation of recombiners under inert atmospheres. During the actual tests, the mechanical deformation if any shall not adversely affect the performance of the recombiner function.

d. Pressure: LOCA based peak pressure

e. Poisons: Iodine, CO, oil vapour & lubricant, dust/aerosols as expected under accident conditions

f. Minimum temperature for the onset of recombination process: 30 oC or lower

g. The structural integrity of the recombiners should be demonstrated to withstand thermal loads as well as various other likely loads such as blowdown jets, seismic etc.; and

h. Ageing studies be carried out to arrive at its deterioration characteristics with time. Based on the results of ageing studies, the frequency of in-sit u maintenance checks of catalyst should be specified.

AERB/NPP-LWR/SC/D(DESIGN OF LIGHT WATER REACTOR BASED NUCLEAR POWER PLANTS)

- Seismically qualified onsite storage of adequate quantity of water shall be available for decay heat removal from core and spent fuel stored under water under all plant states for at least 7 days. In addition, provisions should be available for ensuring continued availability of heat sink beyond 7 days by alternate means. The minimum period of 7 days may be revised to a higher value depending on site/plant characteristics. [6.13.5]
- Robustness of ultimate heat sinks shall be maintained and it shall be able to demonstrate long-term heat removal capability in the event of extended SBO. The means for enhancement in decay heat removal from the core or cooling the spent fuel should:

a. reinforce systems capable of removing decay heat over the long term, such as systems and components being able to maintain the capacity of the steam generators (in pressurised water reactors) to remove heat to the atmosphere (alternate means to feed water and relief valves);

b. use alternate paths and means to supply water to cool the reactor core, spent fuel or molten core catcher as applicable; and

c. use sprinkler systems as an alternative for cooling in the spent fuel pool, especially for situations with large losses of pool water inventory. [7.4.3]

China

Hydrogen requirements in China：

HAF 102 2016 “Safety of nuclear power plants: design”

- 6.3.5.6. Design features to control fission products, hydrogen, oxygen and other substances that might be released into the containment shall be provided as necessary:
    - To reduce the amounts of fission products that could be released to the environment in accident conditions;
    - To control the concentrations of hydrogen, oxygen and other substances in the containment atmosphere in accident conditions so as to prevent deflagration or detonation loads that could challenge the integrity of the containment.

HAD 102/06 “Design of Reactor Containment Systems”

- 6.5.1 In a severe accident, a large amount of hydrogen might be released to the atmosphere of the containment, possibly exceeding the ignition limit and jeopardizing the integrity of the containment. In the event of interactions between molten core material and concrete, carbon monoxide might also be released, contributing to the hazard. To assess the need to install special features to control combustible gases, an assessment of the threats to the containment posed by such gases should be made for selected severe accident sequences. The assessment should cover the generation, transport and mixing of combustible gases in the containment, combustion phenomena (diffusion flames, deflagrations and detonations) and the consequent thermal and mechanical loads, and the efficiency of systems for the prevention of accidents and the mitigation of their consequences.

- 6.5.2 Uncertainties remain concerning the production of hydrogen during severe accident sequences; these uncertainties are essentially linked to such phenomena as flooding of a partially damaged core at high temperatures, the late phase of core degradation, the slumping of molten core material into residual water in the lower head of the reactor pressure vessel, and the long term interactions between molten core material and concrete. For new plants, these uncertainties should be taken into account in the design and layout of the means of mitigation of the consequences of the combustion or deflagration of hydrogen, and in the design of the containment.
- 6.5.3 The efficiency of the means of mitigation of the consequences of combustion or deflagration should be such that the concentrations of hydrogen in the compartments of the containment would at all times be low enough to preclude fast global deflagration or detonation. Possible provisions in the design for achieving this goal are, for example, an enhanced natural mixing capability of the containment atmosphere coupled with a sufficiently large free volume, passive autocatalytic recombiners and/or igniters suitably distributed in the containment, and inerting. For new plants the amount of hydrogen expected to be generated should be estimated on the basis of the assumption of total oxidation of the fuel cladding.
- 6.5.4 The leaktightness of the containment for the most representative accident sequences should be ensured with sufficient margins to accommodate severe dynamic phenomena such as a fast local deflagration, if these phenomena cannot be excluded.
- 6.5.5 Even in an inerted containment, the concentrations of hydrogen and oxygen generated over a long period of time by water radiolysis may eventually exceed the ignition limit. If this is a possible threat, a hydrogen control system, passive hydrogen recombiners or other appropriate systems for mitigation and monitoring (e.g. systems for oxygen control and measurement) should be installed.
- 6.5.6 Provision should be made for hydrogen monitoring or sampling. The concentrations of other combustible gases and oxygen should also be monitored.

General Technical Requirements on post-Fukushima Nuclear Accident Improvement Measures for NPPs (Trail):

- The hydrogen monitoring system should have the ability to monitor the hydrogen concentration over the whole range under severe accidents and corresponding alarms should be set, so as to confirm the status of the nuclear power plant and provide information as possible as practicable for decision making during the accident management.
- The hydrogen concentration should be less than 10%(V/V), assuming the hydrogen generated from the metal-water reaction involving 100% of the fuel cladding metal in the active fuel region and distributed uniformly in the containment.
- The damage of the integrity of containment by combustion or exploration due to local accumulation of hydrogen should be avoided, and the impact on the functions of severe accident mitigation systems or equipment should be minimized.
- The hydrogen concentration monitoring and controlling measures should be included in severe accident management guide or relevant procedures