MDEP Design-Specific Technical Report

TR-AP1000WG-04

Technical Report on Common Understanding of the Hydrogen Control System for the AP1000 Design

PARTICIPATION	
Regulators involved in the MDEP working group discussions:	NNSA (China), AERB (India), NRC (U.S.)
Regulators that support the present technical report:	NNSA (China), AERB (India), NRC (U.S.)
Regulators with no objection:	none
Regulators that disagree:	none

Introduction

During the course of a severe accident in a light water nuclear reactor, a large amount of hydrogen could be generated and released into the containment due to reactor core degradation. Additional burnable gases (hydrogen and carbon monoxide) may also be generated and released into the containment if molten corium/concrete interaction occurs following a possible breach of the reactor vessel that releases core melt into the reactor cavity floor. This could subsequently cause a hydrogen explosion hazard. As observed during the Fukushima Daiichi accidents, hydrogen combustion may cause high pressure peaks that could challenge the integrity of a reactor containment and lead to the failure of surrounding buildings.

In a mixture known to be flammable, hydrogen combustion may be triggered by an energy source of a few millijoules. Consequently, an electrical power source or a hot point may be sufficient to ignite hydrogen when the lower flammability limit is reached. In contrast, a larger energy source (several kilojoules) is required to trigger a stable detonation. This explains why direct detonation can be ruled out for practical purposes; the only mechanism considered likely to provoke detonation is flame acceleration and the deflagration-to-detonation transition (DDT). Due to hydrodynamic instabilities and turbulence (primarily caused by obstacles in the flame's path), an initially laminar deflagration (with a flame velocity of around 1 m/s) may accelerate to a rapid deflagration (a few hundred m/s) and to a DDT (over 1000 m/s). These explosive phenomena pose the biggest threat to the mechanical integrity of the containment and safety components, as they can produce very large, localized dynamic loads.

As the combustion may lead to global and local pressure loads, the hydrogen risk assessment approaches use both global and local aspects. To deal with the global pressure loads, the AICC (adiabatic isochoric complete combustion) pressure is considered. To check the propensity of flame acceleration and DDT, dedicated experimental criteria are used:

- the "sigma" criterion, which compares the rate of expansion (ratio of gas densities before and after non-isochoric combustion) with a limiting value derived from a range of experiments,
- the "7 lambda" criterion which assesses the likelihood of DDT by comparing the gas mixture quality in terms of the detonation cell width, with the degree of confinement and the extent and type of obstacles present in the postulated flame propagation path.

Objective

The objective of this report is to identify a common understanding of the regulatory requirements for the Hydrogen Control System for the AP1000 design. This report will also identify any differences between the AP1000 design proposed in the People's Republic of China, India, and the United States (U.S.) as it relates to hydrogen management, the rationale for the Hydrogen Recombiner Subsystem, and the use of Hydrogen Passive Autocatalytic Recombiners (PARs) and any related regulatory differences. With that goal in mind, the National Nuclear Safety Administration (NNSA), the Atomic Energy Regulatory Board (AERB) and the U.S. Nuclear Regulatory Commission (NRC) have answered the following questions:

1. **Westinghouse Rationale for Hydrogen Control in the AP1000 design (as provided in Section 6.2.4 of AP1000 DCD)**

   The containment hydrogen control system is provided to limit the hydrogen concentration in the containment so that containment integrity is not endangered. Following a severe accident, it is assumed that 100 percent of the fuel cladding reacts with water. Although hydrogen production due to radiolysis and corrosion occurs, the cladding reaction with water dominates the production of hydrogen for this case. The hydrogen generation from the zirconium-steam reaction could be sufficiently rapid that it may not be possible to prevent the hydrogen concentration in the containment from exceeding the lower flammability limit. The function of the containment hydrogen control system for this case is to promote hydrogen burning soon after the lower flammability limit is reached in the containment. Initiation of a hydrogen burn at the lower level of hydrogen flammability prevents accidental hydrogen burn initiation at high hydrogen concentration levels and thus provides confidence that containment integrity can be maintained during hydrogen burns and that safety-related equipment can continue to operate during and after the burns.

The containment hydrogen control system serves the following functions:

- Hydrogen concentration monitoring
- Hydrogen control during and following a degraded core or core melt scenarios (provided by hydrogen igniters). In addition, two (safety-related in China and nonsafety-related in the U.S.) PARs are provided for defense-in-depth protection against the buildup of hydrogen following a loss of coolant accident.

2. Regulatory Requirements, if any

AP1000 US

The AP1000 US regulatory requirements concerning the hydrogen risk are the following:

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.

AP1000 China

In China, general regulatory requirements are in HAF102-2004 “Safety of nuclear power plants: design” and related guidelines and policy statement. Detailed regulatory requirements for the hydrogen assessment from the General Technical Requirements on post-Fukushima Nuclear Accident Improvement Measures for Nuclear Power Plants (NPPs) (tentative) are as follows:

HAF102-2004:

- 6.3.2 Strength of the containment structure
    - Provision for maintaining the integrity of the containment in the event of a severe accident shall be considered. In particular, the effects of any predicted combustion of flammable gases shall be taken into account.
- 6.3.10 Control and cleaning of gas in containment
    - 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.
        - Adequate 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.

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

1. 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 practicably possible for decision making during the accident management.
2. 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;
3. 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;
4. The hydrogen concentration monitoring and controlling measures should be included in severe accident management guide or relevant procedures.

AP1000 India

AERB’s Requirements for Hydrogen Management for Light Water Reactor (LWR) NPPs are brought out in AERB/LWR/SC/D (https://aerb.gov.in/images/PDF/CodesGuides/NuclearFacility/NPPDesign/1.PDF).

Further guidance and the technical aspects related to Hydrogen Management are covered in AERB/NPP-PHWR/SM/D-2 and its latest Appendix on locating of PARs, qualification parameters for PARs. AERB Safety manual is available in following link: (https://aerb.gov.in/storage/uploads/documents/regdocQv0MB.pdf).

The pertinent requirements are reproduced as given below:

AERB/LWR/SC/D, Clause 6.14 (Containment System for the Reactor):

> A containment system shall be provided to ensure, or to contribute to, the fulfilment of the following safety functions at the nuclear power plant: (i) confinement of radioactive

substances in operational states and in accident conditions, (ii) protection of the reactor against natural and human induced events and (iii) radiation shielding in operational states and in accident conditions. In addition to the enclosing building, containment system shall include: (a) leak tight features and structures, (b) associated systems for the control of pressure and temperature, (c) features for isolation, and (d) **features for management and removal of fission products, hydrogen, oxygen, and other substances that may be released into the containment atmosphere**.

6.14.1 The design of the containment system shall take into account all identified design basis accidents and design extension conditions.

6.14.2 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**.

AERB/LWR/SC/D, Clause 6.19.4 Necessary design features shall be provided to: (a) reduce the amounts of fission products that could be released to the environment in accident conditions, and (b) **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**.

Some pertinent clauses from AERB/NPP-PHWR/SM-D2 (AERB Safety Manual on Hydrogen Release and Mitigation Measures Under Accident Conditions in Pressurized Heavy Water Reactors)

AERB/NPP-PHWR/SM/D-2, Clause 4.4.2:

In view of this, hydrogen mitigation, if required, is recommended to be achieved by catalytic recombination principle. 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. For the inert atmospheric conditions (both dry and wet atmospheres), the steam concentration should be as per the Shapiro-Moffette diagram.

Under wet conditions, from among the total test matrix recommended for recombiner performance under clause 4.4.3 below, the qualification tests above 10% (v/v) and up to 30% (v/v) hydrogen concentration are required to characterise the recombiner behaviour in oxygen lean atmospheres.

While designing the hydrogen mitigation system for a specific plant following sub-clauses should also be addressed suitably:

(i) The mean hydrogen concentration in the compartments of the containment where recombiners are installed shall not exceed 9% (v/v) during the progression of the accident and in post-accident conditions.

(ii) The safe performance behaviour of multiple recombiners installed within single/multiple compartments may also be assessed and substantiated, if necessary. Accordingly, the recombiner devices shall be qualified as per the following criteria.

AERB/NPP/SM/D-2, Clause 4.3 Acceptance Criterion for Hydrogen Concentration in Containment

4.3.1 The recommended acceptance criteria for H2 concentration in containment are based on the following considerations:

(a) In case of LOCA [Loss of Coolant Accident] with safety systems including ECCS [Emergency Core Cooling Systems] available, the hydrogen concentration at a location in the containment should generally be maintained outside the deflagration (flammability) limit in the ternary diagram [ref. Fig. 1]. This shall be achieved without taking credit for mitigating measures such as recombiners/igniters. However, credit for mixing and/or purging provisions may be considered in the design.

If hydrogen concentrations cannot be ensured outside the deflagration (flammability) limit, the following should be ensured:

i). the area has no potential ignition sources such as sparks or hot surfaces (however, this may be difficult to ensure over a period of time); or

ii). any components located in the area required for safety function will survive the hydrogen fire, or their failure will not impair relevant safety functions required during the particular accident sequence. Any consequential effect of the fire due to hydrogen shall be considered to ensure that such safety functions are not impaired.

(b) For catering to accident sequences, involving multiple failures considered in design (e.g., LOCA with ECCS not available), the global hydrogen concentration shall remain outside the deflagration (flammability) region in the ternary diagram as shown in the Fig. 1 [24]. However, local hydrogen concentrations shall be such as to prevent local detonation which could affect containment integrity through missile generation or otherwise. This may be achieved with the use of mitigating measures given in section 4.4, if required.

4.3.2 Consideration in developing acceptance criteria:

Since the containment acts as the last barrier to hold the fission products, it is necessary to prevent hydrogen concentrations reaching a level that could threaten its integrity. In this connection, following measures have been suggested in order of importance [19]:

(a) Priority-1: Exclude a global detonation or a deflagration with the potential to reach failure pressure of containment.

(b) Priority-2: Prevention of local detonation, which could affect containment integrity through missile generation.

(c) Priority-3: Prevention of local hydrogen concentration greater than 10 percent by volume [This Clause shall be read in conjunction with 4.4.2 (i)].

(d) Priority-4: Mitigation of the consequences of local, multiple burning, leading to high temperatures (failure of local equipment).

It is seen that the most important requirement is to prevent global detonations. Prevention of ignition deflagration is the next priority to ensure continued availability of systems required for safety.

3. Describe the Containment Environment with Regard to the Hydrogen Control system for the AP1000

AP1000 US and AP1000 China

Containment structures are arranged to promote mixing via natural circulation. For a postulated break low in the containment, buoyant flows develop through the lower compartments due to density head differences between the rising plume and the surrounding containment atmosphere, tending to drive mixing through lower compartments and into the region above the operating deck. There is also a degree of mixing within the region above the operating deck, which occurs due to the introduction of and the entrainment into the steam-rich plume as it rises from the operating deck openings. Thus, natural forces tend to mix the containment atmosphere.

Two general characteristics have been incorporated into the design of the AP1000 to promote mixing and eliminate dead-end compartments. The compartments below deck are large open volumes with relatively large interconnections, which promote mixing throughout the below deck region. All compartments below deck are provided with openings through the top of the compartment to eliminate the potential for a dead pocket of high-hydrogen concentration. In addition, if forced containment air-circulation is operated during post-accident recovery, then non-safety-related fan coolers contribute to circulation in containment.

In the event of a hydrogen release to the containment, PARs act to recombine hydrogen and oxygen on a catalytic surface. The enthalpy of reaction generates heat within a passive autocatalytic recombiner, which further drives containment mixing by natural circulation. PARs reduce hydrogen concentration at very low hydrogen concentrations (less than 1 percent) and very high steam concentrations and may also promote convection to complement passive containment cooling system natural circulation currents to inhibit stratification of the containment atmosphere. The implementation of PARs has a favorable impact on both containment mixing and hydrogen mitigation. Further, the AP1000 design incorporates strategically located hydrogen igniters to address areas that may be more prone to higher local hydrogen concentrations.

AP1000 India

Since AERB has not received any formal application and the submissions for AP1000, no information is available at this time.

4. Rationale for the Hydrogen Recombiner Subsystem

AP1000 US and AP1000 China

The hydrogen recombination subsystem is designed to accommodate the hydrogen production rate anticipated for loss of coolant accident. The hydrogen recombination subsystem consists of two non-safety-related PARs installed inside the containment above the operating deck near the containment shell. The locations provide placement within a homogeneously mixed region of containment. The location is in a predominately up-flow natural convection region. Additionally, the PARs are located azimuthally away from potential high up-flow regions such as the direct plume above the loop compartment.

AP1000 India

AERB Response: Since AERB has not received any formal application and the submissions for AP1000, no information is available at this time. Refer to AERB's requirements as brought out above.

5. Rationale for the Hydrogen Ignition Subsystem

AP1000 US and AP1000 China

The hydrogen ignition subsystem is provided to address the possibility of an event that results in a rapid production of large amounts of hydrogen such that the rate of production exceeds the capacity of the PARs. Consequently, the containment hydrogen concentration will exceed the flammability limits. This massive hydrogen production is postulated to occur as the result of a degraded core or core melt accident (severe accident scenario) in which up to 100 percent of the zirconium fuel cladding reacts with steam to produce hydrogen.

The hydrogen ignition subsystem consists of 66 hydrogen igniters strategically distributed throughout the containment. Since the igniters are incorporated in the design to address a low-probability severe accident, the hydrogen ignition system is not Class 1E. Although not class 1E, the igniter coverage, distribution and power supply has been designed to minimize the potential loss of igniter protection globally for containment and locally for individual compartments. The igniters have been divided into two power groups. Power to each group will be normally provided by offsite power, however should offsite power be unavailable, then each of the power groups is powered by one of the onsite non-essential diesels and finally should the diesels fail to provide power then approximately 4 hours of igniter operation is supported by the non-Class 1E batteries for each group.

Assignment of igniters to each group is based on providing coverage for each compartment or area by at least one igniter from each group.

The locations of the igniters are based on evaluation of hydrogen transport in the containment and the hydrogen combustion characteristics. Locations include compartmented areas in the containment and various locations throughout the free volume, including the upper dome. For enclosed areas of the containment at least two igniters are installed. The separation between igniter locations is selected to prevent the velocity of a flame front initiated by one igniter from becoming significant before being extinguished by a similar flame front propagating from another igniter. The number of hydrogen igniters and their locations are selected considering the behavior of hydrogen in the containment during severe accidents. The likely hydrogen transport paths in the containment and hydrogen burn physics are the two important aspects influencing the choice of igniter location.

The primary objective of installing an igniter system is to promote hydrogen burning at a low concentration and, to the extent possible, to burn hydrogen more or less continuously so that the hydrogen concentration does not build up in the containment. To achieve this goal, igniters are placed in the major regions of the containment where hydrogen may be released, through which it may flow, or where it may accumulate.

AP1000 India

Since AERB has not received any formal application and the submissions for AP1000, no information is available at this time. Refer to AERB's requirements as brought out above.

6. Rationale for Qualification Test, if any

AP1000 US

PARs are provided in the AP1000 as defense-in-depth protection against the buildup of hydrogen following a loss of coolant accident and no qualification tests are done for PARs.

As required by 10 CFR Part 50.44 and GDC 41 and 43, AP1000 Inspections, Tests, Analyses, and Acceptance Criteria includes testing performed for the following of the hydrogen control system before the initial fuel loading:

- The hydrogen monitors are powered by the non-Class 1E dc and uninterrupted power system.
- The hydrogen igniters are powered from their respective non-Class 1E power system.
- Controls exist in the main control room to cause the hydrogen igniters to energize.
- The hydrogen igniters are energized after receiving a manual signal from the diverse actuation system

AP1000 China

Equipment qualification for design basic accident is done for PARs, in environment zone 1-Containment, and with harsh environment conditions (considering either a main steam line break or LOCA environmental envelopes). Equipment survivability evaluation in severe accident environment condition is done for hydrogen igniters and hydrogen monitor system, using best-estimate basis lumped parameter code, experimental data and thermal lag analyses for equipment survivability demonstration.

AP1000 India

AERB Response:
Qualification Parameters for Catalytic Recombiners (Refer AERB/NPP-PHWR/SM/D-2): Based on the functional requirements of the recombiners and the technology available for conducting the experiments, following qualification parameters are worked out.

- Qualification under inert atmosphere: Hydrogen concentration up to 4 % v/v (in dry air medium), up to 30% v/v (in inert steam environment) and Steam concentration: As per Shapiro-Moffette diagram to ensure inert conditions.

- 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

- The catalyst shall be demonstrated to be free from spallation phenomena up to a catalyst temperature of 1000 C 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.

- Pressure: LOCA based peak pressure

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

- Minimum temperature for the onset of recombination process: 30°C or lower

- 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

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

7. Safety Classification, if any

AP1000 US

The hydrogen control system is a nonsafety-related system as it does not fall under the 10 CFR 50.2 definition of safety-related structures, systems and components.

AP1000 China

The hydrogen recombination subsystem consists of two safety-related passive autocatalytic recombiners. The hydrogen ignition system is non-Class 1E, as it is designed to address severe accidents.

The hydrogen concentration monitoring subsystem contains a total of three sensors designated as non-Class 1E serving to provide a post-accident monitoring function. The hydrogen sensors are powered by the non-Class 1E DC and uninterruptable power supply system.

AP1000 India

AERB Response: The PARs or Igniters are of similar safety class as those of DiD-4 additional safety system or complementary safety measures.

8. Do you consider Hydrogen Ignition in the Safety Calculation?

AP1000 US and AP1000 China

Safety calculation refers to the design basis analysis. No hydrogen ignition is considered during a design basis accident because the regulation limits the maximum hydrogen generation: "the calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react." However, beyond design basis analysis involves hydrogen ignition, and these calculations can consider local hydrogen concentrations and subsequent ignitions in containment.

AP1000 India

If deflagration is not avoidable, it should be accounted for in the containment pressure and temperature rise estimations.

9. Hydrogen Monitoring Procedures?

AP1000 US and AP1000 China

The hydrogen concentration monitoring subsystem consists of three hydrogen sensors. The sensors are placed in the upper dome where bulk hydrogen concentration can be monitored. The system contains a total of three sensors designated as non-Class 1E serving to provide a post-accident monitoring function.

The hydrogen sensors are powered by the non-Class 1E dc and uninterruptable power supply system. Hydrogen concentration is continuously indicated in the main control room. Additionally, high hydrogen concentration alarms are provided in the main control room.

The sensors are designed to provide a rapid response detection of changes in the bulk containment hydrogen concentration.

AP1000 India

AERB Response: Specific to design.

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

- For the purpose of severe accident monitoring and management, appropriate means shall be considered for the plant, by which the operating personnel obtain information for event assessment, and for the planning and implementation of mitigating actions. It shall be possible to assess the information about the following:
- Condition of core or debris
- Condition of reactor pressure vessel
- Condition of containment
- Condition of spent fuel storage pool
- Radiological situation in the plant, site and its immediate surroundings
- Status of implemented accident management measures.

The measurement systems/instrument shall be capable of measuring over the entire range within which the measured parameters are expected to vary during accident conditions.

10. How is the Availability of Hydrogen Control Equipment Ensured during the Life of the Plant? (Periodic Test, Inspections, Limiting Conditions of Operation)

AP1000 US

Operability of the hydrogen igniters is addressed by short-term availability controls during modes 1, 2, 5 (with RCS pressure boundary open), and 6 (with upper internals in place or cavity levels less than full).

AP1000 China

Periodic inspection and maintenance are performed correspondingly for hydrogen control equipment during outages to verify their reliability during plant life.

Hydrogen Recombination Subsystem

- Periodic inspection and testing are performed on the two PARs during every refueling outage.
- For each PAR, three adjacent catalytic plates are chosen randomly, and are visually inspected for surface corrosion.
- For each catalytic plate, they are tested in specific equipment, with inlet gas flow rate 6.5 SLM, H_2 volume concentration of 3%, at 40°C. The PAR can be considered reliable if 3 tested plates pass the tests, with 60% hydrogen elimination efficiency in 5 minutes.

Hydrogen Ignition Subsystem

In every refueling outage, periodic inspection and testing are performed to confirm the continued operability of the hydrogen ignition system. Operability testing consists of energizing the igniters and confirming the surface temperature exceeds 1700 °F (926.67 °C).

Hydrogen Concentration Monitoring Subsystem

In every refueling outage, periodic testing and calibration are performed on each hydrogen sensor, to confirm their reliable function of monitoring hydrogen concentration.

AP1000 India

AERB Response: Through periodic testing (during outage) and surveillance.

11. What are the Protected Measures for Hydrogen Control Equipment during Plant Outage, if any, and what are the Checks Before Restart?

AP1000 US

Operability of the hydrogen igniters is addressed by short-term availability controls during modes 1, 2, 5 (with RCS pressure boundary open), and 6 (with upper internals in place or cavity levels less than full).

AP1000 China

The hydrogen igniter function should be available during MODES 1 and 2 when core decay heat is high and during MODE 5 when the RCS pressure boundary is open and in MODE 6 when the refueling cavity is not full. Planned maintenance should be performed on hydrogen igniters when they are not required to meet this availability control. Recently, the applicant submitted a design change (G-NL-GLF-180012) to modify STAC 2.8 requirements for 4 igniters above the refueling cavity.

During plant outages, both of the recombiners are protected by shielding installed to prevent possible impurities in the containment atmosphere from contacting the catalytic plates, as a result of experience feedback from domestic plants. The shielding is removed prior to restart.

AP1000 India

This is specific to design. During plant outages, if any activity leading to the possibility of allowing impurities/dust to get on the PARs, the PARs are to be shielded. The shielding is to be removed before restart. Generally, a check is made for availability of minimum capacity (considering layout) with margin for the hydrogen recombiner prior to restart.

12. Do the Safety Calculations Take into Account Availability of Hydrogen Control Equipment during Shutdown Events?

AP1000 US

No

AP1000 China

The availability of igniters is considered in severe accident management during shutdown events. Calculation and evaluation are carried out by the designer for availability of hydrogen control equipment in the Severe Accident Management Guidelines for low power and shutdown conditions.

AP1000 India

All credible plant states are assessed and accordingly availability of equipment is ensured specific to each design.

13. Is there Hydrogen Control Equipment in the Spent Fuel Building? Rationale for having them or not?

AP1000 US

No. Regulation does not require hydrogen control equipment in the spent fuel building.

AP1000 China

There is no hydrogen control equipment in the spent fuel building for the AP1000 design. Hydrogen concentration in the spent fuel building is prevented by venting reinforcement. 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.

AP1000 India

AERB Response: Based on safety assessment for credible events, the required provisions are to be made for spent fuel building also.

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:
    - 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);

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

Conclusions

The containment hydrogen control system of the AP1000 design is provided to limit the hydrogen concentration in the containment so that containment integrity is not endangered. The function of the containment hydrogen control system is to promote hydrogen burning soon after the lower flammability limit is reached in the containment, and has the following features:

- Hydrogen concentration monitoring
- Hydrogen igniters, strategically located to address areas that may be more prone to higher local hydrogen concentrations, provide hydrogen control during and following a degraded core or core melt scenarios.
- Hydrogen recombination subsystem, including two PARs positioned within a homogeneously mixed region of containment, is provided to prevent the buildup of hydrogen following a loss-of-coolant accident and is designed to accommodate the hydrogen production rate anticipated for a loss-of-coolant accident.

The design of the containment hydrogen control system is based on the assumption that production of hydrogen is dominated by the cladding reaction with water.

The AP1000 design within containment incorporates two general characteristics to promote mixing and eliminate dead-end compartments. First, the compartments below deck are large open volumes with relatively large interconnections, which promote mixing throughout the below deck region. Second, all compartments below deck are provided with openings through the top of the compartment to eliminate the potential for a dead pocket of high-hydrogen concentration. In addition, if forced containment air circulation is operated during post-accident recovery, then non-safety-related fan coolers contribute to circulation in containment.

Regulators in the U.S. and China have reviewed the AP1000 containment hydrogen control system 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 exist. PARs are safety-related in China, but nonsafety-related in the U.S. As such, equipment qualification requirements for PARs exist in China and there are none in the U.S. Hydrogen ignition is considered in the severe accident analysis in China and in the beyond basis analysis in the U.S. Conclusions about the design by the India regulator are pending review of a future applicant submittal.