# Enhanced Safety Measures of Highly Innovative ABWR

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**Abstract:** Based on the international standard ABWR, for which UK Design Acceptance Confirmation (DAC) was granted (UK ABWR), the Highly Innovative ABWR (HI-ABWR) is currently under development aiming for the introduction in the 2030s. The plant design adopts new safety features such as 1) enhanced protection of safety systems against natural disasters, terrorism, internal hazards, 2) suppression of accident expansion with passive safety systems utilizing natural forces, 3) suppression of radioactive material release during severe accident. Specific measures for the above 1)2)3) are as follows. 1): airplane crash countermeasures with the international standard protection designed according to NEI guideline (NEI-07-03), tsunami countermeasures with dry site design, and internal fire/flooding countermeasures with safety-divisional separation barrier. 2): PRCS (Passive Reactor Cooling System), LDF (Lower Drywell Flooder), and COPS (Containment Overpressure Protection System). 3): the noble gas filter and the new iodine filter. Among the above countermeasures, passive safety systems preclude the potential of human errors and active equipment and support system failures and reduce the plant risk. Those effects of the risk reduction were roughly evaluated by PRA.

**Keywords:** Innovative light water reactor, BWR, ABWR, Enhanced hazard countermeasures, Passive safety systems, Noble gas filter, PRA.

## 1. INTRODUCTION

Hitachi-GE Nuclear Energy, Ltd. (Hitachi-GE) has been introducing technologies for Japanese existing nuclear power plants to provide higher safety margins in accordance with the new regulatory standards that incorporate what was learned from the accident at TEPCO's Fukushima Daiichi Nuclear Power Station (the FDNPS accident). The advanced boiling water reactor (ABWR) for the UK (UK ABWR), which was designed from the outset to incorporate the lessons learned from the FDNPS accident into the widely used ABWR design, underwent a Generic Design Assessment (GDA) in 2017 and is now recognized as a globally standardized plant that complies with international safety standards.

Currently, Hitachi-GE is developing the Highly Innovative ABWR (HI-ABWR) aiming for the introduction in the 2030s, which is an innovative light water reactor incorporating a new safety mechanism while still being based on the UK ABWR design [1][2].

This paper elucidates the concept of the HI-ABWR design and provides the preliminary result of PRA regarding the effect of passive safety systems which preclude the potential of human error and failure of active equipment and support systems.

## 2. FEATURES OF HIGHLY INNOVATIVE ABWR

The electric power of the HI-ABWR is planned to be 1,350 1,500 MWe, and the measures for design basis accidents are basically the same as the conventional ABWR, such as the engineered safety feature with three division of emergency core cooling system. With a goal of enhancing safety on the two aspects of "accident prevention" and "mitigation of the impact in the event of a severe accident", the HI-ABWR has the following innovative safety features: 1) enhanced protection of safety systems against natural disasters, terrorism, internal hazards, 2) suppression of accident expansion with passive safety systems utilizing natural forces, 3) suppression of radioactive material release during severe accident.

Furthermore, moving towards carbon neutrality, it is designed to extend the inherent advantages of the flexibile and high-performance operational capabilities of boiling water reactors (BWRs). The above features are described in detail in the following sections.

### 2.1. Enhanced Resistance to Natural Disasters, Terrorism, and Internal Hazards

For external hazards, structural integrity against loads is ensured by exterior walls of the reactor building. For internal hazards, the safety-divisional separation barrier with the fire-resistance/water shut-off walls is introduced. These measures enhance resistance to events that produce common cause failures. Countermeasures for these hazards are explained below.

(1) Airplane Crash Countermeasures
The following measures, which are designed for the UK ABWR with reference to the guideline [3], are adopted.

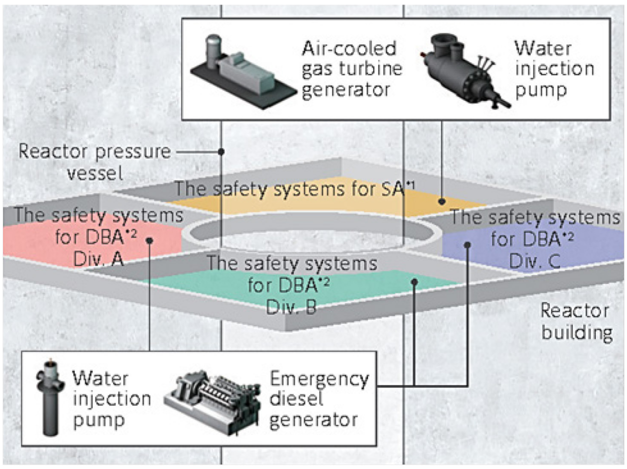
- Physical impact: protection by the exterior wall, which is also seismic resistant, limiting the increase in building materials for economic efficiency (Figure 1).
- Fire: safety-divisional separation barriers protect so that at least one safety division always survives.
- Shock vibration: the exterior wall also minimizes the range of vibration propagation.

Figure 1. Cross-section of the HI-ABWR Building
with Aircraft Crash Countermeasure and Enhanced Seismic Resistance [2]

(2) Seismic resistance
Enhancement of seismic resistance is provided by: further lowering the center of gravity of the building by installing heavy equipment on the lower floors and reducing the slab of higher level, lateral restraint using rocks and backfilling soils around the building, advanced aseismic design of equipment.

(3) Tsunami countermeasures
For the standard tsunami hazard, dry site design with the raised ground level or sea walls. For the beyond-standard tsunami hazard, watertight exterior walls for the ground floor.

(4) Internal fire and flooding countermeasures
The safety-divisional separation barriers, which was designed for the UK ABWR, is adopted (Figure 2). Four divisions, which consist of three divisions of design basis accident (DBA) equipment and one division of severe accident (SA) equipment, are separated by the fire-resistance/water shut-off walls. These configuration limits the impact within one division. Also the concentrated arrangement of equipment in each division reduces the number of penetration treatments for fire-resistance/water-shutoff and fire-resistant cable wrappings, etc. Further, the SA equipment has diversity and additional margin from the DBA equipment.




*1 The safety systems for SA...The safety systems for severe accidents
*2 The safety systems for DBA...The safety systems for design basis accidents

Figure 2. Safety-divisional Separation Barriers

For the specific SAs such as aircraft crash, conventionally, specialized safety facilities that have the function of preventing a primary containment vessel damage, which is the function of SA equipment, are installed independently from DBA and SA equipment. Since the HI-ABWR installs SA equipment in the building with airplane crash countermeasures and safety-divisional separation barriers as described above in (1) and (4), the SA equipment and the specialized safety facilities can be merged to each other. However, facilities that require independence, such as emergency control rooms, will be installed separately same as existing nuclear power plants. With the above arrangement, it is possible to rationalize the equipment configuration and improve the imbalance between levels of “defense in depth”.

### 2.2. Suppression of Accident Expansion with Passive Safety Systems

The HI-ABWR is equipped with the following passive safety systems:

- Passive Reactor Cooling System (PRCS)
- Core catcher and Lower Drywell Flooder (LDF)
- Containment Overpressure Protection System (COPS)

An overview of the PRCS is shown in Figure 3 and below.

- In the event of severe accident, reactor coolant is supplied as steam from the Reactor Pressure Vessel (RPV) to the PRCS heat exchanger (PRCS-Hx), where reactor coolant is condensed, and condensed coolant returns to the RPV. The PRCS-Hx is placed at an elevation above the RPV so that the process is driven passively by gravitational force.
- Capacity of 24 hours decay heat removal, automatic initiation, no manual operation required.

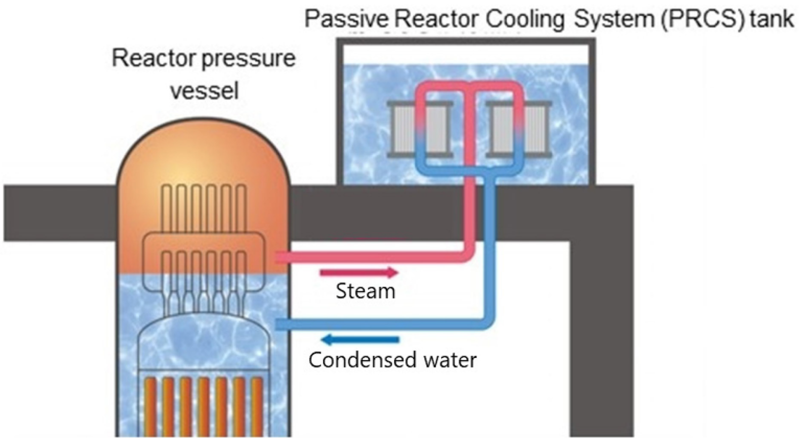



Figure 3. Passive Reactor Cooling System (PRCS)

An overview of the core catcher and the LDF is shown in Figure 4 and below.

(Core catcher)

- In the event of core damage and debris falling from the RPV, the debris is retained and cooled, while preventing floor erosion.
- By installing the core catcher in a ABWR's lower dry well, which is wide enough to reduce the heat flux (decay heat per debris spread area), so no additional debris spreading area is required.
- Refractory materials were developed in the national project[*1] and already applied to existing nuclear power plants.
  *1: Development of passive debris cooling system (Phase II)

(LDF)

- The radiant heat from the debris activates the fusible plug valve, which injects coolant by gravitational force to cool the debris.
- The suppression pool as water source has the capacity to cool debris for three days. No manual operation is required.

Injecting water to cool molten debris carries the potential risk of a steam explosion. The risk of a steam explosion at ABWR has been studied [4], and the injecting water strategy was reviewed in the licensing for UK ABWR and Japanese existing plants. HI-ABWR will basically adopt the same strategy.

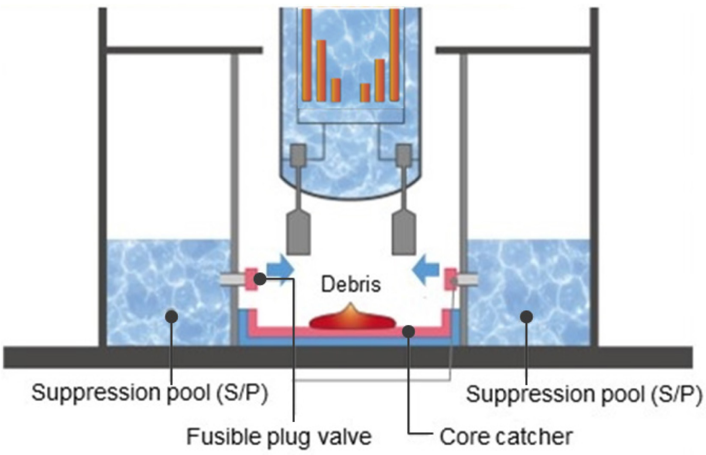



Figure 4. Core Catcher and Lower Drywell Flooder (LDF)

An overview of the COPS is shown in Figure 5 and below.
By installing a rupture disk on the vent line, the COPS automatically vents when the pressure in the primary containment vessel rises due to radiant heat from debris and reaches the pre-set pressure. This prevents overpressure damage to a primary containment vessel.

The above passive safety systems, which are considered as a backup for automated active systems and active systems with manual operation, reduce the plant risk by mitigating human error, failure of active equipment and support systems and reduce the loads on operators.

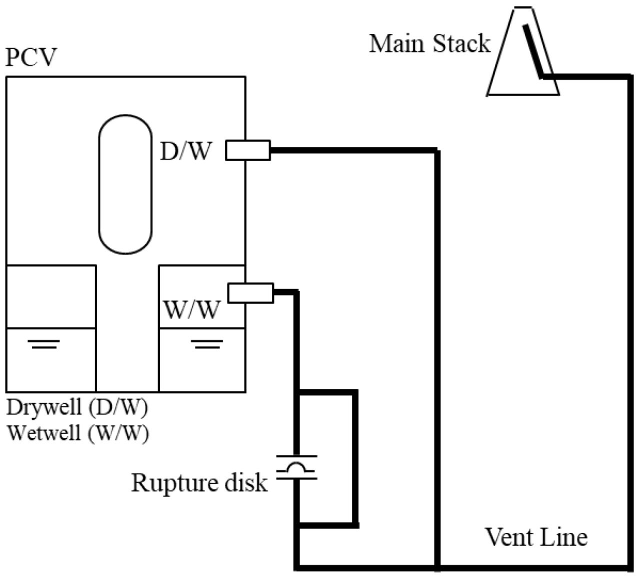



Figure 5. Containment Overpressure Protection System (COPS)

### 2.3. Suppression of Radioactive Material Release during Severe Accident

Since the FDNPS accident, a filter vent system has been introduced to reduce pressure and to remove decay heat in a primary containment vessel while suppressing the release of radioactive materials into the environment as a response to new regulatory standards for existing nuclear power plants. Additionally, noble gas filter and new iodine removal filter are introduced to the HI-ABWR to further control radioactive materials.

Figure 6 shows an outline of a noble gas filter and a new iodine removal filter. The noble gas filter is under development in the national project[*2] and to be installed downstream side of the filter vent tank to separate the noble gas from the vent gas using the difference in transmittance. A new iodine removal filter is also under development in the national project[*3], which uses an ionic liquid as remover to improve decontamination factor compared to conventional iodine removal filters. The above equipment allows only steam and hydrogen to be released from a stack, without releasing nitrogen and noble gases.

The above countermeasures significantly reduce the risk of resident evacuation even in the event of a severe accident. Also earlier venting enhances the robustness of a primary containment vessel and reduce the risk of hydrogen combustion.

*2: Development of a noble gas filter system that reduces exposure during severe accidents and treats hydrogen and water vapor
*3: Development of technologies that contribute to the advancement of radioactive material removal technology for filter vent systems

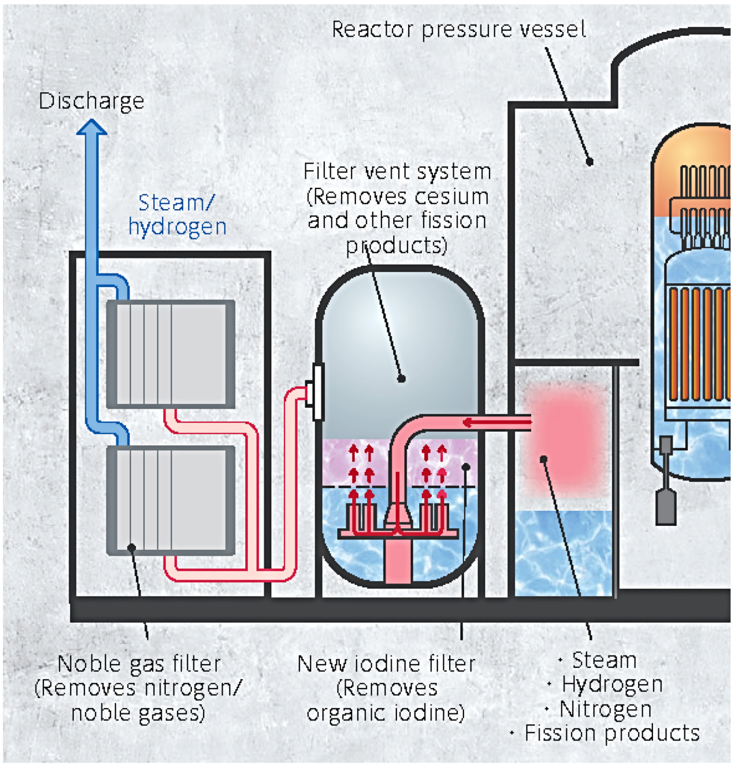



Figure 6. Containment System for Radioactive Substances

### 2.4. Enhanced Response Reliability during Severe Accident

Under the conventional regulations, mobile equipment is necessary to address severe accident scenarios, but the HI-ABWR is basically able to address accidents using only permanent systems. This will reduce human errors (in manual operations at the field), improve reliability, bring the event under control at an early stage, and reduce the loads on operators and emergency response personnel. Mobile equipment will be prepared to address the events that significantly exceed design basis and considered as voluntary efforts to improve flexibility by improving equipment and configuration as appropriate.

### 2.5. Contribution to Carbon Neutrality through Flexible Operation

Aiming to coexist with other power sources such as renewable energy, the HI-ABWR has the capability of flexible operation, such as daily load following and frequency control operation, using both the recirculation flow rate control and the control rod manipulation, which are the advantages of a BWR.

It is also compatible with the latest BWR 10×10 fuel, enabling long-term cycles of up to 24 months and full-core MOX loading.

## 3. EFFECT OF RISK REDUCTION OF PASSIVE SAFETY SYSTEMS

The safety design of the HI-ABWR is based on the UK ABWR. Hitachi-GE developed a full-scope PRA and used the PRA in support of design for the UK ABWR. The overall PRA evaluated all internal and external hazards risks for both at-power and low power/shutdown modes conditions, as well as spent fuel pool and fuel route hazards [5]. The scope of the PRA included Level 1 through Level 3 risk assessments. Multiple peer reviews were conducted for the UK ABWR PRA to demonstrate that the PRA meets the industry's technical adequacy requirements. The extensive set of peer reviews give assurance of the adequacy of each PRA deliverable. As a result, the UK ABWR PRA was certificated as international modern standards PRA through the GDA process.

Based on the certificated the UK ABWR PRA, PRA was performed for the HI-ABWR to examine the degree of risk reduction that can be achieved by the passive safety systems discussed above. The design differences between the UK ABWR and the HI-ABWR were reflected to the UK ABWR PRA model. That includes the

PRCS. Among the passive safety systems, this assessment mainly focuses on the PRCS and its effect on internal events at-power Level 1 PRA (i.e., Core Damage Frequency (CDF)). The PRCS can effectively perform its function (core cooling/reactor depressurization without decay heat transfer to the containment) to prevent core damage in transient sequences. Risk reduction of CDF of the general transient for which the PRCS is effective was assessed. The results are presented in Figure 7. Figure 7 includes CDFs for both the UK ABWR and the HI-ABWR for three major Level 1 PRA end states: TQUV, TQUX and TW. Brief description of these three end states is as follows. The CDFs are normalized by CDF of TQUV for UK ABWR.

- TQUV: Transient event with failure of high-pressure injection and low-pressure injection, resulting in low pressure core damage in short term
- TQUX: Transient event with failure of high-pressure injection and depressurization, resulting in high pressure core damage in short term
- TW: Transient event with failure of containment heat removal, resulting in high/low pressure core damage in long term after containment failure

It can be concluded from this result that the PRCS can reduce risks from core damage sequences where core cooling (injection) function (TQUV), reactor depressurization function (TQUX) or containment heat removal function (TW) is lost. It is noted that the CDF of TW is higher than that of TQUX in the result of HI-ABWR. This follows opposite trend to the UK ABWR result. The main reason for this difference is that ultimate heat sink is changed to cooling tower. This change introduces additional failure mode of ultimate heat sink while this contributes risk reduction for external events.

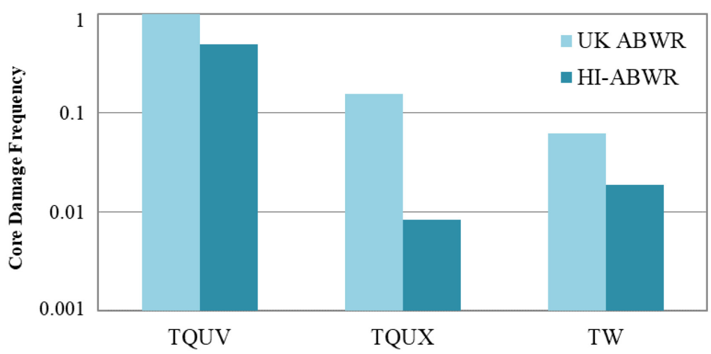



Figure 7. Comparison of CDF of TQUV, TQUX and TW between UK ABWR and HI-ABWR
(General Transients for Internal Events at Power PRA)

Similar risk reduction is expected in the other transient initiating events. Although the PRCS cannot solely prevent core damage in Loss of Coolant Accident (LOCA) sequences due to reactor depressurization, contributions from LOCAs to total risk is low in PRA results of the historical BWRs. Thus, overall plant risks of the HI-ABWR are expected to be decreased.

It is noted that the COPS deployed for both the UK ABWR and the HI-ABWR contributes to reduce risks from core damage sequences where containment heat removal function is lost (i.e., TW). As shown in Figure 7, CDF of TW is much lower than that of TQUV/TQUX. That proves plant risk from TW sequences can be reduced by the COPS since TW dominates CDF of internal events in PRA results of historical BWRs which do not have the COPS. The LDF also deployed for both the UK ABWR and the HI-ABWR can mitigate sequences where debris is discharged from a reactor pressure vessel (i.e., Level 2 PRA). The effect of risk reduction compared to the existing ABWR in Japan will be assessed in Level 2 PRA.

The next light water reactor working group defines numerical risk target of $10^{-5}$ for CDF and $10^{-6}$ for LRF [6]. The total CDF and LRF for the UK ABWR estimated by the full-scope PRA are slightly higher than the targets. It is expected that the HI-ABWR can meet the target as the total plant risk of the HI-ABWR decreases due to the effect of additional safety features including the PRCS compared to the UK ABWR.

One of the important roles of the PRA for design phase plant is to provide risk insights to identify plant potential vulnerabilities/enhancements in support of plant design. A full scope PRA will be performed to develop risk insights in support of the design of the HI-ABWR.

## 4. CONCLUSION

The HI-ABWR is under development aiming for the introduction in the 2030s as an innovative light water reactor incorporating a new safety mechanism such as enhanced resistance to natural disasters / terrorism / internal hazards, passive safety system, and suppression of radioactive material release during severe accident.

In this paper, newly introduced safety systems are presented. Also, among the new systems, the effect of improving the safety with passive safety systems was roughly evaluated by PRA, which indicates that it is expected to meet the numerical target. In the future, design refinement based on the risk insights obtained from PRA will be continuously performed throughout design phase to further improve the plant safety.

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