MDEP Design-Specific Technical Report
TR-HPR1000WG-01

HPR1000 WORKING GROUP

Hydrogen Control During Severe Accidents

PARTICIPATION

Regulators involved in the MDEP working group discussions:	ARN (Argentina), NNSA (China), NNR (South Africa), ONR (UK)
Regulators which support the present technical report:	ARN (Argentina), NNSA (China), NNR (South Africa), ONR (UK)
Regulators with no objection:	none
Regulators which disagree:	none

Introduction

There is potential for large quantities of combustible gases to be generated during severe accident conditions in a light water reactor. The combustion of such gases has the potential to threaten the containment integrity, and result in early releases of radioactive materials. In addition, harsh environmental conditions as a result of hydrogen combustion have the potential to impinge on safety equipment required to perform safety functions during accident conditions. It is therefore an expectation of reactor designers or licensees (referred to as designer herein) to demonstrate that these risks posed by combustible gases have been considered and can be mitigated to safe levels.

There are several combustible gas generating processes that occur during accidents. The analysis of hydrogen risk during design basis accidents is normally treated very differently to that for severe accidents. The significantly slower processes important for design basis accidents add negligible risk during severe accidents, and it is normally appropriate to omit these when performing severe accident analyses. The design of the containment combustible gas control systems is, therefore, largely based on the severe accident phenomena, and more effort is spent on the severe accident analyses.

The dominant processes for combustible gas generation in severe accidents are Molten Corium Concrete Interaction (MCCI) and the steam-metal reaction. The HPR1000 employs the In-Vessel Retention (IVR) strategy. Successful retention of the corium in the Reactor Pressure Vessel (RPV) precludes the MCCI phenomena and, therefore, MCCI is not taken in to account in the design and analysis of the combustible gas control system.

The HPR1000 hydrogen mitigation strategy employs Passive Autocatalytic Recombiners (PARs), and relies upon a large open containment and good mixing in order to reduce hydrogen to acceptable concentrations that prevent large pressure waves that could challenge the containment.

The HPR1000 design is currently under review in the UK and the People’s Republic of China. A Multinational Design Evaluation Programme was established consisting of the following members: Office for Nuclear Regulation (ONR) - UK, National Nuclear Safety Administration (NNSA) - China, Autoridad Regulatoria Nuclear (ARN) - Argentina, and National Nuclear Regulator (NNR) – South Africa.

The purpose of this document is to identify common features of the HPR1000 design and develop a common understanding of the regulatory requirements of the regulators that make up the HPR1000 MDEP Working Group (referred to the ‘regulators’ herein). A survey was produced and sent to all the regulators regarding various aspects of the HPR1000 Containment Combustible Gas Control System (CCGCS). This document compiles the information provided within the responses to the survey and summarizes the information presented by the regulators.

This paper discusses the two variations of the HPR1000 design, referred to as Option 1 and Option 2. Below is a high level summary of the two options.

- Option 1: 75300 m^3 free volume in containment, 1 GWe PWR with active containment heat removal.
- Option 2: 86300 m^3 free volume in containment, 1 GWe PWR with passive containment heat removal.

The text in this document refers to both options unless otherwise specified.

Discussion of Responses

This section summarizes the information in the responses to the survey that are pertinent to the design of the HPR1000.

1. Rationale for PARs

All regulators represent countries which are Contracting Parties to the Convention on Nuclear Safety and therefore share a common goal of the Vienna Declaration on Nuclear Safety that "New nuclear power plants are to be designed, sited, and constructed, consistent with the objective of preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions"

In both prescriptive or goal setting regulatory regimes, it is recognized that early containment failure and damage to equipment providing safety functions due to high energy combustion of hydrogen should be avoided.

None of the regulators have regulatory requirements that specify the type of technology that should be implemented in a Pressurized Water Reactor (PWR) for the management of combustible gases in Severe Accidents. Where regulations or expectations exist, they instead center on the prevention of high energy combustion that could lead to a challenge on the containment structure through imposing limits on combustible gas concentrations. The designers' rationale behind having PARs in the HPR1000 containment is thus in pursuance of this goal. Whilst no country specifies the type of technology required, it is noted that all countries have experience with PARs in existing or new reactors.

2. Rationale for location of PARs

In determining the layout of the PARs in the HPR1000 designs, the following principles have been followed by the designers:

- To locate the PARs in the middle and upper level in the containment to optimize and take advantage of natural convection to promote mixing.
- To locate the PARs in compartments where there is a relatively high hydrogen risk to prevent local build-up.
- To locate the PARs in the compartments where hydrogen may be directly released from the primary circuit.
- Consideration is given to other equipment required for severe accident management which may be affected by PAR operation (including the PARs own supporting structures), and the negative impacts are minimised so far as reasonably practicable.
- The PARs should be easily accessible for testing and maintenance.

In addition to these principles, consideration to external hazards (e.g. external flooding, earthquakes, airplane crash etc) and internal hazards (internal flooding, pipe whip, jet impingement etc) are also considered in the design layout to prevent common cause failure of the [CCGCS].

The number and location of the PARs has been derived and verified by the designer using an iterative analysis using a severe accident analysis integral computer code. As discussed below, the location of the PARs has been informed by requirements set by the reactor designer. For the most penalizing cases identified using a lumped parameter code, the reactor designer performs more sophisticated computational fluid dynamics (CFD) calculations in order more realistically model hydrogen transport and, where necessary, determine dynamic loads from slow and fast deflagrations and determine the possibility of Deflagration to Detonation Transition (DDT) occurrence.

Whilst the severe accident analysis is used for analyses related to equipment qualification and survivability, the main purpose of the analysis to verify that the sizing and location of the PARs adequately mitigates risk of containment failure through hydrogen combustion.

3 - How many PARs available and how many of those are necessary for safety report calculation?

Option 1: The CCGCS consists of 29 PARs. For design basis accidents in which significant quantities of H_2 can be generated over a long period, 2 large capacity PARs are located in the containment dome. For severe accident conditions, an additional 27 (16 large and 11 small) PARs are available. For design basis analysis, the single failure criterion is taken into account, and only 1 PAR is assumed available in the analysis. For severe accident analysis, all 29 PARs are credited (assumed available).

Option 2: The CCGCS consists of 33 PARs. For design basis accidents in which significant quantities of H_2 can be generated over a long period, 2 large capacity PARs are located in the containment dome. For severe accident conditions, an additional 31 (20 large and 11 small) PARs are available. For design basis analysis, the single failure criterion is taken into account, and only 1 PAR is assumed available in the analysis. For severe accident analysis, all 33 PARs are credited (assumed available).

The number of PARs required for Options 1 and 2 is different due to containment design and cooling philosophy. However there should be consistency in the assumptions made on availability in the analysis.

4. Regulatory Requirements

Only China has specific requirements that apply to hydrogen management. The requirements are as follows:

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 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 addition to the above, NNSA have issued the report “General Technical Requirements on post-Fukushima Nuclear Accident improvement Measures for NPPs (Trail)”. It places requirements upon: hydrogen monitoring range, global hydrogen concentration, damage to containment integrity, degradation of safety functions and severe accident management guidelines regarding H_2 mitigation.

The UK, Argentina and South Africa do not have specific regulatory requirements regarding hydrogen management. However, as goal setting regimes, these regulators look to relevant good practice (such as IAEA SSR2/1 and SSG-53) as a benchmark for hydrogen management in pursuance of reducing risks to as low as reasonably practicable.

5. Safety Classification and Seismic Categorisation, if any

In general, all the regulators recognize that the safety classification for PARs allocated to design basis accidents (such as LOCA faults) should be higher than those used to mitigate severe accident conditions.

Whilst there are differences in the methodologies for categorization and classification of safety functions and safety measures, it is generally recognized that nuclear codes and standards are applied to the provision of the safety function for design basis PARs, and non-nuclear codes and standards apply to those for severe accidents.

Further, the regulators recognize that whilst the classification/categorization of the safety function decreases as the likelihood of its demand decreases, the seismic categorization should remain high in order to prevent external hazards defeating all PARs in severe accident scenarios.

6. Rationale for qualification test (used for DBA and SA) and what qualification test are planned for the reference plants, if any

As the supplier for HPR1000 PARs has not been selected for the UK and Argentina plants, there are no specific qualification requirements or planned qualification tests identified by the designer. However, all regulators expect that appropriate qualifications tests under normal, accidental and seismic conditions should be performed to the relevant codes and standards commensurate with their safety classification and seismic categorisation. All regulators expect that the environmental conditions for qualification of the PARs can be derived using severe accident analysis which is underpinned by validation and verification of the codes used.

7. Does the HPR1000 design include PARs with ignitors? If yes, rationale for ignitors location?

None of the HPR1000 designs include ignitors.

8. Does the HPR1000 design consider hydrogen ignition by PARs in the safety calculation?

Ignition by PARs is a supplier-specific feature, the progress of test and validation on this matter should be tracked continuously. Ignition should be considered in future submissions when performing more detailed calculations (such as CFD) of the containment. However, no safety submissions currently consider ignition by overheating of the PARs, and no specific requirements from the regulators on this matter.

9. How is hydrogen concentration in the containment monitored?

Option 1: Two low class (industry standard) safety trains of five hydrogen monitors are placed in various positions in the containment. Whilst PARs are passively initiated, the hydrogen monitoring instrumentation and control must be manually operated following transition in to severe accident mitigation strategies. Hydrogen concentration can be measured and monitored in the main control room.

Currently, in the FCG3 design, the range of hydrogen concentration that can be measured by the I&C system is 0-15%.

Option 2: Six hydrogen monitors are placed in various positions in the containment, three of them are powered by Train A while the other three ones are powered by Train B. The hydrogen monitor system will be triggered manually during a severe accident. Hydrogen concentration can be measured and monitored in the control room. The measuring range of hydrogen concentration system is 0 -15%.

10. How is the availability of PARs ensured during the life of the plant (examination, inspection, maintenance and testing)?

None of the working group regulators have received and assessed detailed maintenance and testing information, it is the regulators' expectations that examination, inspection, maintenance and testing (EIMT) will be performed commensurate with the safety significance and frequency of demand of the safety function (i.e. dependent on its safety function categorization). In general, throughout the plant lifecycle, EIMT of the PARs includes visual inspections to verify integrity and corrosion of the shell and catalytic drawer to confirm support function of structures and testing of samples of the catalytic plates to ensure adequate catalytic performance is achieved. If required replacement or regeneration of the plates is performed.

11. What are the measures to protect the PARs during plant outage, if any, and what are the checks before restart

Excluding NNSA, details of measures to protect the PARs during plant outage have not been provided by the designer to any regulators. However, it is generally expected that the PARs be protected by preventing potential impurities from contacting the catalytic plates, resulting in a reduction of efficiency. Any protective measures should be removed to restore the PARs to their initial configuration (e.g. shielding or removal of plates should be rectified) prior to entering any operating mode when their safety function is potentially required.

12. Do safety calculations take into account availability of PARs during shutdown events

For severe accidents, it is generally expected by the regulators that availability of equipment providing low classification safety functions are available when their safety function could be potentially demanded, and therefore any analysis can take credit for correct performance of the PARs when they are expected to operate. PARs are not required in the containment building during complete unloading of the core.

For design basis accidents (e.g. LOCA in RHR mode), only 1 higher classification PAR is credited in the analysis.

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

There are currently no PARs in the spent fuel building for any design. Whilst safety submissions related to the severe accident mitigation strategy for the spent fuel building have been submitted to all regulators, the rationale for not having PARs is expected to be based on arguments regarding the slow nature of transients in the spent fuel pool, prevention of uncovery through redundant means of water injection, the low likelihood of a fuel melt scenario and the ventilation panel that exists in the design.

Summary

The HPR1000 Containment Combustible Gas Control System is included in the design in order to mitigate the risk of containment failure due to high energy combustion of hydrogen.

The HPR1000 Containment Combustible Gas Control System includes the following two sub-systems:

- Passive Autocatalytic Recombiners (PARs) sub-system;
- Hydrogen monitoring sub-system.

The HPR1000 hydrogen mitigation strategy employs Passive Autocatalytic Recombiners (PARs), and relies upon a large open containment and good mixing in order to reduce hydrogen to acceptable concentrations that prevent large pressure waves that could challenge the containment.

The two options of the HPR1000 design differ mainly in the number of PARs and monitors. Nevertheless the principle of design and safety goal of both options are similar.

In addition, among the principles followed in deciding the locations of PARs are the need to establish good in and outflow conditions of the PARs and to be located away from any equipment used in severe accident, such that damage caused by the hot gas from the PARs can be avoided. Periodic testing should be carried out to ensure the claimed reliability and effectiveness of the PARs through life.

Moreover, safety calculations are presented for severe accidents occurring during normal operation but no specific calculations are presented for shutdown events, assuming that the PARs are available during shutdown conditions. This is important to keep in mind because the rules for protected measures for PARs during plant outage and in particular the rules to ensure that these protected measures have been removed before restart are not presently known for the different HPR1000 designs. For plant operating states where the safety function of the PARs may be called upon, the plant availability rules and procedures should ensure those functions are available.

Regulators in China have reviewed the HPR1000 Containment Combustible Gas Control System [CCGCS] and have determined that it meets applicable regulatory requirements, and that the system has been designed to accommodate hydrogen generation equivalent to a 100 percent fuel clad-coolant reaction. Although regulations are similar, some differences in the regulations and design acceptance process exist. Conclusions about the design by the regulators of South Africa and Argentina are pending review in case of a future applicant submittal.

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
1. Rationale for PARs	High energy combustion of combustible gases generated during hypothetical severe accidents (and some design basis accidents) has the potential to challenge the integrity of the containment and the correct performance of safety measures. As the corium cooling strategy is in-vessel retention, hydrogen generated from the steam-metal reaction forms the majority of the combustible gases. Whilst ONR has no preference for technology to mitigate risks of high energy combustion during both design basis and severe accident conditions, ONR expects that accident conditions that have the potential to lead to large or early releases are practically eliminated. ONR has issued design acceptance confirmations for the EPR, ABWR and AP1000. The hydrogen risk strategy for these designs includes PARs and ignitors. ONR is a contracting party to the Convention for Nuclear Safety, and has adopted the Vienna Declaration for Nuclear Safety, 2015.	Containment failure due to hydrogen explosion is one of the events that shall be practically eliminated. 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; PARs also prevent failures to the equipment located inside the containment, which might be caused by fast combustion of gaseous hydrogen. When hydrogen concentration in the containment reaches the start threshold, PARs launched automatically and recombines hydrogen and oxygen in gas mixture to water vapour, which can effectively keep hydrogen concentration in containment under safety range.	According to the regulatory standard, AR 3-4-3 rev 1,"Nuclear Power Plant Confinement systems", the different physical barriers provisions in the design shall assure the fulfilment of criteria for limitation the radiological consequences as stated in AR 3-1-3 "Radiological criteria relating to accidents in nuclear power plants". For accident conditions involving severe fuel damage or core melt/severe accidents, the main safety objective in order to fulfil the above regulatory expectations is to maintain containment structure integrity throughout the course of such a an accident. In order to maintain the containment structure integrity, its strength shall be high enough to withstand (with sufficient margins) static and dynamic loads during core melt accidents that have not been practically eliminated (pressure, temperature, missile, radiation and reaction forces). Containment failure caused by the significant releases of combustible gases can be practically eliminated by avoiding the hydrogen deflagration/explosion. So, there	Given the temperature conditions prevailing in the reactor coolant system, the core and the containment, core coolant water and containment spray water are both liable to react with certain metal compounds and/or to decompose by radiolysis during a loss of coolant accident, thus producing hydrogen. Hydrogen can also be generated inside containment by molten core concrete interaction during the ex-vessel phase. A potentially explosive hydrogen-air mixture may develop inside the containment as hydrogen is produced. Such conditions represent a potential challenge to containment integrity. In the case of the Koeberg PWR plant, in order to maintain the hydrogen concentration at a sufficiently low value during a design basis LOCA, mobile H_2/O_2 recombiners are provided. The mobile recombiners are sized for a Design Basis LOCA. The Passive Autocatalytic Recombiners (PARs) are sized for a Beyond Design Basis LOCA and were also installed in the Koeberg PWR plant.

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
			shall be appropriated design provisions, like PARs to prevent containment failure due to combustion of hydrogen.	
2. Rationale for location of PARs	The reactor designer has used experience from the CPR1000 as an initial estimate as to the number of PARs required. the following principles for location of the PARs have been followed: • To locate the PARs in the middle and upper level in the containment to optimise the natural convection; • To locate the PARs in the compartments where there is relatively high hydrogen risk to avoid build-up of hydrogen; • To locate the PARs in the compartments where hydrogen may release into it directly; • Consider the layout of other important equipment to avoid damage. • To locate PARs in where it is easy to access and keep in good repair. In addition, the reactor designer has considered external (flooding, earthquakes, explosions etc.) and internal hazards (flooding, pipe-whip, jet impingement, dropped loads, fires) in the positioning of its PARs. For severe accidents, the design of the CCGCS will be confirmed through an	The general scheme of PARs location in HPR1000 design is based on the following aspects: • locate the PARs in the area where the hydrogen is prone to concentrate locally, and guarantee the hydrogen elimination effectiveness of PARs, • the PARs shall be able to support general convection in containment, and promote the atmosphere homogenization, • the PARs shall be accessible for the implement of maintenance, periodic test and in-service inspection. • the PARs shall not have negative effect on other systems located in the localizing area. The numbers and location of PARs design are verified and validated by safety analysis.	For the preliminary design: selection of recombination capabilities and locations of the equipment, the regulatory expectation is that the decision making process be justified by deterministic analysis. For the existent plants, MELCOR code was used to develop a model for the severe accident progression allowing optimization of PARs's location and assessing their efficiency to face different accident scenarios. When determining PARs's location, design of support structures and stress analysis considering dead, thermal and seismic loads, shall also be considered. Other aspects needed to support a further safe operation have to be also considered early in the design stage, like accessibility for maintenance and functional tests.	The PAR locations and the unit sizes are selected to optimise hydrogen removal in severe accident conditions, and are based on studies performed for Tricastin (sister plant of Koeberg NPP in France). Detailed H_2 distribution analyses have been performed at Tricastin to determine the best location of the PARs for optimal H_2 reduction. As Tricastin and Koeberg have the same CP1 reference plant configurations, the PAR locations at Koeberg are the same as the PAR locations at Tricastin. The PARs are either wall or floor mounted depending on the layout of the area and available support base. To allow flexibility in the arrangement of these devices in the various compartment areas of containment, the PARs are available in various sizes. The PARs were distributed in the equipment rooms to start the removal as early as possible and to support global/local convection and homogenizing

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
	iterative process, using both the severe accidents integral code and more sophisticated computation fluid dynamics codes, to show that high energy combustions that can challenge the containment integrity can be prevented and that equipment important to safety will not be effected.			the atmosphere considering possible hydrogen release areas. Further PARs were installed in the dome area to minimize build-up of hydrogen concentration in the upper part of the containment. Besides the global convection which will be supported by the bigger PAR type, local construction constraints were considered for optimal inflow and outflow condition (no obstruction at the gas outlet and inlet, minimal distance to the floor) to obtain the nominal depletion rate. The minimum required hydrogen reduction capacity specification was the basis for the selection of installation locations in the predefined compartments considering: • hydrogen release areas, • main flow paths between zones of hydrogen • enhance containment atmosphere mixing • take advantage of global convection paths. As an aside, it should be noted that core coolant water and containment spray water are not the only sources of hydrogen

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			through their liability to react with certain metal compounds and/or to decompose by radiolysis during a loss of coolant accident, thus producing hydrogen. Hydrogen is also produced by the hydrogen production and storage system. The hydrogen produced is used in the generator hydrogen supply system and the chemical and volume control system (RCV). A hydrogen blanket is maintained in the volume control tank. In addition to this, there are hydrogenated wastes that originate from the volume control tank and primary waste tank. The wastes are also generated during the treatment of primary waste by the TEP degassers. The wastes are made up of hydrogen, fission gases (e.g. xenon and krypton), and nitrogen. In the RCV, RPE, TEG, and TEP tank rooms, the equipment capable of containing significant quantities of hydrogen present a potential risk of explosion in the event of an accidental leak. In addition, there is the risk that, should the RCV piping fail,

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
				hydrogen could gather in these rooms and cause a risk of fire or explosions. Koeberg has taken additional measures to address these additional hydrogen risks. It may be prudent for HPR1000 considerations to also consider such additional sources of hydrogen.
3. How many PARs available and how many of those are necessary for safety report calculation?	In the UK HPR1000 there are 29 PARs available in total. • There are 2 dedicated to design basis accidents. Only 1 is credited in design basis analysis taking in to consideration the single failure criterion. • There are 27 dedicated to severe accidents, however, credit is taken from all 29 in the analysis. ONR expect that sensitivity studies are performed in order to demonstrate that no cliff-edge effects are observed.	The number of PARs depends on the plant design. In option 1, 29 PARs are assumed available in safety report calculation; in option 2, 33 PARs are assumed available in safety report calculation. The failure of some PARs for safety analysis is not mandatory, but it considered certain margin in design.	The number of PARs depends on the plant design. In the case of Atucha I (PHWR) the number is 32 and for Atucha II (PHWR), the number is 54. It is expected that in the design of HPR1000, the safety features designed to mitigate the consequence of core melt accident (level 4) be independent from equipment designed to mitigate DBA (level 3a) and DEC (level 3b). Safety demonstration shall be done for level 3a, through conservative methodology. It is also possible to include best estimate verification for level 3b. a	To prevent hydrogen (H_2) build-up during a Beyond Design Basis LOCA, twenty four PARs are installed inside the containment building of the Koeberg NPP. An observation of more general significance than just for this question: There appears to be examples of how beyond design basis measures of Generation II technology/design are naturally being converted to design basis measures of Generation III technology/design whilst moving from Generation II technology/design to Generation III technology/design. One of example of this is as follows: The Containment Atmosphere Control system (ETY) of the Koeberg NPP consists of two systems to reduce hydrogen concentration, namely the originally installed mobile recombiners and the later installed Passive Autocatalytic Recombiners

ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
			(PARs). The mobile recombiners are sized for a Design Basis LOCA. The PARs are sized for a Beyond Design Basis LOCA. In the UK HPR1000 design, in design basis accidents, hydrogen generated is removed by two sets of PARs. Under severe accident conditions (DEC-B sequences) the hydrogen is removed by 27 sets of PARs. Thereby, when comparing with the Koeberg example, in effect, converting beyond design basis measures of Generation II to design basis measures of Generation III in moving from Generation II technology/design to Generation III technology/design. One also encounters examples of where the return periods for extreme external events are in beyond design basis territory for Generation II considerations but move to design basis territory for Generation III considerations, thereby, in effect, converting beyond design basis conditions of Generation II to design basis conditions of Generation III in moving from Generation II technology/design to Generation III technology/design. In summary, nuclear regulators need to remain cognizant of this

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
				shifting of the meaning of "design basis" to include more stringent requirements in moving from Generation II design considerations to Generation III design considerations and, therefore, not forget that the further development of design extension conditions and measures (associated with Generation III considerations) is not the only tightening of requirements imposed on authorization applicants and -holders when moving from Generation II considerations to Generation III considerations. Tightening of requirements also happens in the shifting meaning of what is meant by "design basis" as one moves from Generation II to Generation III. This should be a source of caution for nuclear regulators to remain reasonable and pragmatic when imposing evolving requirements by not forgetting what tightening of requirements might already be "buried"/implied in the use of the words "design basis" when comparing the Generation II and Generation III contexts.
4. Regulatory Requirements	ONR's SAPs state that early or large releases should be practically eliminated. The SAPs are benchmarked against relevant good practice (RGP)	**HRP1000 China** In China, general regulatory requirements are in HAF 102-2016 "Safety of nuclear power plants: design" and related	N/A	The analysis of Beyond Design Basis Accidents (Including Severe Accidents) shall show compliance with risk criteria as

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
	e.g.(SSR2/1). The requirement for risks to be As Low As Reasonably Practicable (ALARP) is fundamental and applies to all activities within the scope of the Health and Safety at Work Act 1974 [HSWA]. The minimum expectation for demonstration of ALARP is RGP. ONR is bound by the Article 8a of the EU Nuclear Safety Directorate that states that ONR requires that early or large releases are avoided.	guidelines and policy statement. Detailed regulatory requirements for the hydrogen assessment are written in General Technical Requirements on post-Fukushima Nuclear Accident Improvement Measures for NPPs (Tentative): **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. **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		stated in NNR Requirements Document RD-0024, "Requirements on Risk Assessment and Compliance with principal Safety Criteria". At Koeberg, the PARs are credited in the Level 2 PSA. Level 2 PSA studies were performed to compare the impact of PARs on cases such as SBO and reactor coolant system (RCP) small break LOCA. This was done using MAAP4.07 which has options to model the AREVA type PARs that have been installed at Koeberg. Small break LOCA in the reactor coolant system (RCP) is a dominant severe accident scenario for Release Category 6 in the Level 2 PSA. As part of ALARA considerations for this case, a comparative analysis was done with and without the installation of PARs.

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
		practicably possible 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.		
5. Safety Classification and Seismic Categorisation, if any	PARs for design basis accidents are safety function categorization 2, meaning that nuclear codes and standards apply, and the single failure criterion applies. PARs for severe accident conditions are safety function categorization 3, meaning industry standards apply, and the single failure criterion doesn't need to be applied. All PARs are the highest seismic category.	In HPR1000 design, 2 PARs for design basis accident are categorized as safety class, and other PARs for severe accident are categorized as non-safety class. Additionally all PARs are items important to safety.	Safety classification for items important to safety must be done using IAEA, SSG-30: "Safety Classification of Structures, Systems and Components in Nuclear Power Plants" (2014). PARs for DBA shall be safety class and the others are non-safety class.	It should be noted that the Containment Atmosphere Control system (ETY) of the Koeberg NPP consists of two systems to reduce hydrogen concentration, namely the originally installed mobile recombiners and the later installed Passive Autocatalytic Recombiners (PARs). The mobile recombiners are sized for a Design Basis LOCA.

ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
			The PARs are sized for a Beyond Design Basis LOCA. Hydrogen monitoring and reduction of hydrogen concentration to a safe level are essential to safety and containment integrity. Therefore, the post-accident containment atmosphere subsystem (mixing, sampling, and mobile recombining) of the Containment Atmosphere Control system (ETY) is a safety-related Class 2 subsystem. The safety classification of the PAR units are still subject to a separate design study to classify the PARs – more about this lower down below. All safety-classified parts of the ETY system are designed to operate following a safe shutdown earthquake (Seismic Class 1) and are protected against missiles. Since the PARs are sized to deal with a Beyond Design Basis LOCA, they will be capable of controlling the post DBA hydrogen build-up. However, the current design for the PAR installation function has the PAR units conservatively classified as NSF (No Safety Function) and the seismic classification is ND

	ONR (UK)	NNSA (China)	ARN (Argentina)	NNR (South Africa)
				(Non Destruct), which is not sufficient to allow the PARs to officially take over the design basis safeguard function of the mobile recombiner (two mobile hydrogen recombiners, one on each unit). This requires a separate design study to re-classify the PARs.
6. Rationale for qualification test (used for DBA) and what qualification test are planned for the reference plants, if any	Qualification will be performed to demonstrate that all PARs can perform their safety functions under severe accident environmental conditions, and that they can perform their safety functions following seismic activity. No detailed qualification information has yet been provided.	As PARs are necessary equipment in severe accident, qualification test of PARs are performed under severe accident environmental conditions. The rationale for qualification test is to prove the functionality of the PARs at environmental conditions expected in a severe accident. Referenced to RCC-E standards, K1 and severe accident procedures are sequentially used, with different severity of thermal and chemical conditions, test methods, acceptance criteria from design basic accident.	Equipment qualification includes three items: environmental, seismic and electromagnetic immunity (not for PARs). The requisites for the process of qualification are based on IAEA, Equipment Qualification in Operational Nuclear Power Plants: Upgrading, Preserving and Reviewing, Safety Report Series No. 3. For PARs, the rationale for environmental qualification test is to prove the functionality in a severe accident conditions. For seismic qualification, SSE earthquake is used to define the vibratory limits that have to be tolerated. However, the vibratory motions experienced by NPP equipment will vary on the basis of the filtering, amplification and dampening of intervening structures.	The titles of the following test programs provide an indication of the rationale for qualification of the PARs used in the Koeberg NPP. The PAR qualification test database is derived from the following national and international test programs: • Integrated Core-Melt-Simulation-Test • EDF H2- Kali Tests with spray including chemicals • EPRI / EDF Tests for BWR and PWR conditions • PAR Tests in the Battelle Containment • PHEBUS Catalytic Coupon Test • Development and Qualification Tests in AREVA NP Laboratories in Karlstein. A qualification program over a number of decades was performed. The test programs allow the behaviour of the AREVA NP PARs in case of design basis- or severe accidents in PWR and BWR

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				nuclear plants with release of combustible gases to be assessed. The PAR tests were performed under a wide range of hydrogen concentrations, initial ambient gas temperatures and pressures, steam and nitrogen as inert gases, and potential poisons. In addition, the effects of wetness and low ambient temperature on PAR start-up were studied. The Integrated Core-Melt-Simulation-Test program in Cadarache concerns poisoning, deposition and contamination of catalyst in a post accident atmosphere. During this program, the AREVA NP PAR was subjected to a realistic aerosol exposure generated by a molten core. This test answers the question on the effect of aerosols on the catalytic recombination as well as the catalytic poisoning by fission products in a severe accident atmosphere.
7. Does the HPR1000 design include PARs with ignitors? If yes, rationale for ignitors location?	The UK HPR1000 design only includes PARs.	To prevent hydrogen accumulation leading hydrogen detonation, HPR1000 design installs only PARs and no igniters. However, NNSA have no preference; the CANDU-6 units in Qinshan NPP, AP1000 units in Sanmen and Haiyang NPP utilize PARs with igniters in containment as hydrogen control measure.	No igniters are used.	No igniters are used.

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8. Does the HPR1000 design consider hydrogen ignition by PARs in the safety calculation?	With regards to severe accident analysis, ONR expects that all phenomena are modelled on a best estimate basis and adequately underpinned by V&V. Currently, the submitted analysis is performed in a lumped parameter code and ignition from PARs has not been analyzed. Further work is to be performed using more sophisticated CFD analysis where the possibility of ignition from PARs will be explored.	Hydrogen ignition by PARs is not considered in safety calculation up to now. At present, PAR ignition is still under R&D stage.	Hydrogen ignition by PARs is not considered in the safety calculation.	Hydrogen ignition by PARs is not considered in the safety calculation.
9. How is hydrogen concentration in the containment monitored?	Two trains for five hydrogen sensors (10 in total) are able to measure the hydrogen concentration in various location in the containment. The operator can observe the hydrogen concentration from the main control room. The hydrogen monitoring equipment is manually actuated and has a measuring range of 0-15% vol concentration.	In HPR1000, hydrogen concentration in containment is continuously monitored by using two measurement trains, which consists of hydrogen detectors in different parts of the containment, and the information is displayed in main control room.	Hydrogen concentration is monitored at specific locations supporting SAMGs.	Hydrogen concentration is monitored at specific locations supporting SAMGs. Hydrogen concentration is also monitored in the context of alternative hydrogen sources described in the last three paragraphs of the South Africa response in Section 2 above.
10. How is the availability of PARs ensured during the life of the plant (examination, inspection, maintenance and testing)?	Submission describe at a high level how the examination, inspection maintenance and testing will be performed. The examination, inspection, maintenance and testing (EIMT) involves visual inspections and testing of PAR performance, with regeneration of plates where required.	HPR1000 is under construction, according to experience feedback of domestic plants, periodic inspection and maintenance are performed correspondingly for PARs during outage, to verify their reliability during plant life. • In every refueling outage, visual inspection are performed for all PARs, to verify integrity and corrosion of shell and catalytic drawer, and to confirm support function of structures, etc. • According to locations and inspection route, all recombiners are divided in groups for function test, and a complete	Availability of PARs is assured by maintenance and inspection activities, during planned outages. The inspection is done using a so called “Transportable Inspection and Regeneration Equipment” (TIRE) device. This equipment was designed to inspect the catalytic plates and allow their regeneration, if needed. In case of efficiency reduction, the plates are exposed to a high temperature in order to eliminate the humidity or	A visual and functional check is required periodically (during shutdown). The functional check uses special mobile equipment to determine the efficiency of the catalytic plates (i.e. mobile trolley, heated cabinet, measurement devices, operation panel, analysis unit and gas supply). The efficiency is tested by removing 3 catalytic plates from each selected PAR and then testing them in the mobile tester for recombination rates, temperatures, etc.

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		test cycle is finished in 2 to 4 refueling cycles. • For each recombiner, 3 adjacent catalytic plates are chosen randomly, and are respectively tested in specific equipment, with inlet gas flow rate 6.5 SLM, H_2 volume concentration of 3%, at 60°C. PAR can be considered reliable if 3 tested plates pass the tests, with 75% hydrogen elimination efficiency in 15 minutes.	impurities that may be deposited over the surface. Visual inspection is also performed for all PARs, to verify indication of shell and catalytic drawer corrosion. Supports and anchorages are verified for structural integrity, as well.	Specific maintenance and repair work necessary during outages may result in higher concentrations of adverse materials in the containment atmosphere. These could include solvents from decontaminable paint, solvents for cleaning purposes, aerosols from drilling, grinding or demolition work as well as welding gas and fumes, etc. The functional resistance of the catalyst against welding fumes and solvents has been investigated and principally proven. Nevertheless to avoid an unnecessary exposure of the catalyst it is recommended to remove the catalyst-bearing insert or to temporarily protect it by covering inlet and outlet openings during such work.
11. What are the measures to protect the PARs during plant outage, if any, and what are the checks before restart	No details have been submitted.	HPR1000 is still under construction, and protecting measures of PARs during plant outage have not been fixed. In reference to experience feedback of domestic plants, all recombiners are protected by shielding that prevents the possible impurities in the containment atmosphere from getting into contact with the catalytic plates during plant outage. The shielding are removed before refueling mode ends, and checks are subsequently conducted to confirm no block.	N/A	Specific maintenance and repair work necessary during outages may result in higher concentrations of adverse materials in the containment atmosphere. These could include solvents from decontaminable paint, solvents for cleaning purposes, aerosols from drilling, grinding or demolition work as well as welding gas and fumes, etc. The functional resistance of the catalyst against welding fumes

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				and solvents has been investigated and principally proven. Nevertheless to avoid an unnecessary exposure of the catalyst it is recommended to remove the catalyst-bearing insert or to temporarily protect it by covering inlet and outlet openings during such work. In the unlikely event that poisoning of a catalyst plate occurs, thermal regeneration of the catalyst could be performed. The regeneration process of catalytic plates is an efficient method to refresh their catalytic activity.
12. Do safety calculations take into account availability of PARs during shutdown events	No analysis for hydrogen management has been presented for shutdown states. For severe accidents, it is generally expected that availability of equipment providing low classification safety functions are available when their safety function could be potentially demanded, and therefore any analysis can take credit for correct performance of the PARs when they are expected to operate. PARs are not required in the containment building during complete unloading of the core. For design basis accidents, the availability of only one FC2 PAR is credited.	The availability of PARs is considered in safety calculation.	(Not answered)	The safety calculations for the case of events at power could be considered enveloping for the case of shutdown events. See also the South Africa response in Section 4 above.

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13. Are there PARs in the spent fuel building? Rationale for having them or not?	Not in the current UK HPR1000 design. The severe accident analysis of the spent fuel pool will be provided in the course of GDA. Arguments for not having PARs are expected to be: • Slow progression of severe accident • Many water sources before fuel uncovery • And therefore the likelihood of fuel uncovery • The UK HPR1000 design includes a ventilation panel in the fuel building.	There are no PARs in the spent fuel building for HPR1000 design. Rationale for not having them is that the process of spent fuel melting is very slow, with a duration time from dozens to hundreds of hours, and the main accident response measure is water injection to avoid fuel uncovering, and the means of water injection is diverse and redundant. There are venting systems installed in spent fuel building, which can be prevent hydrogen concentration when needed.	There are no PARs in the spent fuel building.	There are no PARs in the spent fuel building.