MDEP Design-Specific Technical Report TR-APR1400WG-04

APR1400 Working Group

Technical Report on the Hydrogen Recombiner Survey Results for APR1400 design in place, or proposed, for the MDEP Member Countries

Participation

Regulators and TSOs involved in the MDEP working group discussions:	KINS (Korea), FANR (UAE), NRC (US)
Regulators and TSOs which support the present report:	KINS (Korea), FANR (UAE), NRC (US)
Regulators with no objection:	none
Regulators that disagree:	none

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1. Introduction

In a light water reactor, generation of hydrogen in large quantities under severe accident conditions involving a degraded core can pose a significant threat to the containment integrity. During the severe accident, hydrogen is primarily produced by a reaction between steam and the fuel cladding. Additional amount of hydrogen can also be produced from the interaction of the molten core with the containment basemat concrete. Depending on atmospheric conditions in the containment, hydrogen can cause combustion or explosion, resulting in a damage to the containment function. If the containment function is damaged, it becomes impossible to maintain leak-tightness, and radioactive materials can be released to the outside.

For most light water reactors, severe accidents lead to hydrogen release rates that exceed the capacity of hydrogen control measures aimed at conventional design basis accidents (DBAs). High local hydrogen concentrations can be reached in a short time frame, leading to combustible gas mixtures in the containment.

The flammability of the containment atmosphere, and the magnitude, timing, and location of potential hydrogen combustion is strongly influenced by the rate and quantity of hydrogen production. The modes of hydrogen combustion, such as deflagration, fast or accelerated flames, deflagration to detonation transition (DDT) and detonation, can vary depending on such parameters.

In order to evaluate the effect and mitigate the consequences of hydrogen combustion, detailed studies are typically required to determine the hydrogen generation rates and overall amount released to the containment. Based on the local and global hydrogen concentration within the containment, the modes of combustion and the associated local and global pressure loads can then be evaluated, thus providing an insight into the risk of hydrogen combustion and any potential challenges to the containment integrity.

The APR1400 hydrogen mitigation strategy adopts the use of passive autocatalytic recombiners (PARs) and igniters. As the design and implementation of the mitigation measures are largely influenced by the governing legislative requirements of the country in which the Nuclear Power Plant is to be constructed and/or operated, a common understanding of regulatory requirements on hydrogen control measures is needed.

The objective of this report is to identify a common understanding of the regulatory requirements pertaining to the hydrogen control for the APR1400 design. To this end, a survey on hydrogen control system was conducted amongst the APR1400 Multinational Design Evaluation Program (MDEP) members (Republic of Korea, The United Arab Emirates, and the United States), and this report compiles and summarizes the information presented by each member in response to the survey.

2. Discussion of Responses

This section summarizes the responses provided by APR1400 MDEP members concerning the survey on the hydrogen control system.

2.1 Rationale for PARs

All APR1400 designs are provided with Hydrogen Mitigation System (HMS) that consists of PARs and igniters. The PARs are effective in accident sequences in which mild or slow hydrogen release rates are expected while the igniters supplement PARs for accidents of vary low probability where very rapid release rates of hydrogen are expected.

The APR1400 HMS is designed to accommodate hydrogen production from 100% fuel clad metal-water reaction and limit the average hydrogen concentration in containment to 10% v/o. These limits are imposed to preclude detonations in containment that could jeopardize containment integrity or damage essential equipment.

2.2 Rationale for location of PARs

For all APR1400 designs of the MDEP considered in this report, the location of PARs was chosen based on hydrogen concentration analyses. Varying sizes of PARs (small, medium, and large) equipped with different number of autocatalytic recombiner units are selected based on the following general guidance:

- Total number of PARs installed is distributed in approximate proportion to the local free volume
- PARs are distributed such that the convection flow generated by the PARs is large and crosses boundaries between containment compartments
- PARs are installed in elevated locations above the potential sources of hydrogen releases
- PARs should be easy to handle for installation and removal
- PARs installation locations should minimize any counter-productive effects on operation and maintenance activities

In addition, hydrogen igniters, as supplementary to the PARs, provide an effective means of controlling local hydrogen concentration in compartments where the hydrogen release rate is greater than the depletion capability of PARs during a certain period of severe accident progression.

2.3 Number of PARs and Consideration for Safety Analysis

All APR1400 designs have a total of 30 PARs. 12 PARs are located in different regions of the containment for design basis events (8 large capacity in the upper dome area and 4 medium capacity at the In-containment Refueling Water Storage Tank (IWRST) and vent gate). 6 PARs are considered in the design basis analyses for the Republic of Korea and the United Arab Emirates. For the United States, no PARs are credited in the design basis analyses. PARs for SA actually use the same PARs for DBA. However, it is classified according to the requirements applied for maintenance. For severe accidents, additional 18 PARs are available, and all are considered in the analyses.

2.4 Regulatory Requirements and Criteria

United Arab Emirates

- FANR-REG-03 Article (69) Item 1 - Systems to control fission products, hydrogen, oxygen and other substances that may be released into the reactor containment shall be provided as necessary. Systems for cleaning up the containment atmosphere shall have suitable Redundancy in components and features to ensure that the Safety Group can fulfill the necessary Safety Function, on the assumption of a Single Failure
- FANR-REG-03 Article (69) item 2 - Consideration shall be given to the control of fission products, hydrogen and other substances that may be generated or released in the event of a Severe Accident.
- FANR-REG-03 Article (24), design activities shall take into account the following: c. Provisions for combustible gas control.
- FANR- RG-004 Article (12) item 3. c. the Design should provide a system for hydrogen control that can safely accommodate hydrogen generated by the equivalent of a 100 percent fuel-clad metal-water reaction. In addition, the Design should be capable of precluding uniform concentrations of hydrogen from exceeding 10 percent (by volume), or should provide an inerted atmosphere within the Containment.

Republic of Korea

Regulatory Guideline 16.1.II,2 (a) and (b):

- (a) Hydrogen concentration shall not exceed 10% during and after severe accident where hydrogen generated from reaction of 100% cladding metal and water under the assumption of uniform distribution of hydrogen inside containment building. The concentration of combustible gas in each compartment of containment building shall be low enough for preventing wide-scale flame acceleration or deflagration to detonation transition. Facility shall be installed for protection of containment building from damage due to combustion of combustible gas in containment building.
- b) Structural integrity of containment building shall be kept intact during and after severe accident where hydrogen is generated and released by reaction of 100% classing metal and water, and pressure is increased due to deactivation after hydrogen combustion or accident (assuming carbon dioxide as deactivation agent). As for steel containment building, the requirements for Class C acceptable operating limit of Korea Electric Power Industry Code (KEPIC) MNE 3220 shall be satisfied. As for concrete containment building, the acceptable factored load category defined in Korea Electric Power Industry Code SNB 3720 shall be satisfied.

United States

- 10 CFR Part 50.44(c), as it relates to pressurized water reactor plants being designed to accommodate hydrogen generation equivalent to a 100 percent fuel clad-coolant reaction; limit containment hydrogen concentration to no greater than 10 percent composition; have the capability for ensuring a mixed atmosphere during design bases and significant beyond-design-bases accidents (a significant beyond-design-basis accident is an accident comparable to a degraded core accident at an operating light-water reactor (as of October 16, 2003) in which a metal-water reaction occurs involving 100 percent of the fuel cladding surrounding the active fuel region (excluding the cladding surrounding the plenum volume); and provide containment-wide hydrogen control (such as igniters or inerting), if necessary, for certain severe accidents. Post-accident conditions should be such that an uncontrolled hydrogen/oxygen recombination would not take place in the containment, or the plant should withstand the consequences of uncontrolled hydrogen/oxygen recombination without loss of safety function or containment structural integrity.
- 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 41, as it relates to systems being provided to control the concentration of hydrogen or oxygen that may be released into the reactor containment following postulated accidents to ensure that containment integrity is maintained; systems being designed to suitable requirements, i.e., that there be suitable redundancy in components and features, and suitable interconnections to ensure that for either a loss of onsite or a loss of offsite power the system safety function can be accomplished, assuming a single failure; and systems being provided with suitable leak detection, isolation, and containment capability to ensure that system safety function can be accomplished.
- GDC 42, as it relates to the design of the systems to permit appropriate periodic inspection of components to ensure the integrity and capability of the systems.
- GDC 43, as it relates to the systems being designed to permit periodic testing to ensure system integrity, and the operability of the systems and active components.
- 10 CFR 52.47(b)(1), which requires that a design certification application contain the proposed inspections, tests, analyses, and acceptance criteria that are necessary and sufficient to provide reasonable assurance that, if the inspections, tests, and analyses are performed and the acceptance criteria met, a plant that incorporates the design certification is built and will operate in accordance with the design certification, the provisions of the Atomic Energy Act, and the NRC's regulations.

2.5 Safety Classification and Seismic Categorization

For APR1400 designs in the United Arab Emirates and Republic of Korea, PARs available for the design basis events are designated as Safety Class 3. For severe accident applications, PARs are considered as non-safety related. In the case of the US APR1400, PARs are considered as non-safety related. All APR1400 designs of the MDEP considered in this report, PARs are designated as Seismic Category I.

2.6 Rationale for Qualification Test

Equipment qualification and seismic qualification is performed for the design basis applications. Equipment qualification relies on the test program data conducted by the Electric Power Research Institute (EPRI), supplementing the existing PAR test database with performance data under the conditions of interest. The qualification is extended for severe accident applications (i.e., evaluation of equipment survivability under the severe accident conditions of temperature, pressure, and radiation). For United States, it is expected that the applicant of the Combined License (COL) would develop a suitable test plan for the demonstration of equipment survivability under severe accident conditions.

2.7 Use of PARs with Igniters and Rationale for Igniter Location

For all APR1400 designs of MDEP considered in this report, igniters are used to supplement PARs for accidents of vary low probability where very rapid release rates of hydrogen are expected. The igniters are placed near source locations to promote the combustion of hydrogen in a controlled manner such that the containment integrity is maintained. For United Arab Emirates and Republic of Korea APR1400 designs, there are a total of 10 igniters, whereas for US 8 igniters are provided.

2.8 Consideration of Hydrogen Ignition by PARs in Safety Analysis

None of the APR1400 designs consider ignition by PARs in the current design basis safety analysis submissions.

2.9 Monitoring of Hydrogen Concentration in Containment

For APR1400 designs of the United Arab Emirates and Republic of Korea, two hydrogen concentration sensors are provided with a minimum sensor indication range of 0 to 15% by volume as part of the post-accident monitoring system. For US APR1400 design, redundant Seismic Category I hydrogen monitoring system is designed to measure 0-15% volume of hydrogen in a pressure range of -0.352 kg/cm2 (-5 psig) to the maximum containment design pressure.

2.10 Ensuring the availability of PARs during the life of the plant

Throughout the life of the plant, PARs are subjected to test and surveillance requirements (e.g., sampling and sample test during outage enforced by Technical Specification – 25% of all catalysts in each PAR shall be sampled for the test in accordance with the manufacturer's recommendation) to ensure the function of PARs is maintained.

2.11 Protective Measures for PARs during plant outage

No specific protective measures during plant outages are available. However, based on the operational experiences, start-up performance can be degraded due to deposited particles of dust and volatile organic compounds in the atmosphere. In addition, a portion of PARs are not available during shutdown state because of test and maintenance. Considering the degradation in function and uncertainty, it is assumed that 25% of PAR is not available in the US and Korea for safety analysis.

2.12 Consideration of PARs Availability during Shutdown Events in the Safety Analysis

Availability of PARs during shutdown is not considered in safety analysis submissions in the United Arab Emirates and Republic of Korea, as the associated operability requirements are not enforced in Modes 5 and 6 or in Refueling. For the US APR1400 design, the Level 2 low power and shutdown Probabilistic Risk Assessment (PRA) in the Design Control Document (DCD) assumes 25% of the PARs are unavailable due to test and maintenance. The remaining 75% of the PARs and all of the igniters are assumed available. The results showed that with either the igniters or PARs available, neither global or local hydrogen concentrations exceed 10% vol.

2.13 Consideration of PARs in Spent Fuel Pool Building

There are no regulatory requirements for PARs in the spent fuel pool building for all APR1400 designs of MDEP and no accident scenario generating hydrogen in the spent fuel pool is postulated as fuel remains covered with water. As such, no PARs are provided in the spent fuel pool building. However, for United Arab Emirates APR1400 design 2 PARs are provided in the spent fuel pool building as a defense-in-depth measure. No specific technical justification is provided.

3. Summary

The APR1400 HMS is designed to accommodate hydrogen production from fuel clad metal-water reaction and limit hydrogen concentration in containment to maintain containment integrity. The APR1400 HMS consists of PARs and igniters. The hydrogen igniters as supplementary to the PARs provide an effective means of controlling local hydrogen concentration in compartments where the hydrogen release rate is greater than the depletion capability of PARs during a certain period of severe accident progression.

PARs provided in the APR1400 designs of MDEP have been subjected to qualification tests and have the relevant seismic classification. In the United Arab Emirates and Republic of Korea, PARs available for the design basis events are designated as Safety Class 3. For severe accident applications, PARs, which are installed in addition to the DBA application, are considered as non-safety related. In the case of the US APR1400, all PARs are considered as non-safety related.

While some specific design and implementation of the hydrogen risk mitigation measures are different among the different APR1400 designs of MDEP surveyed in this report, no significant differences in principle were identified. This can be attributed to similarities in regulatory requirements applied to the control of hydrogen that ultimately assure the risk of hydrogen is minimized.

Although APR1400 designs of MDEP are currently at different stages of licensing review and/or have varying degree of associated operating experiences among each respective member country, the effectiveness of APR1400 HMS has been confirmed through each relevant regulatory review process.

Table 1. APR1400 Passive Autocatalytic Recombiners (PARs)

No.	Item	UAE	Republic of Korea	US
1	Rationale for PARs	**DBA**: Designed to accommodate the hydrogen production rate anticipated for a design basis accident and provide 200% capacity of the required PARs **BDBA**: Designed to accommodate hydrogen production from 100% fuel clad metal-water reaction and limit the average hydrogen concentration in containment to 10 v/o.	**DBA**: Designed to accommodate the hydrogen production rate with 200% capacity. **BDBA**: Designed to accommodate hydrogen production from fuel clad metal-water reaction and limit average hydrogen concentration in containment to 10 v/o.	DBA is bounded by BDBA. Designed to accommodate the hydrogen generation from 100 percent fuel clad metal-water reaction and to limit the uniformly distributed hydrogen concentration in the containment and IRWST below 10 percent by volume, assuming the representative severe accident sequences.
2	Rationale for Location	**DBA**: Eight (8) PARs are installed around the polar crane in the containment and four (4) PARs are installed in the IRWST above the operating water level. **BDBA**: The PARs are distributed such that the overall average hydrogen concentration limit is achieved. General installation guidance is as follows: 1) The total number of PARs installed is distributed in approximate proportion to the local free volume.	The location was chosen through hydrogen concentration analyses with the nodalization comprised of around 40 compartments of MAAP4 or MAAP5. **DBA:** Twelve (12) positions are selected based on the analysis, including 4 at IRWST vent stack area. **BDBA:** Total 18 PARs for severe accident were installed. The size of PARs (small, medium and Large equipped with different number of	The PARs and igniters are located throughout the containment open volumes and compartments using the following criteria: a. Flow path requirements b. Consideration of enclosed spaces c. Equipment performance efficiency d. Installation and maintenance e. Consideration of dynamic effect. Igniters as supplementary to the PARs provide an

No.	Item	UAE	Republic of Korea	US
		2) PARs are distributed such that the convection flow generated by the PARs is large and crosses boundaries between containment areas. 3) PARs are installed in elevated locations above the potential sources of hydrogen releases. 4) To maximize PAR performance an attempt should be made to place the devices away from walls. 5) PARs should be easy to handle for installation and removal. 6) PARs installation locations should minimize negative effects on operations and maintenance activities. 7) PARs should be easy to inspect and test, e.g., easy removal of catalyst inserts. 8) PARs should be located away from potential missile and pipe whip impact locations and other potential accident damage locations. 9) PARs should have no adverse effects on nearby components for example, overheating from nearby equipment or impact from adjacent components during earthquakes.	PAR units) are decided by following criteria: 1) local free volumes 2) flow path 3) sources of hydrogen release 4) installation and maintenance	effective means of controlling local hydrogen concentration in compartments where the hydrogen release rate is greater than the depletion capability of PARs during a certain period of severe accident progression.

No.	Item	UAE	Republic of Korea	US
3	How many PARs available and how many of those are necessary for safety analysis	**DBA**: 12 PARs – only 6 are considered in the calculations (4 in the dome and 2 in the IRWST) **BDBA**: 18 PARs – all are considered in the calculations	**DBA**: 12 PARs – 8 (large) at upper dome area and 4 (medium) at IRWST vent stack area **BDBA**: 18 PARs – 6 medium at annulus space, 4 Large PARs at steam generator compartment area and 4 small PARs at other area	30 PARs and 8 Igniters None is credited for the DBA analysis.
4	Regulatory Criteria, if any	**DBA**: REG-03 Article (69), item 1, Systems to control fission products, hydrogen, oxygen and other substances that may be released into the reactor containment shall be provided as necessary. Systems for cleaning up the containment atmosphere shall have suitable Redundancy in components and features to ensure that the Safety Group can fulfil the necessary Safety Function, on the assumption of a Single Failure. **BDBA**: REG-03 Article (69), item 2, Consideration shall be given to the control of fission products, hydrogen and other substances that may be generated or released in the event of a Severe Accident. REG-03 Article (24), design activities shall take into account the following: c. Provisions for combustible gas control.	Regulatory Guideline 16.1.II,2 (a) and (b): (a) Hydrogen concentration shall not exceed 10% during and after severe accident where hydrogen generated from reaction of 100% cladding metal and water under the assumption of uniform distribution of hydrogen inside containment building. The concentration of combustible gas in each compartment of containment building shall be low enough for preventing wide-scale flame acceleration or deflagration to detonation transition. Facility shall be installed for protection of containment building from damage due to combustion of combustible gas in containment	10 CFR 50.44(c), GDC 41, GDC 42, GDC 43, and NRC Regulatory Guide 1.7

No.	Item	UAE	Republic of Korea	US
		RG-004 Article (12) item 3. c. the Design should provide a system for hydrogen control that can safely accommodate hydrogen generated by the equivalent of a 100 percent fuel-clad metal-water reaction. In addition, the Design should be capable of precluding uniform concentrations of hydrogen from exceeding 10 percent (by volume), or should provide an inerted atmosphere within the Containment.	building. b) Structural integrity of containment building shall be kept intact during and after severe accident where hydrogen is generated and released by reaction of 100% cladding metal and water, and pressure is increased due to deactivation after hydrogen combustion or accident (assuming carbon dioxide as deactivation agent). As for steel containment building, the requirements for Service Level C acceptable operating limit of Korea Electric Power Industry Code (KEPIC) MNE 3220 shall be satisfied. As for concrete containment building, the acceptable factored load category defined in Korea Electric Power Industry Code SNB 3720 shall be satisfied.	
5	Safety Classification, if any	NNS, Safety Class 3, Seismic category 1	**DBA**: Safety class 3 and seismic category I **BDBA**: non safety class	PARs: non-safety related, seismic Category I Igniters: Non-class 1E but powered from Class 1E bus (Train A or B) with the electrical isolation

No.	Item	UAE	Republic of Korea	US
				device in order to enhance the reliability of igniters; seismic Category I
6	Rationale for Qualification Test, if any	EPRI Report, "Qualification of Passive Autocatalytic Recombiners for Combustible Gas Control in ALWR Containments," EPRI ALWR Program, April 8, 1993	For DBA, EQ report and Seismic qualification required according to Article 12 (Safety Classes and Standards) of Regulation on Technical Standards for Nuclear Reactor Facilities. For BDBA, equipment survivability is required according to Article 85-20 (Equipment for accident management) of the above Regulation.	Covered under equipment survivability for temperature, pressure, and radiation. COL applicant will develop a test plan.
7	Do you use PARs with igniters? If yes, rationale for igniter's location?	Only for **BDBA**: Igniters are placed near source locations to promote the combustion of hydrogen in a controlled manner such that the containment integrity is maintained.	Yes, 10 hydrogen igniters for BDBA in order to cope with release of hydrogen with a high rate	Yes. See above under "Rationale for Location"
8	Do you consider Hydrogen ignition by PARs in the safety calculation	No	No (Assuming "safety calculation" refers to DBA analysis)	No (Assuming "safety calculation" refers to DBA analysis)
9	How do you get information about Hydrogen concentration in containment	Two hydrogen concentration sensors are provided with a minimum sensor indication range of 0 to 15% by volume as part of the post accident monitoring system.	Two hydrogen concentration sensors for four locations (two for upper containment area and two for lower area) are provided with a minimum sensor indication range of 0	Redundant seismic Category I hydrogen monitoring system consisting of hydrogen analyzer cabinets and monitoring cabinets. Two channels are designed to measure 0~15 percent volume of hydrogen in a

No.	Item	UAE	Republic of Korea	US
			to 15% by volume as part of the post accident monitoring system.	pressure range of -0.352 kg/cm²G (-5psig) to the maximum containment design pressure.
10	How is the availability of PARs ensured during the life of the plant? (periodic test, inspections, operating limiting conditions)	**DBA**: OTS surveillance requirements **BDBA**: OTS surveillance requirements	Sampling and sample test during outage.	Sampling and sample test during outage.
11	What are the protected measures for PARs during plant outage, if any, and what are the checks before restart?	Unknown at this time	Based on the operational experiences, start-up performance can be degraded due to deposited particles of dust and volatile organic compounds in the atmosphere. With this concern, licensee has an operating procedure in which extended samples are tested. Uncertain or unknown risks upon the catalyst performance are reflected in design calculations with 25% start-up failure.	Risk insight in the DCD stating that the Level 2 low power and shutdown PRA assumes 25% of the PARs are unavailable due to test and maintenance. The remaining 75% of the PARS and all the igniters are available.
12	Do the safety calculations take into account availability of PARs during shutdown events?	No (currently awaiting further information on accident analysis at shutdown)	No. (On-going review on the Accident Management Program will confirm the necessity of hydrogen control during low power shutdown conditions.)	Analysis of low power and shutdown accident sequences assumed with and without cavity flooding, containment sprays, hydrogen igniters, and PARs. The results showed that with either the igniters or PARs available, neither global nor local hydrogen

No.	Item	UAE	Republic of Korea	US
				concentrations exceed 10%.
13	Are there PARs in the spent fuel building? Rationale for having them or not?	2 PARs in the spent fuel building as a defence-in-depth measure – no technical justification provided.	No. There is no specific regulatory requirement for PARs in the spent fuel building. (On-going review on the Accident Management Program will confirm the necessity of hydrogen control in the spent fuel building.)	No. There is no regulatory requirement. No accident scenario generating hydrogen in the spent fuel pool is postulated as fuel remains covered with water.

4. Revision Summary

Revision No.	Date	Summary of Changes
0	July 2019	New document
1	October 2019	KINS comments incorporated
2	November 2019	US part suppressed
3	November 2020	Revised as report format based on MDEP-STC input
4	March 2021	USNRC comments incorporated