Discussions of Fukushima nuclear power plant accidents by a viewpoint of PSA

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Abstract: On 11th March, 2011, most sever nuclear power plant accidents in the history have been occurred at the Fukushima site due to the massive earthquake and subsequent large Tsunami. As the results of the loss of all AC power, the reactor cores have melted down in Unit 1 through Unit 3. In the present study, the core damage probabilities for Units 1 through 3 have been evaluated by event tree analyses under the condition of the loss of all AC power. The core damage probability at 168 hours (7 days) after the Tsunami are obtained as 0.71(Unit 1) and 0.12 (Units 2 and 3). The discussions are made based on the discrepancy between the analysis results and the actual situation, that is, all the three reactor cores have melted down.
Keyword: Fukushima nuclear power plant; PSA; loss of all AC power; core damage probability

1 Introduction

On 11th March, 2011, most sever nuclear power plant accidents in the history have been occurred at the Fukushima nuclear power plant due to the massive earthquake and subsequent large Tsunami.

Probabilistic safety assessment (PSA) can perform a risk analysis (core damage frequency, *etc.*) for a nuclear power plant before its construction. The evaluation results are utilized as important information for modification of plant design, operational procedures, countermeasures against accidents, and also for the decision of plant construction.

In the United Sates, it is required to perform PSA for all the nuclear power plants[1]. In Japan, PSA is used for the evaluation of effectiveness of accident management in case of nuclear power plant accident, and for quantitative safety evaluation in periodic safety review. It is now being discussed to use PSA for the reactor site evaluation[2].

In the present study, the core damage probabilities have been evaluated by event tree analyses under the condition of the loss of all AC power, for the Fukushima-Daiichi nuclear power plant.

In the actual accidents at Fukushima nuclear power plant, all the three reactor cores have melted down. Discussions are made based on the discrepancy between the analysis results and the actual situation.

2 Emergency core cooling system of Boiling Water Reactor

If an incident happens in nuclear reactor system, many kinds of safety systems are activated for the prevention of accident. These safety systems will stop their function because of random failure of system components (internal events), external events as fire/earthquake, operator's mistakes, and so on. In PSA, the occurrence probabilities of these system failures are quantitatively evaluated and core damage frequencies are calculated.

Under the normal conditions of Boiling Water Reactor (BWR), generating heat is removed from a reactor core by condensing steam after it passes through the turbine, and condensed steam (water) is fed back into the reactor. If this normal circulation system fails to its function, other cooling systems (Emergency core cooling systems) are activated and heat is removed from the core.

Emergency core cooling systems of general BWR are shown in Fig. 1[3]. A little different action is required according to various incidents, but in most cases the following procedure is taken when some incident occurs to a reactor system.

First, high pressure coolant injection system (HPCI)

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is started since it can be used while the reactor vessel is still highly pressurized. After the reactor vessel is depressurized, low pressure coolant injection system (LPCI) is used. Residual heat removal system (RHR) is used for cooling the core over long term period after some failed components are repaired. If HPCI system fails during the pressure of reactor vessel is still high, LPCI is used with the aid of depressurizing system (ADS or safety relief valve).

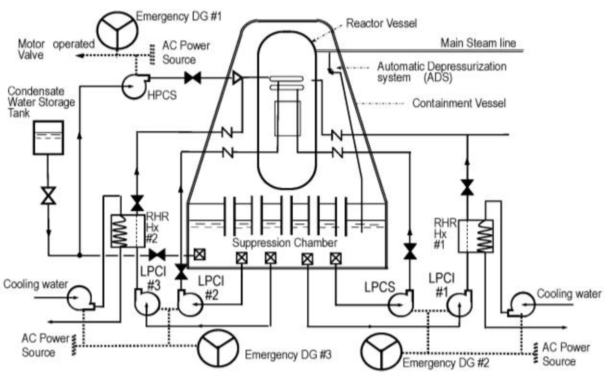

Fig. 1 Emergency core cooling system (ECCS) of BWR.

Figure 2 shows the detailed layout of HPCS. This system consists of a pump that has sufficient pressure to inject coolant into the reactor vessel while it is pressurized. At the initial time, water is supplied from condensate water storage tank (CWST), then from pressure suppression chamber. Two actions are required for the start of HPCS; opening of one motor operated valve (MOV) and startup of HPCS pump.

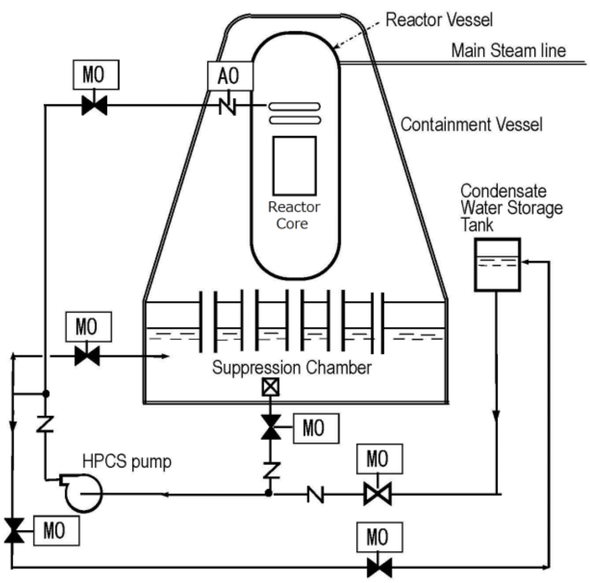

Fig. 2 High pressure core spray system (HPCS) of BWR.

Low pressure coolant injection systems (LPCI, LPCS) have similar configuration to HPCS, and water resources are from pressure suppression chamber or outside from reactor system. Four equivalent systems are equipped for low pressure systems and one of the four systems can supply enough water for removing the heat from core. There are two RHR systems in a reactor system, and one RHR can cool the reactor core.

If the reactor building is isolated from turbine building, reactor core isolation cooling system (RCIC) is used for providing enough water to safely cool the reactor. Figure 3 shows the layout of RCIC of Fukushima- Daiichi units 2 and 3[4]. This system is driven by a steam turbine (RCIC turbine), and does not require large amounts of electricity to run. It is a defensive system against a condition known as station blackout. Containment ventilation is necessary to prevent the excess increase of temperature and pressure inside the containment vessel for the long term operation of this system, without outside cooling water (sea water).

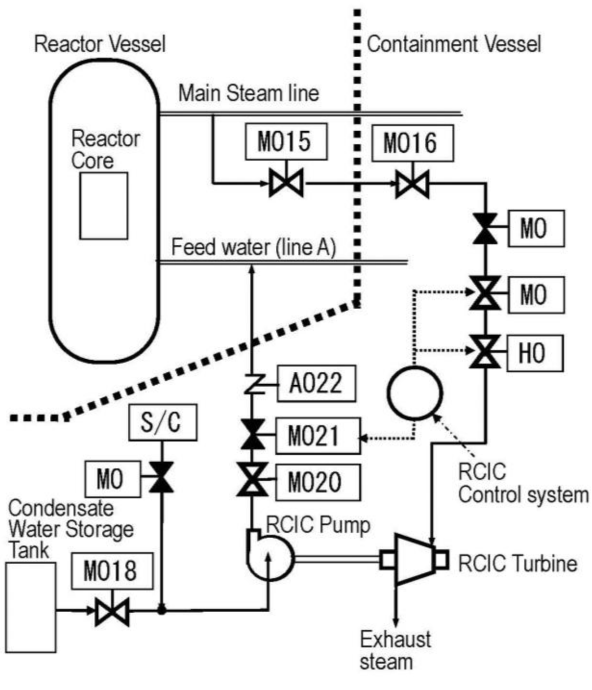

Fig. 3 Reactor core isolation cooling system (RCIC) of Fukushima-Daiichi units 2&3.

3 Procedure of seismic PSA

A standard for procedures of seismic PSA[5] is published from the Japan atomic energy society. Present analysis is based on this procedure.

3.1 Classification of earthquake induced initiating events

Various kinds of initiating events occur when earthquake attacks a nuclear power plant. They are classified into hierarchy event tree based on the amount of their influence, as shown in Fig. 4. This event tree indicates that any initiating event occurs inevitably by earthquake. Therefore, conservative analysis results are expected, that is, larger probability of core damage is estimated.

In the Fukushima-Daiichi nuclear plant accidents, initiating event "Loss of offsite power (LOSP)" has occurred. It was a relatively slight degree event in the hierarchy event tree. At more sever initiating events as "reactor building damage", core damage is directly produced.

3.2 LOSP event tree

Core damage does not directly occur in case of offsite power loss. Many kinds of safety functions are started in order to prevent the occurrence of reactor accident, and usually reactor will be reached in cold shutdown state.

Figure 5 is an event tree with "LOSP" initiating event, which is constructed based on the standard for procedures of Level 1 PSA published by Japan Atomic Energy Society [6].

This event tree is the one for general BWR plant, and only the first 27 lines are expressed in the figure. Rest of the tree is the repeat of similar blanching and sequences.

The symbol "O" at the far right of sequences means soundness of plant state, and "X" means that reactor core will be damaged immediately or later.

Headings of the event tree are the success or failure of function of safety systems. For the successful operation of safety system, it is required to be supported by support systems, like component cooling water system, instrumentation air system, fuel storage pool, and so on.

Fault tree analysis is used for the quantitative evaluation of support systems' failure probability.

The component cooling water system is the most important system among the support systems. There are four sea water pumps (A, B, C, D), and pumps A and B supply sea water to the first group of components in the reactor system, pumps C and D supply to the second group. One sea water pump can supply enough amount of cooling water to all the components in one group. Each group of components has two heat exchangers, and one heat exchanger can cool all the components in one group.

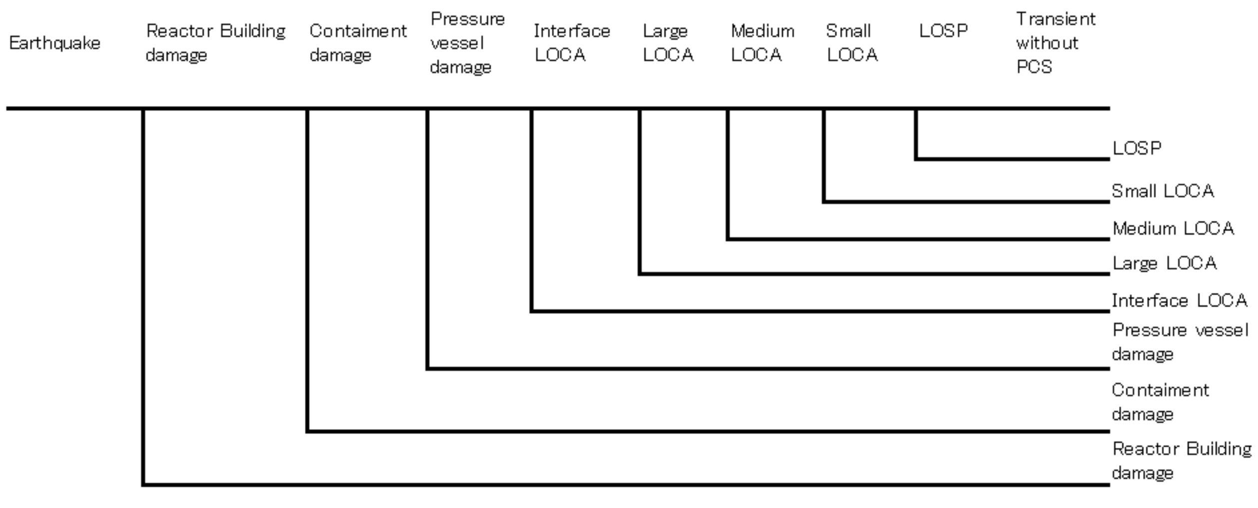

Fig. 4 Hierarchy event tree for earthquake induced initiating events.

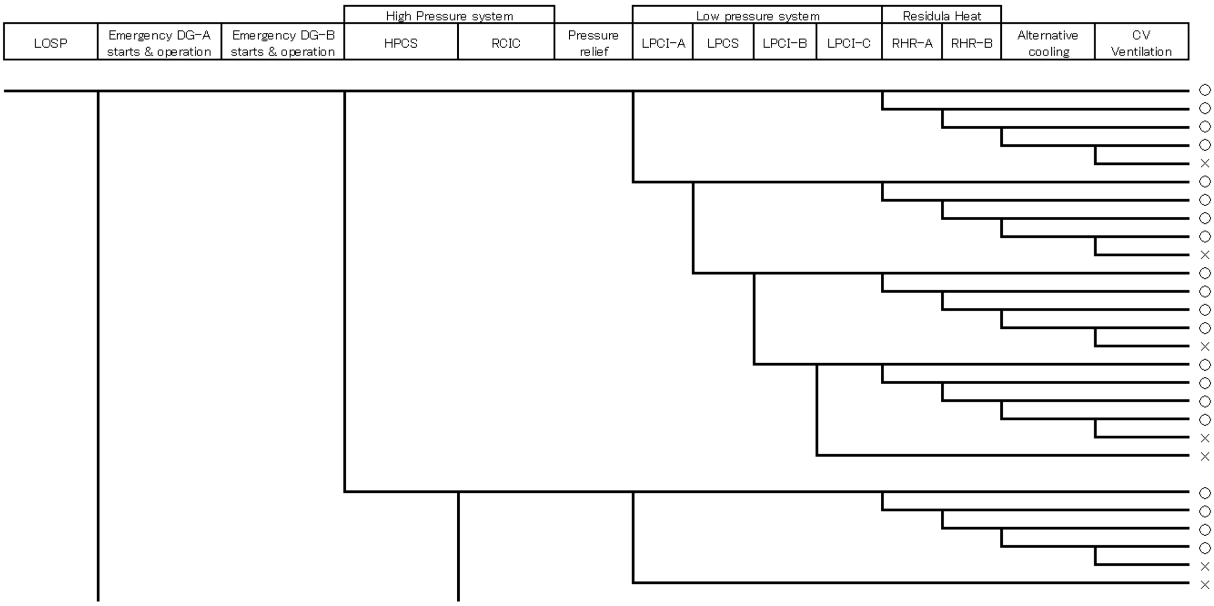

Fig. 5 LOSP event tree for general BWR plant system.

3.2.1 Quantitative evaluation of LOSP event tree

It is reported that any component of Fukushima-Daiichi nuclear power plant has not been damaged by the acceleration force induced by the East Japan great earthquake. Then, LOSP event tree shown in Fig.5 is quantitatively evaluated by only considering random failure of components. The result indicates the core damage probability of general BWR plant in case of LOSP event.

Failure rates of components in safety systems are assigned as follows based on the data shown in the standard for procedures of Level 1 PSA[6].

Emergency diesel generator	
fails to start	$1.1\text{x}10^{-3}$/D
failure during operation	$2.0\text{x}10^{-4}$/hour
Motor operated valve	
failure of open/close action	$3.6\text{x}10^{-3}$/D
failure during usage	$2.0\text{x}10^{-7}$/hour
Pump	
fails to start	$3.6\text{x}10^{-3}$/D
failure during operation	$1.4\text{x}10^{-4}$/hour
Manual depressurization/Failure of CV ventilation	
	$3.9\text{x}10^{-2}$/D

Mission time is set as 168hours (7days) after the LOSP initiating event occurs. In the sequence indicated by "X", all the safety systems or cooling functions for the prevention of core damage are stopped. It requires certain time duration for the progress of accident, so even in these sequences reactor core is sound at first, but it will be damaged sooner or later without any action.

Failure probabilities of safety systems (heading in event tree) are evaluated by failures of main components in the system. For example, HPCS system (Fig. 2) can be started by the start of one pump and the open action of one MOV. Then, continuous operation of 72 hours is required for the cooling of reactor core by HPCS.

$3.6\text{x}10^{-3}$ (pump fails to start) + $1.4\text{x}10^{-4}\text{x}72\text{h}$ (failure of pump during operation) + $3.6\text{x}10^{-6}$ (MOV fails to open) $+2\text{x}10^{-7}\text{x}7\text{x}72\text{h}$(MOV failure during usage)

$$=1.74\text{x}10^{-2}$$

Success probability of HPCS’s function

$$=1.0-1.74\text{x}10^{-2}=0.983$$

The number "7" in the equation means the number of MOV using for the continuous operation of HPCS as seen in Fig.2.

Successive operations of low pressure systems and residual decay heat removal systems are required after the operation of HPCS for the prevention of core damage. This is a typical phased mission problem [7], but the exact treatment becomes tiresome.

So, in the present analysis, approximate method is used, that is, simply multiplying success probabilities of continuous operation of safety systems during 168 hours.

If LPCI works long time, RHR does not start during 168 hours. In this case, RHR is not necessary during the mission time (168hours). But, success probability of the operation of RHR system is always considered in the present analysis, and the analysis result becomes conservative.

The core damage frequency is obtained as 2.95×10^{-5} at 168 hours after the occurrence of LOSP event, for general BWR plant.

3.3 Tsunami PSA

In the guideline of seismic design review published in 2006, the need of Tsunami analysis has been emphasized. At the present time, standard for procedures of Tsunami PSA is not published, but the following procedure is now discussed.

The first step is Tsunami hazard assessment. Tsunami hazard curve, that is the relation between Tsunami height and its occurrence frequency, is estimated based on the Tsunami source model.

The second step is fragility evaluation. The region and water level around nuclear plant are evaluated, and the component failure probabilities are estimated under these Tsunami condition.

The third step is the evaluation of accident scenarios. Event tree and fault tree methods are widely used, and occurrence frequencies of accidents are calculated. By these procedures, Tsunami risk of nuclear power plant is estimated.

A fundamental condition of nuclear power plant must be clarified. The elevations of, seawall, outside setting components, and openings of reactor building are important information. As an example, the elevation of these structures is assumed as the same, that is, H m from the sea level. Sea water pump is usually near sea side, then, its height is assumed as H-5 m.

There is no well-established method for Tsunami fragility. Sometimes, following engineering judgments are used.

Failure probability of a component suffered by H+2 m height Tsunami is 1.0. Sea water pump has also 1.0 failure probability for H+2 m height Tsunami. For H m height Tsunami, all the components have 0.1 failure probability. Under the H-1 m height Tsunami, the following probabilities are assigned; 0.01(pump), 0.001(sea water pump), 0.0001(oil tank). Component failure probabilities between H-1 and H+2 heights Tsunami are estimated by interpolation.

Plant condition is assumed as follows for the evaluation of accident scenario. The reactor is shutdown before Tsunami arrival. All the components are not damaged by the acceleration force due to earthquake. Restoration of damaged components by Tsunami is not considered.

If Tsunami height is less than the seawall height, it is judged there is no core damage. If sea water pump fails, only RCIC is available as the safety system. If startup transformer is damaged, operations of safety system are supported by emergency diesel generator(s).

For the case of water infiltration to the reactor building, Tsunami fragility evaluations are performed and core damage probability is calculated.

3.3.1 Quantitative evaluation for 15m height Tsunami

Now take up 15m height Tsunami for a nuclear plant with H=10 m, which is the same condition of Fukushima-Daiichi nuclear power plant. Under this condition, sea water pumps are damaged and only RCIC are available for the prevention of core damage.

Event tree shown in Fig.5 is modified as to satisfy the above condition. Emergency diesel generators A and B fail with probability 1.0. Safety systems HPCS, LPCS and LPCI are not available. Long term cooling by RHR is not expected, because of LOSP condition. In this case, 72hours (3days) is considered as mission time.

The core damage probability is obtained as 5.92×10^{-2} at 72 hours (3days) after the arrival of Tsunami, for general BWR plant.

4 Actual correspondences taken at the Fukushima-Daiichi nuclear plant

Tokyo Electric Power Company reported the correspondences taken at the Fukushima-Daiichi nuclear power plant after the East Japan great earthquake [8]. The estimated time of core melt down is based on the analysis of Nuclear and Industrial Safety Agency, Japanese Government.

4.1 Fukushima-Daiichi Unit 1

11th, March 14:46 Earthquake
14:47 Two emergency DGs start.
14:52 Isolation Cooling system (IC) automatically starts.
15:27 First Tsunami attacks.
15:35 Second Tsunami attacks.
15:37 Two emergency DGs stop.
18:10 Valves 2A, 3A in IC are opened.
Steam is generated.
18:25 Valve 3A recloses.
20:00 Core meltdown occurs.
21:19 Lineup of fire water pump
21:30 Valve 3A reopens.

12th, March 01:48 Pump failure, IC stops.
(Continuous operating time is 4^h23^m)
09:15 MOV in CV ventilation line is manually opened (25%).
09:30 Second trial of MOV opening
10:07 Several times trial of AOV opening, but unsuccessful result.
14:00 Settlement of air compressor
Success of CV ventilation.
Pressure of CV decreases.
15:36 Hydrogen explosion
20:20 Injection of sea water and boric acid solution is started into reactor core

4.2 Fukushima-Daiichi Unit 2

11th, March 14:46 Earthquake
14:47 Two emergency DGs start.
15:02 RCIC is manually started.
15:27 First Tsunami attacks.
15:28 RCIC stops.
15:35 Second Tsunami attacks.
15:41 Two emergency DGs stop.
16:00 RCIC is restarted at around this time.

12th, March 02:55 RCIC is operating.
04:20-05:00 Change of water source of RCIC from CST to Suppression chamber.

13th, March 11:00 Ventilation line is established.

14th, March 11:01 Failure of valve open action, Failure of ventilation
13:25 RCIC stops (estimation)
(Continuous operating time is less than 70^h23^m)
16:00 Safety relief valve (SRV) is opened.
16:20 SRV is discovered to be closed.
16:34 SRV is reopened. State of SRV is unstable.
Start of sea water injection to reactor core
18:00 Pressure of RV decreases.
Later SRV is reclosed.
21:00 Failure of CV ventilation trial
21:20 Settlement of air compressor
23:00 Core meltdown occurs.

15th, March 06:10 Sound of explosion around Suppression chamber.

4.3 Fukushima-Daiichi Unit 3

11th, March 14:46 Earthquake
14:47 Two emergency DGs start.
15:05 RCIC is manually started.
15:25 RCIC stops.
15:27 First Tsunami attacks.
15:35 Second Tsunami attacks.
15:38 Two emergency DGs stop.
16:03 RCIC is manually restarted.

12th, March 11:36 RCIC stops.
(Continuous operating time is 19^h52^m)
12:35 HPCI starts.

13th, March 02:42 HPCI stops.
(Continuous operating time is 14^h07^m)

	08:41	Ventilation line is established.
	09:08	SRV is opened. SRV is reclosed due to exciter trouble.
	09:20	CV pressure decreases.
	11:17	AOV in ventilation close due to loss of air.
	11:55	Start of fresh water injection to reactor core
14th, March	11:01	Hydrogen explosion
	22:00	Core meltdown occurs.

4.4 Summary of correspondences taken at the Fukushima-Daiichi nuclear power plant

Just after the earthquake attack, all the reactors were safely shutdown, and emergency diesel generators were started as expected.

Isolation cooling system (IC) was automatically started at unit 1 for cooling the reactor core. RCICs were manually started at units 2 and 3, but their starting times are a little later, that is, 16 minutes and 20 minutes after the reactor stop for units 2 and 3, respectively.

The change of plant state in unit 1 was as follows. A valve in IC line was opened 24 minutes later (18:10). The reactor core was not cooled till this time, and 15 minutes later (18:25), the valve was closed again. The time duration of core cooling was only 15 minutes.

About 3hours later (21:30), the core cooling was started by opening of valve 3V. There was three hours downtime for core cooling.

At 01:48 on the next day (12th), pump failure happened and IC stopped. The HPCI could not start because emergency battery failed due to submergence.

At 20:20, injection of sea water and boric acid solution into reactor core was started by a fire water pump. There was about 18 hours downtime for core cooling, again.

The core melt was happened at early stage in unit 1, about 5 hours after the earthquake.

The change of plant state in unit 2 was as follows. The RCIC was stopped at 26 minutes after the start. Then start again 30minutes later. Water source of RCIC was changed from CST to Suppression chamber. Core cooling was continued for long time (70^h23^m), and stopped at 13:25 on 14th, because of pump failure.

At 16:34 on 14th, injection of sea water into reactor core was started by a fire water pump. There was about 3 hours downtime for core cooling.

The core melt was happened at 23:00 on 14th in unit 2, about 80 hours after the earthquake.

The change of plant state in unit 3 was as follows. The RCIC was stopped at 19 minutes after the start. Then start again 38minutes later. Finally RCIC was stopped at 11:26 on 12th, about 20 hours after the restart.

The HPCI was started at 12:35 on 12th, after one hour downtime for core cooling. The cooling by the HPCI continued during 14 hours and stopped. Then, injection of fresh water into reactor core was started by a fire water pump. There was again about 9 hours downtime for core cooling.

Relatively proper actions were made for the cooling of reactor cores in units 2 and 3. But, there were many downtimes and sometimes they continued long time duration, even in units 2 and 3.

5 Event tree for loss of all AC power

Emergency core cooling systems in Fukushima-Daiichi have different design[4,8] from a general BWR power plant.

The HPCI is driven by turbine as shown in Fig. 6. It is advantageous for operating under the condition of the loss of all AC power. Long term operation of HPCI requires a ventilation of containment vessel (CV) for the prevention of excess increase of temperature and pressure.

Unit 1 is an old type nuclear power plant and has Isolation Cooling system (IC) instead of RCIC. The

IC has redundancy with two lines, as shown in Fig. 7. Maximum operating time of IC is estimated as 8 hours from the amount of cooling water in condenser.

The event trees for loss of all AC power become as shown in Figs. 8 and 9, with the consideration of above design characteristics.

The event tree for unit 1 is in Fig. 8. Removal of the decay heat from the core during 72 hours requires two lines of IC and HPCI systems, as IC has only 8 hours maximum operating time.

After the 72 hours core cooling, it is assumed that fire water pump is connected and it injects cooling water into rector core.

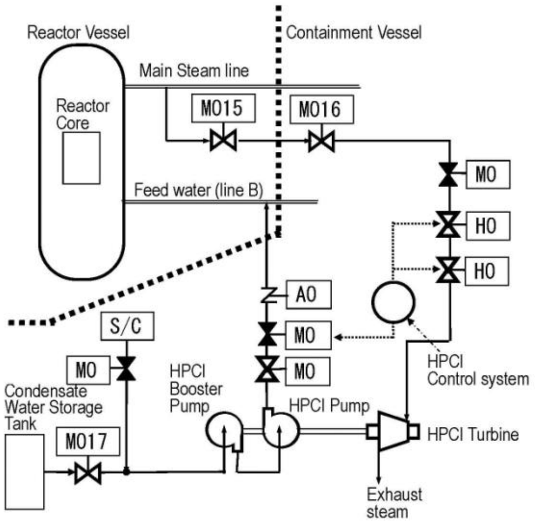

Fig. 6 HPCI of Fukushima-Daiichi units 1, 2, and 3.

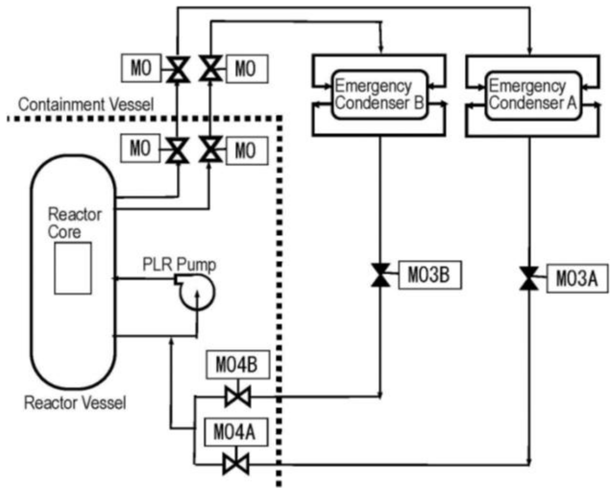

Fig. 7 IC of Fukushima-Daiichi units 1.

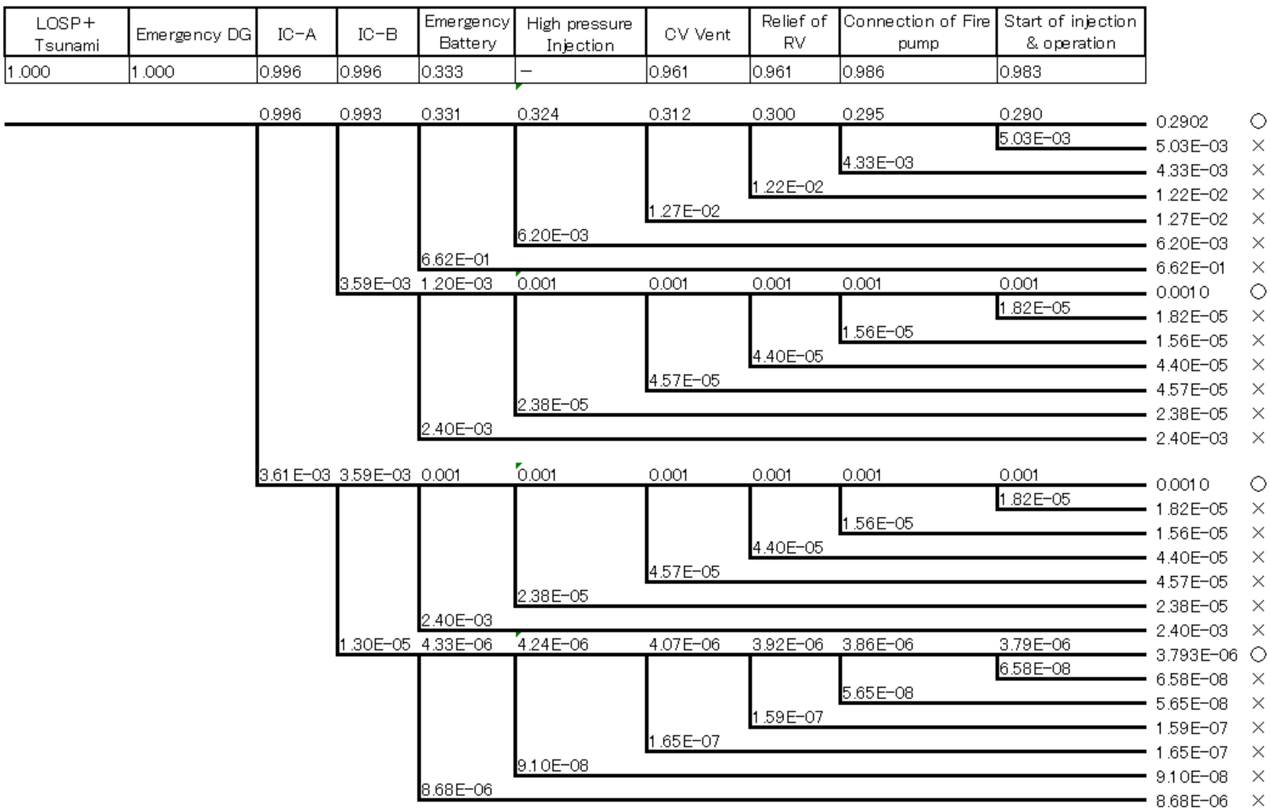

Fig. 8 Event tree of loss of all AC power for Fukushima-Daiichi unit 1.

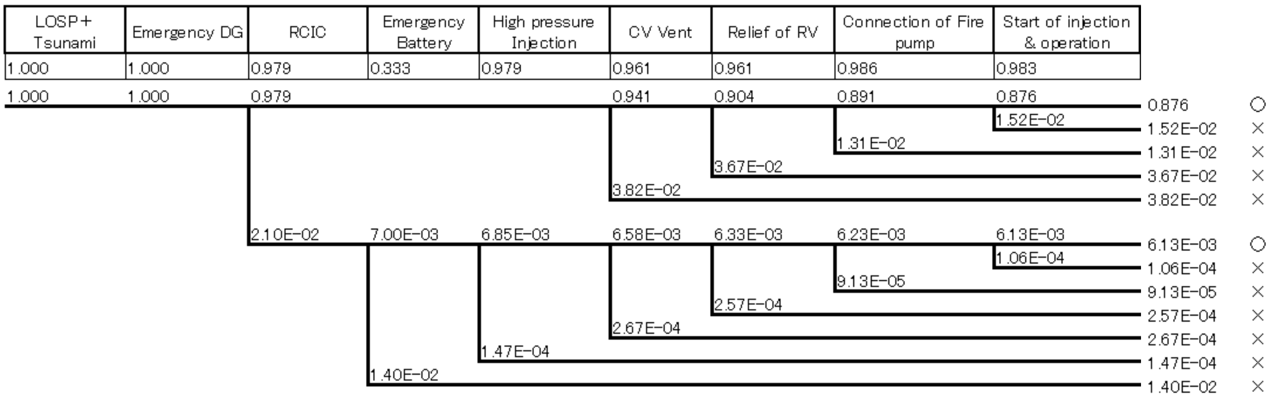

Fig. 9 Event tree of loss of all AC power for Fukushima-Daiichi units 2 and 3.

5.1 Quantitative evaluation of the event trees of loss of all AC power

The values assigned in section 2.1 are used for component failure rates, and event tree analyses are performed.

Emergency batteries were not functioned at 2 units out of 3 units, after Tsunami arrival at Fukushima-Daiichi plant. Then, the value 0.333 is assigned as success probability of the heading "emergency battery" in the event tree.

The core damage probabilities are obtained as $6.86x10^{-1}$ and $5.26x10^{-2}$, at 72 hours (3days) after the arrival of Tsunami, for unit 1 and units 2&3, respectively.

At 168 hours (7days), the core damage probabilities become as $7.08x10^{-1}$ and $1.18x10^{-1}$, for unit 1 and units 2&3, respectively.

Core damage probability of unit 1 has large value. This is because of short time duration of 8 hours for IC's continuous operation, and the low success probability of emergency battery under Tsunami condition.

6 Discussions

The analysis results are summarized as shown in Table 1. It is necessary to be taken notice that the core damage probabilities (CDP) shown here are conditional probabilities. Occurrence frequency of plant state "Loss of all AC power" is smaller than LOSP by the factor of the probability of simultaneous failure of two emergency diesel generators. If we consider only random failure of components, this factor becomes $0.015x0.015=2.25x10^{-4}$.

Table 1 Core damage probabilities

	72hours	168hours
LOSP (General BWR)	1.93×10^{-5}	2.95×10^{-5}
Loss of all AC power (General BWR)	5.92×10^{-2}	
Loss of all AC power (Fukushima unit 1)	6.86×10^{-1}	7.08×10^{-1}
Loss of all AC power (Fukushima units 2&3)	5.26×10^{-2}	1.18×10^{-1}

As the CDP at loss of all AC power, more than one order larger value is obtained for Fukushima unit 1 comparing to general BWR plant. The reasons are short time duration of IC's possible continuous operation, and the low success probability of emergency battery under Tsunami condition. It could be said that the design of unit 1 was not adequate for the case in which long time was required for recovery of offsite power.

Almost the same value is obtained for Fukushima units 2&3 and general BWR as the CDP of loss of all AC power at 72 hours. There are two turbine driven cooling systems; RCIC and HPCI, in Fukushima units 2&3. It was expected small CDP because of this redundancy, but the protection against Tsunami was not sufficient for emergency battery.

With the core cooling by fire water pump after 72 hours, the CDP of loss of all AC power is kept low even at 168 hours (7days) after Tsunami arrival.

Simultaneous occurrence probability of core damage of both units 2 and 3 reactor is calculated as $0.118 \times 0.118 = 1.4 \times 10^{-2}$ based on the analysis results. But, the core melts of both two reactors, actually occurred in this accident. It is very difficult to understand for this situation to happen accidentally.
Ii is reported that there is no component failure due to the earthquake itself. It could be supposed that any degradation or failure of components actually occurred and the core damages happened.

In the present analysis, core cooling is assumed to be successively performed without any interruptions. But, there were many interruptions or downtime of the operation of safety systems as seen in the record of actual correspondences (in section 4). It could be said that operators' actions were not appropriate for the prevention of accident in this Tsunami situation.

Finally, we have to modestly examine that there is any methodological mistake or unconsidered matter in the present analysis. Could we properly incorporate the actual accident conditions or work environment, into event tree analyses? If the past PSA could not properly consider these factors, we have to reconsider the results of safety evaluation by past PSA.

Discussions are made by a viewpoint of PSA. I would be very glad if the contents of the present paper are referred to the consideration of nuclear power plant safety in the future.

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