Level 1 PRA Considering Optimization of Safety Systems for the iB1350

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Abstract: The iB1350 stands for innovative, intelligent and inexpensive BWR 1350 which is the first Generation III.7 reactor after the Fukushima Daiichi accident, and incorporates the lessons from the accident and the WENRA safety objectives. It has a double cylinder RCCV (Mark W containment) and an in-depth hybrid safety system (IDHS). The IDHS currently consists of 4 division active safety systems for DBA, 2 division active safety systems and built-in passive safety systems (BiPSS) consisting of isolation condensers (IC) and innovative passive containment cooling systems (iPCCS) for Severe Accident (SA), which brings the total to 6 division active safety systems. One of the unique features of the BiPSS combined with the Mark W containment enables the iPCCS to remove the heat from the S/P without any active components, while the conventional PCCS cannot. This excellent feature affords us the opportunity to suggest several options for the IDHS configuration to reduce the plant cost while enhancing the safety level. In this study, we perform the internal Level 1 PRA and sensitivity analysis relating external events to present risk insights of 3 possible options of the IDHS configuration for best choice.

Keywords: iB1350, PRA, ABWR, Mark W, Fukushima

1. INTRODUCTION

The innovative, intelligent and inexpensive boiling water reactor 1350 (abbreviated to iB1350 hereafter) incorporates lessons learned from the Fukushima Daiichi accident in 2011 and the safety objectives of the Western European Nuclear Regulators Association (WENRA) [1,2]. However, main features of the iB1350 had been developed before the accident. It was originally called Severe Accident Tolerant and Optimized Reactor (SATOR). A paper on the SATOR was published in ICONE19 [3]. ICONE19 was originally scheduled in April, 2011 in Makuhari, Japan about 200 km south from the Fukushima Daiichi nuclear power station. The conference was postponed due to the accident and held in Osaka in southern Japan later in the year. The present paper on the iB1350 is mostly based on the ICONE19 paper on the SATOR in 2011 [3], ICONE22 paper [4], ICONE23 paper [5] and ICONE24 paper [6]. This paper provides the PRA analysis and comparison of the 2 new optimized configurations for iB1350 that are expected to reduce cost and enhance reliability from the original design.

2. MAIN CHARACTERISTICS OF THE iB1350

Main characteristics of the iB1350 are similar to those of SATOR [3]. Although the basic design of SATOR has been developed before the Fukushima Daiichi accident, it satisfies the requirements based on the lessons from the accident and WENRA safety objectives. This is because design objectives of the SATOR/iB1350 had originally envisaged the residual risks coming from devastating external hazards written in the ICAPP09 paper [9] before the Fukushima Daiichi accident including:

- Extremely severe earthquake far beyond design basis
- Extremely strong cyclone, hurricane, and typhoon
- Extremely large tsunami
- Large airplane crash
- Intentional attack by terror.

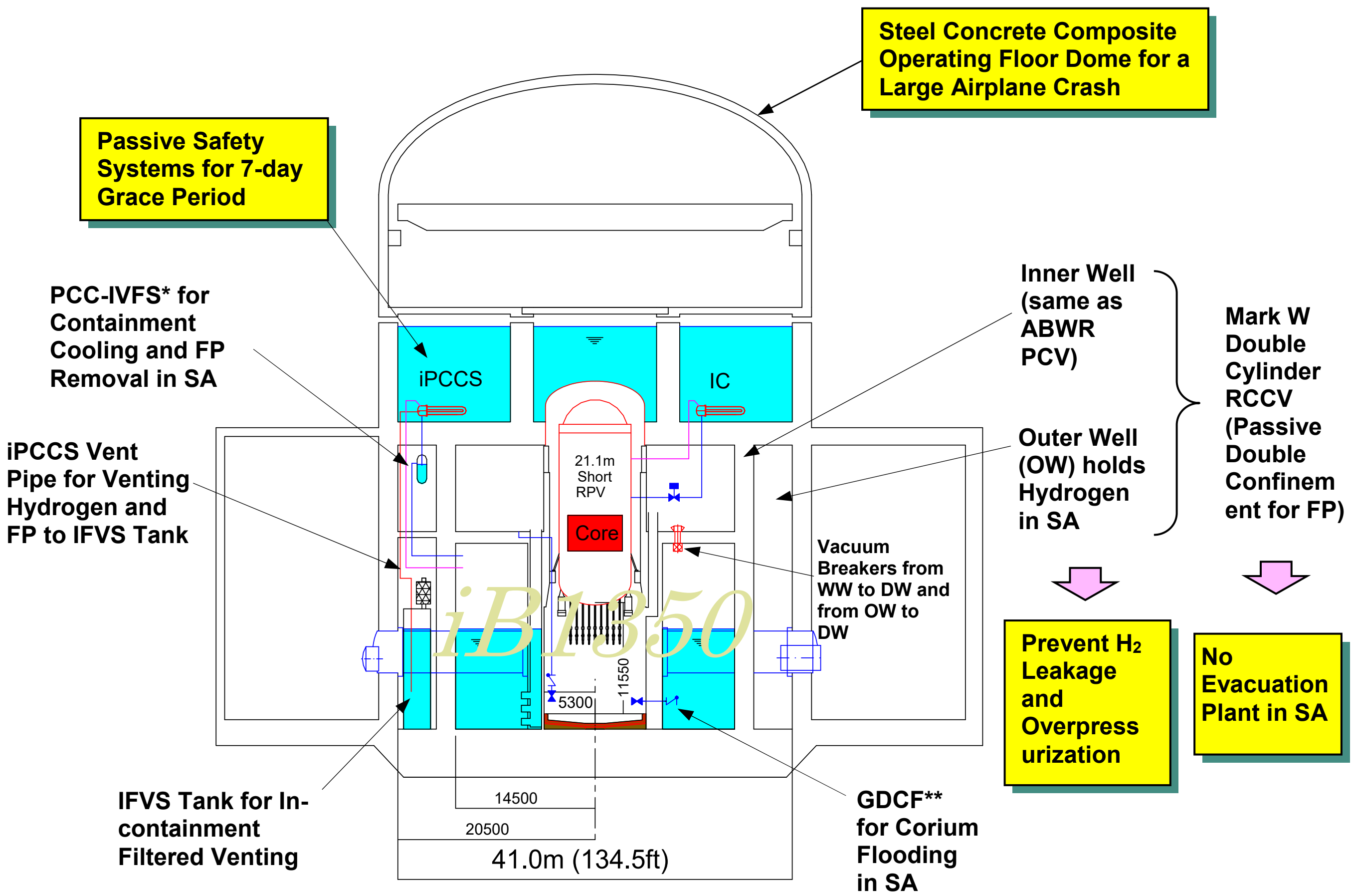
In order to cope with the most probable scenarios, a SISBO and a LUHS [7,10], caused by devastating external hazards, passive safety systems are extensively utilized and constitutes in-depth hybrid safety systems (IDHS) [8].

Figure 1 shows the main characteristics of the iB1350. The heights of the reactor pressure vessel (RPV) and the primary containment vessel (PCV) are exactly the same as those of the ABWR. The height of the ABWR PCV is the lowest among the existing LWR containment vessels. It is possible to arrange cooling water pools on the PCV. The MarkW containment has a double cylinder configuration consisting of the inner well and the outer well. The inner well has exactly the same configuration as the ABWR PCV. It is also made of reinforced concrete as the reinforced concrete containment vessel (RCCV) of the ABWR. The isolation condenser (IC) / innovative passive containment cooing system (iPCCS) pools contain enough cooling water to provide 7-day grace period [11]. The dome of the operating floor is made of steel concrete composite and provides a protective shield against external events such as a large air plane crash. The gravity-driven corium flooder (GDCF) floods the corium on the core catcher passively in a SA. The iPCCS vent pipe vents hydrogen and fission products (FP) to the in-containment filtered venting system (IFVS) tank then to the outer well. The outer well is a compartment to hold a large amount of hydrogen in a SA and prevent overpressurization of the containment due to the hydrogen. The Mark W double cylinder RCCV provides passive double confinement of FP and enables a no evacuation plant in a SA without help of the standby gas treatment system (SGTS) [12].

2.1. In-depth Hybrid Safety Systems (IDHS) of the iB1350

Figure 2 shows in-depth hybrid safety systems (IDHS) of the iB1350. The IDHS of the iB1350 are based on those of the SATOR [3]. The IDHS comprises active safety systems for a DBA and passive safety systems for a SA independently [13]. The iB1350 also has active safety systems and passive safety systems based on the IDHS. The IDHS corresponds to DiD levels 3 and 4 in the four levels of

Figure 1: Main Characteristics of the iB1350



*PCC-IFVS: Passive Containment Cooling and In-containment Filtered Venting System

**GDCF: Gravity-Driven Corium Flooder

safety or defense in depth for residual risks [9]. The DBA systems correspond to the DiD level 3. They can cope with not only DBA but also internal multiple failure events including a fire + N-2. The DBA systems consist of 4 division LPFL/RHR and EDG. The SA systems consist of two important sections. The first SA section corresponds to DiD level 4a for preventing core melt when a SISBO and a LUHS occur due to severe external events. The second SA section corresponds to DiD level 4b for eliminating containment failure and emergency evacuation when core melt occurs due to severe external events. Both the DiD levels 4a and 4b provide complete protections against severe external events including the Fukushima Daiichi accident.

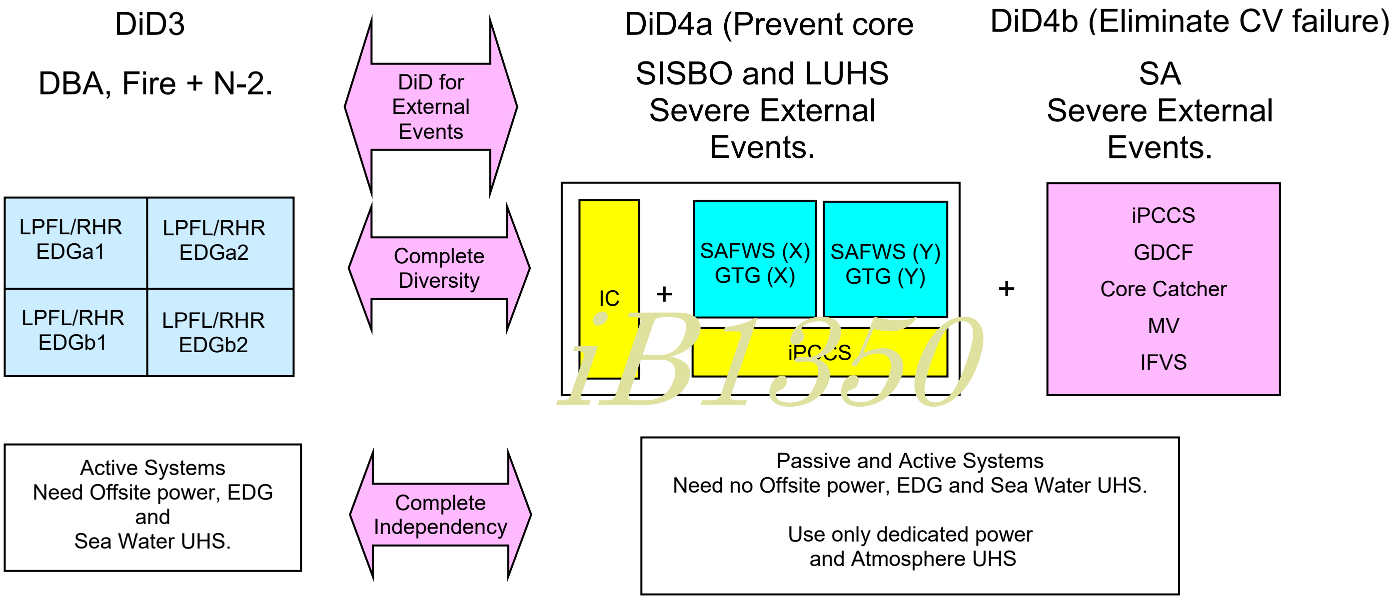
DiD level 4a of the IDHS is somewhat similar to DiD 3b of WENRA [1, 2] because safety systems are the same between these two DiD levels. However, these two DiD levels are quite different. DiD 3b of WENRA [1, 2] is multiple failures where recovery of failures can be implicitly expected within a short period such as 24 hours. For example, recovery of AC power is expected within 24 hours in a SBO. The EPR has cooling water that can cool the core up to 24 hours in the safeguard building. After that it needs recovery of AC power to replenish the cooling water [14, 21, 22]. On the contrary, no recovery is expected in DiD 4a of the IDHS because it is not mere multiple failures but devastation caused by severe external events including Fukushima Daiichi accident where no recovery of AC power for safety systems was established. Station blackout in DiD 4a of the IDHS is not a simple SBO caused by recoverable multiple failures but a seismically induced station blackout (SISBO) that continues much longer period. Therefore, safety systems in DiD 4a of the IDHS has cooling water that can cool the core up to 7 days in the containment building. After 7 days there is an installed alternate feedwater injection system (AFI) to replenish the cooling water. The AFI also has an independent power source. Neither recovery of offsite power nor EDG can be expected in DiD 4a of the IDHS. In general, in DiD 4a and 4b of the IDHS, passive and active systems need no offsite power, EDG, and see water UHS. They use only dedicated power and atmosphere UHS.

The first SA section includes the IC, the SAFWS and the iPCCS. If a SISBO or a LUHS occurs, the IC works at first which can function without both the AC power and the sea water UHS. If the IC is successful, then nothing more is necessary up to 7 days. Moreover, the iB1350 installs two divisions of the severe accident feedwater system (SAFWS) which is the high-pressure injection system having exactly the same capacity as the HPCF of the current ABWR each of which has a dedicated GTG, and an air fin cooler (AFC) for component cooling. The SAFWS is the backup of the IC in such conditions where the IC can fail as the failure to open the initiating valve of the IC, the stuck open of SR/V, or the seismic induced piping break accompanied with SISBO. The SAFWS is arranged in the reactor building close to the containment building and use the S/P water to cool the core.

The second SA section includes the iPCCS, the GDCF, the core catcher, the MV and the IFVS. If the IC and the SAFWS or the GTG fail core melt occurs. Under these conditions, there is no AC power source. Therefore, all the systems in the DiD level 4b must be passive or active that is independent of AC power source. In WENRA report it is said as follows: “The emergency power supply on DiD level 3.b may be also used for DiD level 4. The rationale for this is that additional independent on-site provisions are not likely to significantly increase the reliability of the emergency AC power supply.” [2]. The IDHS philosophy of the iB1350 follows it and provides passive safety systems instead of additional independent on-site provisions for the emergency AC power supply. However, allowing the emergency power supply to be used both in DiD levels 3.b and 4 absolutely causes loss of independency between the DiD levels 3.b and 4. If the SBO DG on DiD level 3.b fail and cause core melt in a SBO, then the containment heat removal system (CHRS) on DiD level 4 that also uses the SBO DG AC power supply must fail to cool the core catcher. Then the containment vessel fails in the long term. In order to avoid this kind of loss of independency between DiD levels the iB1350 uses only passive safety systems or active safety systems that are independent of AC power source in DiD level 4b.

In order to facilitate this rationale, the core catcher of the iB1350 must be cooled only by passive means even in the long term. It should be noted that a SISBO continues for a long time. A SISBO is not a mere internal multiple failure event like a simple SBO in DiD 3b. When a vessel failure occurs

Figure 2: In-Depth Hybrid Safety Systems (IDHS) of the iB1350



and core debris drops on to the core catcher, the GDCF fusible valves open automatically owing to high temperature of the corium. The cooling water flows onto the core catcher. Once the corium is flooded steam from the flooding water is vented to the S/P via the LOCA vent pipes and condensed therein. The S/P water also flows into the radial cooling channels of the core catcher and returns to the S/P again. Once the S/P initiates boiling the iPCCS cools the S/P passively and automatically. Hence the decay heat from the corium is constantly cooled by the iPCCS and S/P. The GDCF keeps the corium flooded. This recycling cooling mechanism of the iPCCS, the S/P and the GDCF can cool the corium passively up to 7 days. After that the AFI replenishes the IC/iPCCS pools with on-site water source in the water storage tank. The AFI is a low pressure small injection system using a small GTG. The AFI also makes up the fuel pool. The small GTG also supplies AC power to the SGTS and the control room.

3. IDHS OPTION COMPARISON

The US-ABWR will be used as a benchmark in this analysis. Its safety system configuration can be summarized as follows:

1. 3 combined high/low pressure DBA divisions:
   a. 2 with HPCF/LPFL/RHR/EDG
   b. 1 with RCIC/LPFL/RHR/EDG
2. 1 turbine driven RCIC is arranged one of the ECCS divisions. It is used for a DBA LOCA analysis as an ECCS. It also can be credited to mitigate transients, small LOCA, SBO and ATWS in PRA analysis.
3. There are 3 high pressure and 3 low pressure core cooling systems. No IC.
4. Power diversity consisting of 3 EDGs, 1 shared GTG and 1 steam turbine.
5. No iPCCS.

The basic iB1350 IDHS configuration is summarized as follows:

1. 4 DBA LPFL/RHR/EDG divisions.
2. 2 SA SAFWS/GTG divisions.
3. IC.
4. No RCIC.
5. There are 3 high pressure and 4 low pressure RPV cooling systems including the IC.
6. Power diversity consisting of 4 GTGs and 2 EDGs
7. The iPCCS credited both for SAs and DBAs in PRA analysis but not credited for DBA analysis

Since this configuration is fully N-2 compliant and designed to mitigate the consequences of both DBAs and SAs, it improves safety while maintaining the same number (6) of active safety systems as the US-ABWR. In the basic iB1350 IDHS configuration, mitigation for DBAs and SAs is considered independently, but this is not required for PRA or even for the original DiD of the three levels of safety advocated by Clifford Beck [19,20]. The three levels of safety rather require complete independency between the core systems in the second level of safety and the containment systems in the third level of safety. The bottom line of the design philosophy of the iB1350 is that containment systems designed to contain a core melt accident must be passive and completely independent from the core systems such as the ECCS/EDG and the reactor protection systems. On the contrary, in the proper original DiD, there is no restriction that the containment systems must not be used in a DBA. Actually, the containment vessel is credited in transients, DBA and multiple failures without exceptions. Therefore, the passive safety system such as the iPCCS designed to cool the containment vessel also can be credited in transients, DBA and multiple failures. It can provide benefits prior to core melt such as indirect RPV cooling during a DBA LOCA and a SBO. It can be credited in applicable analyses and is especially beneficial during events where electric power is unavailable.

Crediting the iPCCS can improve the safety level while reducing the number of the active RHR systems. The RHR system requires the reactor sea water system (RSW) for the ultimate heat sink (UHS) and the EDG for the electric power. If the RHR system is not used in a safety division we can diversify the UHS and the electric power in the safety division. We can enhance system and power diversity by rather reducing the number of active RHR systems in this way. Sato came up with the two optimized safety system configurations OS1 and OS2 [14].

The optimized safety system configuration 1 (OS1) [14] is intended to enhance safety by crediting the iPCCS for DBAs and eliminate the RHR systems in two DBA divisions. Two RHR systems, however, are retained in the rest of the DBA divisions in order to enable cold shutdown for a seismic event. The OS1 can be summarized as follows:

1. LPFL/RHR/EDG divisions are replaced with FLS, dedicated GTGs, and dedicated air fin coolers (AFC). This modification enhances power and system diversity over EDGs and RSW.
2. The 2 SAFWS/GTG divisions are diversified to 1 SAFWS/GTG and 1 turbine driven RCIC because two GTG divisions are included in the DBA divisions.
3. The RCIC is arranged in its dedicated division and can be credited to mitigate transients, small LOCA, SBO and ATWS in PRA analysis.
4. There are 3 high pressure and 4 low pressure RPV cooling systems including the IC.
5. Power diversity consisting of 3 GTG, 2 EDG and 1 turbine
6. The iPCCS credited in both SA and DBA.

The OS2 [14] provides a similar option to the OS1 but favours high-pressure systems:

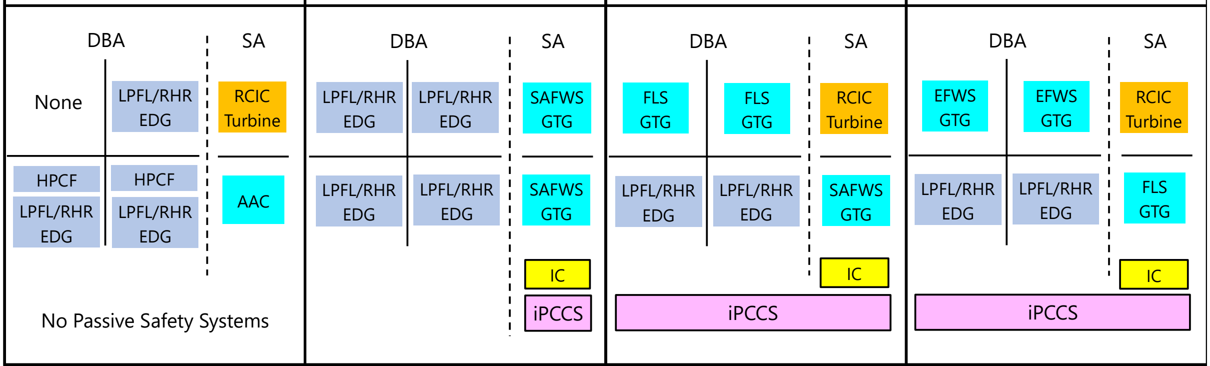
1. In division 1 and 2, low-pressure FLS is replaced with high-pressure EFWS. Each of the 2 EFWS also has the dedicated GTG and the dedicated AFC.
2. The RCIC is arranged in its dedicated division and is used for a DBA LOCA analysis as an ECCS. It can be credited to mitigate transients, small LOCA, SBO and ATWS in PRA analysis.
3. The high-pressure SAFWS is replaced with the low-pressure FLS system because there are 2 high-pressure EFWS in the DBA divisions.
4. There are now 4 high pressure and 3 low pressure RPV cooling systems including the IC.
5. Power diversity consisting of 3 GTG, 2 EDG and 1 turbine
6. The iPCCS credited in both SA and DBA.

Figure 3 shows the comparison of the safety system configurations described above. The iB1350 Basic enhances safety level over the US-ABWR by 4 division RHR/EDG, 2 division SAFWS/GTG and IC/iPCCS. This safety improvement is very extensive and effective. The OS1 further improves power diversity by incorporating 2 GTG in the DBA divisions. The OS2 furthermore improves safety by incorporating 2 high-pressure EFWS in the DBA divisions.

4. PRA INPUT AND ASSUMPTION

Initiating events and frequencies used in the analysis are listed in Table 2. These frequencies come from the PRA database in NUREG/CR-6928 [15]. General transients include total loss of condenser heat (LOCHS), total loss of main feedwater (LOMFW), and MSIV closure. SORV includes both a stuck open relief valve that opens at a transient and fails to reclose and an inadvertent open relief valve (IORV). These frequencies are applied to all 4 safety system configurations.

Figure 3: Comparison of Safety System Configuration



US-ABWR	iB1350 Basic	iB1350 OS1	iB1350 OS2
3 DBA divisions	4 DBA divisions	4 DBA divisions	4 DBA divisions
6 pumps	6 pumps	6 pumps	6 pumps
3 RHR/RCW/RSW	4 RHRRCW/RSW	2 RHR/RCW/RSW	2 RHR/RCW/RSW
3 EDG	4 EDG	2 EDG	2 EDG
1 AAC	2 GTG	3 GTG	3 GTG
1 RCIC	0 RCIC	1 RCIC	1 RCIC
No passive safety systems	IC/iPCCS	IC/iPCCS	IC/iPCCS

Simplified system models were used in the fault trees which conservatively account for dependencies and common cause failures (CCF). CCF parameters used in this study are shown in Table 1. The parameters are set based on the listed NUREG/CR document. The other high degree parameters not available in the tables are calculated by the equation (1). [23]

$$\beta_{i+1} = \frac{\beta_i + 1}{2} \qquad (1)$$

Where:

i is the number of degrees of component to fail due to a common cause,
and β_i is the CCF parameter of i degree.

Table 1: Initiating Events and Frequencies

Initiating Event	Freq. per Ry.
Transients	0.8
LOOP	0.04
SORV	0.02
Small LOCA	0.0005
Med/Large LOCA	0.0001

Table 2 through 7 show the success criteria for the 4 safety system configurations for each Initiating Event. These assumptions vary according to the system configurations. However, the criteria of the reactivity control is defined in the same manner such as the success of the RPS actuation for the IEs except ATWS, and the success of the combination of RPT, and ARI, FMCRD motor run-in or SLC actuation for ATWS events.

Table 2: CCF parameter for Components

Components	β	γ	Data Sources
Pump	0.039	0.52	NUREG/CR-1205 [16]
Valve	0.13	0.565	NUREG/CR-1363 [17]
DG/GTG	0.021	-	NUREG-1150 [18]
Battery	0.008	-	NUREG-1150 [18]

Table 3: Success Criteria for Transients and LOOP of Each Safety System Configuration

System Configuration	Reactivity Control	Core Cooling	Heat Removal
US-ABWR	RPS	FW*, RCIC, 1/2 HPCF, or Dep. + 1/3 LPFL or CP*	PCS*, 1/3RHR, or COPS
Basic	RPS	2/2 IC	-
		FW*, 1/2 SAFWS, or Dep. + 1/4 LPFL or CP*	PCS*, 1/4 RHR, or 2/4 iPCCS
OS1	RPS	2/2 IC	-
		FW*, RCIC, SAFWS, or Dep. + 1/2 FLS, 1/2 LPFL or CP*	PCS*, 1/2 RHR, or 2/4 iPCCS
OS2	RPS	2/2 IC	-
		FW*, RCIC, 1/2 EFWS, or Dep. + FLS, 1/2 LPFL or CP*	PCS*, 1/2 RHR, or 2/4 iPCCS

* Systems cannot be taken credit during LOOP event.

Table 4: Success Criteria for SORV of Each Safety System Configuration

System Configuration	Reactivity Control	Core Cooling	Heat Removal
US-ABWR	RPS	FW, 1/2 HPCF, or Dep. + 1/3 LPFL	1/3RHR, or COPS
Basic	RPS	1/2 SAFWS, or Dep. + 1/4 LPFL	1/4 RHR, or 2/4 iPCCS
OS1	RPS	SAFWS, or Dep. + 1/2 FLS or 1/2 LPFL	1/2 RHR, or 2/4 iPCCS
OS2	RPS	1/2 EFWS, or Dep. + FLS or 1/2 LPFL	1/2 RHR, or 2/4 iPCCS

Table 5: Success Criteria for SLOCA of Each Safety System Configuration

System Configuration	Reactivity Control	Core Cooling	Heat Removal
US-ABWR	RPS	RCIC, 1/2 HPCF, or Dep. + 1/3 LPFL	1/3RHR, or COPS
Basic	RPS	1/2 SAFWS, or Dep. + 1/4 LPFL	1/4 RHR, or 2/4 iPCCS
OS1	RPS	RCIC, SAFWS, or Dep. + 1/2 FLS or 1/2 LPFL	1/2 RHR, or 2/4 iPCCS
OS2	RPS	RCIC, 1/2 EFWS, or Dep. + FLS or 1/2 LPFL	1/2 RHR, or 2/4 iPCCS

Table 6: Success Criteria for M/LOCA of Each Safety System Configuration

System Configuration	Reactivity Control	Core Cooling	Heat Removal
US-ABWR	RPS	1/2 HPCF, or Dep. + 1/3 LPFL	1/3RHR, or COPS
Basic	RPS	1/2 SAFWS, or Dep. + 1/4 LPFL	1/4 RHR, or 2/4 iPCCS
OS1	RPS	SAFWS, or Dep. + 1/2 FLS or 1/2 LPFL	1/2 RHR, or 2/4 iPCCS
OS2	RPS	1/2 EFWS, or Dep. + FLS or 1/2 LPFL	1/2 RHR, or 2/4 iPCCS

Table 7: Success Criteria for ATWS of Each Safety System Configuration

System Configuration	Reactivity Control	Core Cooling	Heat Removal
US-ABWR	RPT+ ARI* RPT+ FMCRD**	Same as Transients	
	RPT+SLC***	2/2HPCF or RCIC + 1/2HPCF	1/3RHR, or COPS
Basic	RPT+ ARI* RPT+ FMCRD**	Same as Transients	
	RPT+SLC***	2/2 SAFWS, or IC + 1/2SAFWS	1/4 RHR, or 2/4 iPCCS
OS1	RPT+ ARI* RPT+ FMCRD**	Same as Transients	
	RPT+SLC***	IC + SAFWS or RCIC, or RCIC + SAFWS	1/2 RHR, or 2/4 iPCCS
OS2	RPT+ ARI* RPT+ FMCRD**	Same as Transients	
	RPT+SLC***	2/2 EFWS, IC + 1/2EFWS or RCIC, or RCIC + 1/2EFWS	1/2 RHR, or 2/4 iPCCS

*for electrical failure of CR insertion
**for mechanical failure of CR insertion
***both electrical and mechanical failures of CR insertion

5. RESULTS AND DISCUSSION

5.1. Results of Initiating Events (IE) Analysis

As expected, all 3 options for the iB1350 IDHS are similar or superior to the US-ABWR. Figure 4 compares the total CDFs among the reactor safety configurations for each initiating event. Overall CDF for all the iB1350 IDHS configurations is about two orders of magnitude lower than for the US-ABWR. Other notable findings are as follows:

1. For transients, CDF for the US-ABWR is decided by TW and TQUX sequences. All the other iB1350 configurations have the iPCCS and CDF are decided by mostly TQUX sequence. The iB1350 Basic has the IC and 2 SAFWS. The OS1 has the IC, 1 SAFWS and the RCIC. The OS2 has the IC, 2 EFWS and the RCIC. The OS2 has the best performance for TQUX sequence.
2. LOOP performance is primarily based on the IC, RCIC and diversity of emergency AC power sources. The US-ABWR has no IC and the fewest AC power sources with 4. The iB1350 Basic has the IC and 6 AC power sources but no RCIC. The OS1 has the IC, RCIC and 5 AC power sources. The OS2 has the same system diversity for LOOP as the OS1. The OS1, however, has 2 high-pressure EFWS and better performance for TQUX component in LOOP resulting in lower CDF.
3. CDF during SORV is tricky because both the IC and the RCIC cannot be credited due to reactor depressurization. Actually, the RCIC can continue operation until the low-pressure injection systems initiate operation. However, this is not credited in the study for conservatism. SORV still requires depressurization by the failure of the ADS causes TQUX sequence. The US-ABWR has two HPCF and as good performance as the other iB1350 configurations for TQUX. It, however, has only 3 RHR and no iPCCS. As a result, TW sequenced is dominant component for the US-ABWR. The other 3 iB1350 configurations have the iPCCS and TW sequence is not the most dominant component. As for the 3 iB1350 configurations TQUX sequence is rather the most dominant sequence. The number of the high-pressure impacted by the number of RHR divisions, so the base iB1350 with 4 RHR divisions is clearly superior to the US-ABWR. It is also slightly more effective than OSSC1 and OSSC2. Diversity of the iB1350's AC power sources explains the remaining differences in CDF.
4. For SLOCA the US-ABWR has 6 pumps and CDF is decided by loss of 3 RHR, namely, TW sequence. All the other 3 iB1350 configurations have the iPCCS and much lower CDF. The CDF of the iB1350 Basic is decided by TQUV due to common cause failure of the core cooling systems.

5. For M/LLOCA, the RCIC cannot be credited. CDF for all rector configurations are decided by loss of all core cooling systems. The US-ABWR has 5 pumps in 3 divisions. CDF of the US-ABWR is decided by dependent failure of the HPCF and the LPFL due to the RCW/RSW failure in a same safety division. The other 3 iB1350 configurations also have 5 pumps but arranged in each dedicated safety division resulting in lower CDF.
6. For ATWS all the reactor configurations have the same RPS and ATWS countermeasures.

5.2. Results of Damage Class Analysis

Figure 5 compares the total CDFs for each damage class. As in the IE analysis, all 3 options for the iB1350 IDHS are similar or superior to the US-ABWR. Notable findings are as follows:

1. TQUX first challenges the high pressure cooling systems, so configurations with larger numbers of and passive high pressure systems (OS2) perform better in this event. The remaining differences are due to the IC and the RCIC being unavailable as a high pressure system during an SORV.
2. CDF for TQUV is decided by number of high and low pressure injection systems including the IC and the RCIC. The US-ABWR has no IC and CDF of the US-ABWR is decided by LOOP. All the iB1350 options perform similarly well compared to the US-ABWR due to having the IC and greater numbers and diversity of AC power sources. CDF of the iB1350 Basic is decided by SLOCA because the IC is unavailable. The OS1 and OS2 have the RCIC available for SLOCA and smaller CDF that is decided by MLOCA where the RCIC is unavailable.
3. CDF for TB is decided by the IC, the RCIC and the number and diversity of AC power sources available. The US-ABWR has no IC and only 4 AC power sources. The iB1350 Basic has the IC and 6 AC power sources. The OS1 and OS2 has the IC, the RCIC and 5 AC power sources.
4. TW is directly impacted by the number of heat removal systems (RHR, PCS, IC and the passive iPCCS). The US-ABWR has neither IC nor passive iPCCS and must rely on the RHR and the PCS. CDF of the US-ABWR is decided by SORV and LOOP where the PCS is not available. For the 3 iB1350 configurations SORV also decides CDF because the IC is unavailable.

6. SENSITIVITY ANALYSIS CONSIDERING EXTERNAL HAZARD

Sensitivity analyses for each plant configuration were performed to gain insights on their tolerance to external hazards. Loss of offsite power (LOOP) was selected as the initiating event induced by external hazards in this study. This is because external hazards disturb the structures, systems, and components (SSCs) outside the plant before inside, and the offsite power system large part of which is located outside and their structure strength are usually non-safety class would be most affected by the external hazards. The following two sensitivity analysis cases were performed while the further influences from the external hazards on the plant were took into account. Since the frequencies of external hazards were site-specific, Conditional Core Damage Frequency (CCDP) was evaluated instead of CDF. The CCDP is the probability that the plant fails to safety shutdown given condition where the initiating event occurs and some SSCs are lost due to the external event at the same time, and more suitable than the CDF if the analysis cases will be applied to any locations.

<u>Base case</u>
The LOOP event tree and fault trees of the internal events PRA discussed in the previous sections were used, and the frequency of the LOOP was set to 1.0 to obtain CCDP. The other conditions and parameters were not changed, that is, the offsite power recoveries were credited within 30min, 8h and 24h. The CCDP obtained in this case shows the tolerance to the LOOP event during the normal operation when the external hazards do not occur.

<u>Case (1)</u>
In the case (1), it was assumed that such external hazards as severe tornado or earthquake disturbed the offsite power system, which induced the LOOP event as the initiating event, and disabled the plant either to recover it or obtain alternative offsite power sources in the short term. The same event tree

Figure 4: CDF Comparison by Initiating Event

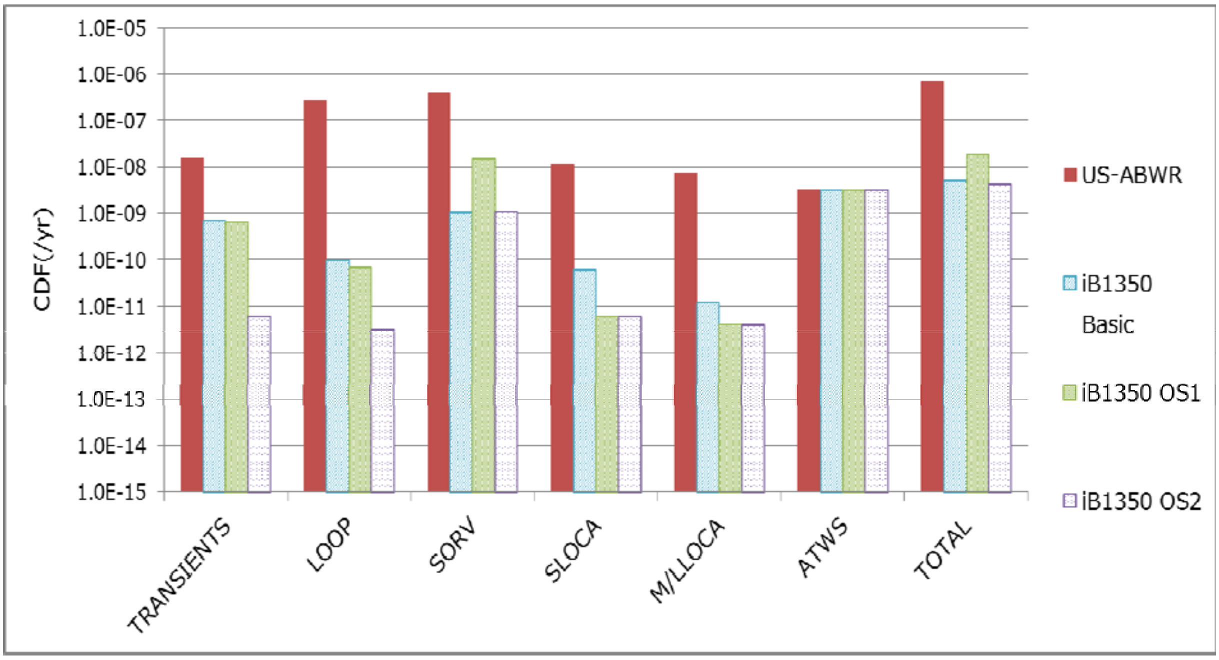


Figure 5: CDF Comparison by Event Sequence

and fault trees as the base case were used, but the offsite power recoveries were not credited in this case as mentioned above.

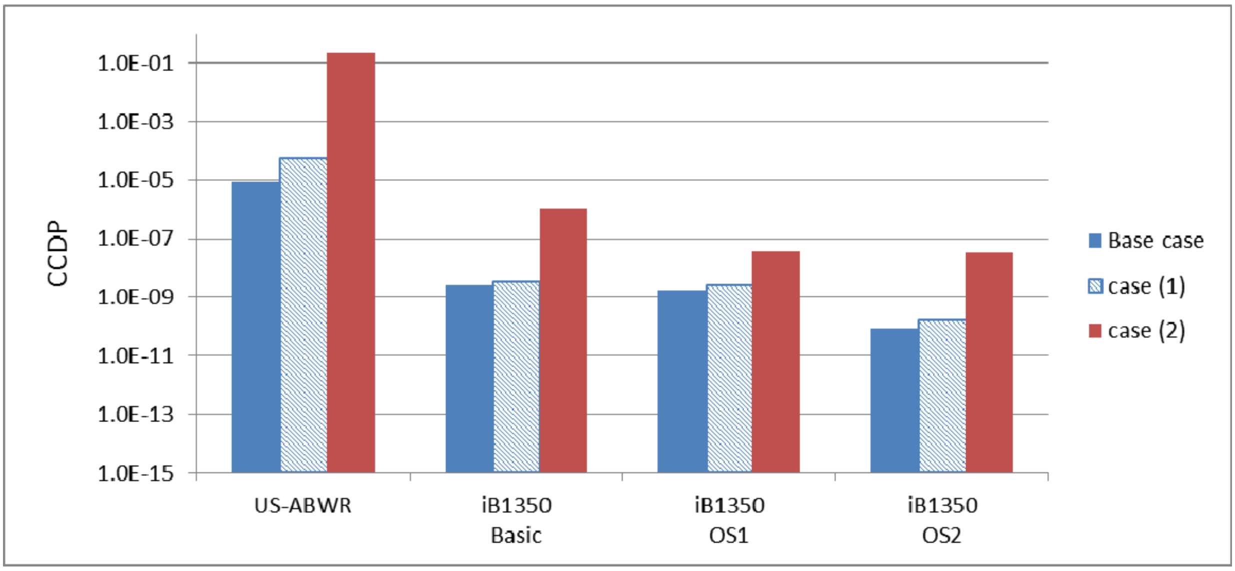
Case (2)

In the case (2), it was assumed that such devastating external hazards as extremely large tsunami or extremely strong cyclone, hurricane, typhoon hit the plant, and damaged, like the Fukushima Daiichi accident, not only the offsite power system, but also the component cooling systems to transport the heat generated inside the plant to the sea water ultimate heat sink (UHS) whose SSCs were located outside. In this case, the sea water UHS cannot be credited, which resulted in the losses of all of the EDGs and LPFLs/RHRs in all plant configurations, and HPCFs in the US-ABWR plant whose component heats were released to the sea water through the cooling systems. The recovery of the offsite power cannot be credited too due to the same reason as the case (1). The same event tree and fault trees as the case (1) were used, but the systems associated with the sea water UHS were assumed to be failed and its failure probabilities were set 1.0 in this case.

Figure 6 shows the result of CCDPs of each case of all configurations. In all cases, the iB1350s show the remarkable tolerances to the external hazards compared with the US-ABWR. Notable findings are shown below

1. In the case (1) where the external hazard disturbs the offsite power system and the recovery attempts of it are not credited, the increase in CCDP from the base case is the highest for the US-ABWR, which is almost one order magnitude increase, while those are negligible for iB1350s. The offsite power is one of the AC power sources; therefore, the increase in CCDP shows how degree the plant depends on the AC power. While the US-ABWR does not install the IC system that is independent from AC power, and only needs the DC power, all options of the iB1350 install it. This is why the increase in CCDP for the US-ABWR is significant, while those for iB1350 options are negligible.
2. In the case (2) where the external hazard disturbed both the offsite power system and the sea water UHS relating systems, and the recovery of neither of them is not credited, 3 EDGs fail due to the loss of the sea water UHS, and only 1 Alternate AC power source remains available to the US-ABWR. This results in extremely high CCDP of the US-ABWR in the case (2) In contrast, 4 EDGs and 2 EDGs fail due to the loss of the sea water UHS in the case of the basic option, and the OS1 and the OS2, respectively; however, 2 GTGs or 3 GTGs are still available to each plant. Moreover, the IC system is also available to the iB1350 options because it is independent from both the AC power and the sea water UHS. As a result, the CCDPs of iB1350 options become sufficiently low in this case.
3. The CCDPs of the iB1350 OS1 and OS2 options are 1 order magnitude lower than that of the iB1350 basic option in the case of (2). This is because 3 GTGs remain available to the OS1 and OS2 options, while 2 GTGs remain available to the basic option.

Figure 6: CDF comparison by External hazard case



7. DISCUSSION ON MODELING CONCERNS

Even though the PRA results well describe the risk insights reflecting the design features of each configuration, there are some modeling issues as follows:

<u>CCF</u>

In this study, NUREG series documents are basically used to calculate the CCF parameters, but some parameters are not available in those documents to such high redundant components as 8 redundant RSW pumps of iB1350 Basic. For such components, the equation (1) is used to calculate the parameters. This assumption gives very conservative results to higher redundant components. For example, while the number of RHRs that mostly effects on the CDF for TW sequence is decreased from 4 for iB1350 Basic to 2 for iB1350 OS1 and OS2, the increase in CDFs for TW sequence of the

OS1 and OS2 remains slight in Figure 5. It is noted that this result depends on the CCF assumption, and could be changed. However, it wouldn't affect the total CDFs of the OS1 and OS2, since both the OS1 and OS2 reduce other sequence risks such as TQUV and TB where the redundancy of the RHR has less effect.

<u>Mission time for external events</u>
In this study, the mission time for the external events in the sensitivity analyses is assumed to be 24 hours as well as the internal events cases. Any external supports from outside the plant in a short period may not be expected at such devastating hazard as the Fukushima accident; therefore, the mission time should be adjusted for the external events considering such situations. This would impact specifically on the US-ABWR since it requires the makeup water source to continue the feed and breed strategy for a long period; therefore, the CCDP of the US-ABWR can increase when such long mission time is selected.

8. CONCLUSIONS

Even though the two iB1350 IDHS options each remove two RHR systems, enhancing diversity in the DBA systems and crediting iPCCS results in negligible change to the overall CDF. All 3 iB1350 options result in similar overall CDFs; however, any changes to initiating event frequencies will impact these results. Performance of the iB1350 IDHS varies as different IEs challenge different individual system types (high pressure, low pressure, depressurization, etc.). Additional research is also required to determine the impact to overall design, construction, and maintenance costs; however, reduction in the number of components is likely to result in a favorable impact. The results of this study also highlight the drastic reduction in CDF and remarkable tolerance to external hazards owing to iB1350's passive IDHS features.

In both OS1 and OS2, using a more diverse configuration than the 4 identical RHR divisions considered in the base case results in less equipment yet no negative impact to the overall CDF. It should be noted that OS2 has rather better performance than the iB1350 Basic for most IEs and accident sequences. One important lesson learned from the Fukushima Daiichi event was that diversity of safety systems and passive safety systems greatly reduces overall CDF of the significant events. The two options suggested in this report show additional benefits against these types of the external events such as the tsunami that directly challenges to the availability of the sea water UHS. This diversity and remarkable tolerance to the external hazards are the most important benefits of choosing OS1 or OS2 over the base case and should be thoroughly analyzed as the next step in the iB1350 IDHS design.

Nomenclature

AAC: alternate AC, ABWR: advanced boiling water reactor, AC: alternating current, ADS: automatic depressurization system, AFI: alternate feedwater injection system, ARI: alternative rod insertion system, BiPSS: built-in passive safety systems, BWR: boiling water reactor, CCDP: conditional core damage probability, CCF: common cause failure, CHRS: containment heat removal system, CV: containment vessel, DBA: design basis accident, DG: diesel generator, DiD: Defense in Depth, CP: condensate pump, CR: control rod, DW: dry well, ECCS: emergency core cooling system, EDG: emergency diesel generator, EFWS: emergency feedwater system, EPR: European pressurized water reactor, EU-ABWR: European ABWR, FW: feed water system, FMCRD: fine motion control rod drive system, Dep: depressurization, FLS: flooder system, FP: fission products, GDCF: gravity-driven corium flooder, GTG: gas turbine generator, iB1350: innovative, intelligent and inexpensive BWR 1350, IC: isolation condenser, IDHS: in-depth hybrid safety systems, IFVS: in-containment filtered venting system, iPCCS: innovative passive containment cooling system, LOCA: loss of coolant accident, LOCHS: loss of condenser heat sink, LOMFW: loss of main feedwater, LLOCA: large size of loss of coolant accident, LOOP: loss of offsite power, LPFL: low pressure flooder system, LUHS: loss of ultimate heat sink, LWR: light water reactor, MV: modulating valve, MLOCA: medium size of loss of coolant accident, NPP: nuclear power plant, PCS: power conversion system, PCV: primary containment vessel, PCCS: passive containment cooling system, PRA: probabilistic risk assessment, RCIC: reactor core isolation cooling system, RCCV: reinforced concrete containment vessel, RCW: reactor coolant water system, RHR: residual heat removal system, RPS: reactor protection system, RPT: recirculation pump trip, RPV: reactor pressure vessel, RSW: reactor sea water system, SA: severe accident, SATOR: severe accident tolerant and optimum reactor, SAFWS: severe accident feedwater system, SBO: station blackout, SGTS: standby gas treatment system, SISBO: seismically induced SBO, SLC: standby liquid control system, SLOCA: small size of loss of coolant accident, SORV: stuck open safety relief valve, S/P: suppression pool, SR/V: safety relief valve, TB: failure of core cooling and containment heat removal loss of AC power, TQUV: failure of core cooling under low pressure state, TQUX: failure of core cooling under high pressure state, TW: failure of containment heat removal, UHS: ultimate heat sink, WENRA: Western European Nuclear Regulators Association, WW: wet well

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