

# **A Study of Fukushima Nuclear Power Plant Accidents by the 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 or station blackout, 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 or station blackout. The core damage probability at 168 hours (7 days) after the Tsunami are obtained as 0.80(Unit 1), 0.40(Unit 1) and 0.30 (Unit 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.

**Keywords:** Fukushima Nuclear Power Plant, PSA, Loss of all AC Power, Core Damage Probability

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## **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 or station blackout, for the Fukushima-Daiichi nuclear power plant.

In the actual accidents at the 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. CORE COOLING SYSTEMS OF FUKUSHIMA-DAIICHI NUCLEAR POWER PLANT IN CASE OF LOSS OF ALL AC POWER**

If all AC power is lost and normal circulation system fails to its function, the reactor core has to be cooled without motor driven pump.

Fukushima-Daiichi nuclear power plant prepares Isolation Cooling system (IC), Reactor Core Isolation Cooling system (RCIC) and High Pressure Core Injection system (HPCI) for the core cooling in case of loss of all AC power.

Emergency core cooling systems in Fukushima-Daiichi have different design[3,4] from a general BWR power plant. Unit 1 is an old type nuclear power plant and has Isolation Cooling systems (IC) instead of RCIC. The IC has redundancy with two lines, as shown in Fig. 1. Maximum operating time of IC is estimated as 8 hours from the amount of cooling water in condenser.

The HPCI is driven by turbine as shown in Fig. 2. 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. The HPCI is equipped in Units 1, 2 and 3.

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 also 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).

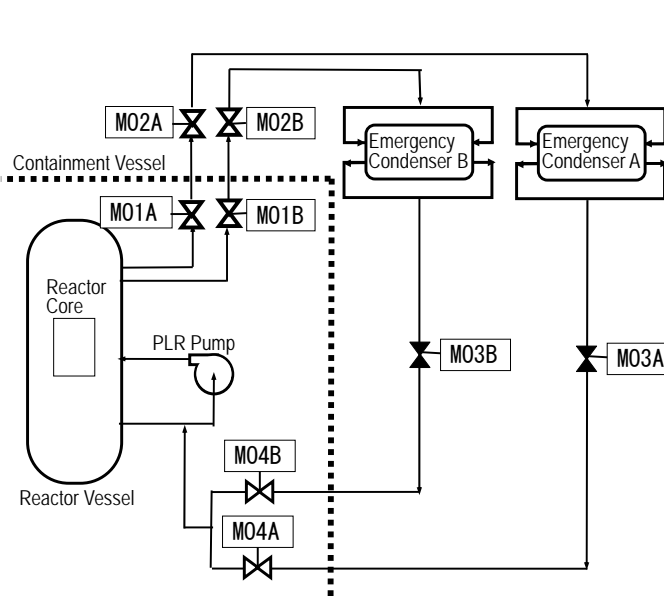


Figure 1. IC of Fukushima-Daiichi unit 1.

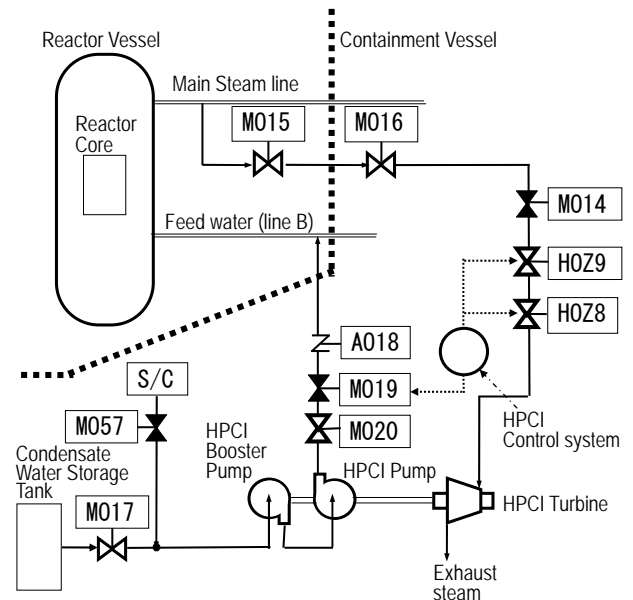


Figure 2. HPCI of Fukushima-Daiichi units 1,2,3.

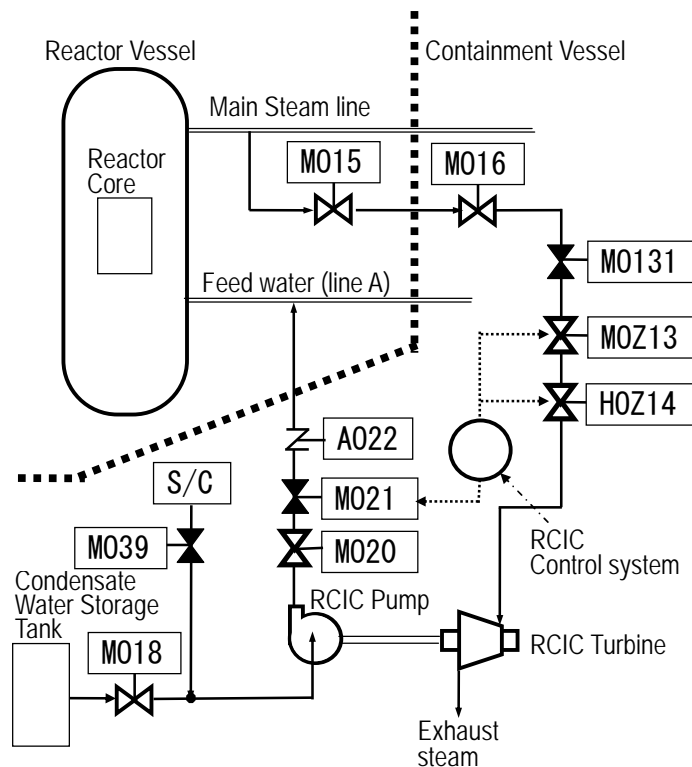


Figure 3. Reactor core isolation cooling system (RCIC) of Fukushima-Daiichi units 2&3.

### 3. 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 [5]. The estimated time of core melt down is based on the analysis of Nuclear and Industrial Safety Agency, Japanese Government.

#### 3.1. Fukushima-Daiichi Unit 1

11th, March	14:46	Earthquake
	14:47	Two emergency DGs start.
	14:52	Isolation Cooling system (IC) automatically starts.
	15:03	IC-B line manually stops.
	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 in IC is manually reclosed. This information was not clearly transfer to the accident action center held at Fukushima site.
	20:00	Core meltdown occurs.
	21:19	Lineup of fire water pump
12th, March	21:30	Valve 3A in IC is reopened.
	01:48	Pump failure, IC stops.(Continuous operating time is 4h23m)
	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	Start of injection of sea water and boric acid solution into reactor core.

#### 3.2. Fukushima-Daiichi Unit 2

11th, March	14:46	Earthquake
	14:47	Two emergency DGs start.
	14:50	RCIC is manually started.
	15:51	RCIC automatically stops with the signal of high water level.
	15:02	RCIC is manually started again.
	15:27	First Tsunami attacks.
	15:28	RCIC automatically 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
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 by unknown reason. (time is estimation) (Continuous operating time is less than 70h23m)
	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 into 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

### 3.3. Fukushima-Daiichi Unit 3

11th, March	14:46	Earthquake
	14:47	Two emergency DGs start.
	15:05	RCIC is manually started.
	15:25	RCIC automatically 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 by failure. (Continuous operating time is 19h52m)
	12:35	HPCI automatically starts.
13th, March	02:42	HPCI manually stops. (Continuous operating time is 14h07m)
	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 into reactor core.
14th, March	11:01	Hydrogen explosion.
	22:00	Core meltdown occurs.

### 3.4. 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 19 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 intentionally closed. The time duration of core cooling was only 15 minutes. About 3hours later(21:30), the core cooling was started by opening of valve 3A. 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 Unit 1 reactor core was started by an external 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 second start. Then about 30minutes later, RCIC was started again. Water source of RCIC was changed from CST to Suppression chamber. Core cooling was continued for long time (70h23m), and the RCIC stopped at 13:25 on 14th with unknown reason.

At 16:34 on 14th, injection of sea water into reactor core was started by an external 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 intentionally stopped. Then, try to inject fresh water into reactor core, and it was started about 9 hours later by an external fire water pump.

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

#### **4. ANALYSIS BY EVENT TREE**

##### **4.1. Premise of the analysis**

Tsunami attacks 45 minutes after the loss of offsite power(LOSP). During this 45 minutes, plant personnel takes maximum measures against the station blackout which will be caused by anticipated Tsunami.

Reactor core is cooled by high pressure system (IC or RCIC or HPCI) during 72 hours (3days) and successively cooled by water injected by external fire pump during 96 hours (4days). During the total 7 days' continuous cooling, off site power will be recovered and the reactor will be led to stable condition.

Core damage probability is evaluated at time 72 hours and 168 hours after the start of LOSP.

##### **4.2. Analysis condition**

Reactors are safely shut down just after the LOSP. DC power is available only in Unit 3 after the Tsunami attack. DC power is prepared with the rate of  $\mu=0.05/h$  for Units 1&2. Then the success probability of DC power preparation becomes 0.33 (8h), 0.8(36h) and 0.973(72h).

Air tank must be replaced by new one before exhausting the air for air operated valves (AOV). Success probability of the tank replace within 72 hours is assumed as 0.973.

Motor operated valve (MOV) cannot make open/close action without DC power. AOV cannot make open/close action without air supply and DC power.

Ventilation of containment vessel (CV) requires AOV's open action. The action of the pressure vessel's relief valve requires DC power.

HPCI does not start without DC power, because steam flows through stop valve and adjust valve to HPCI turbine and the opening of these valves(HOZ8, Z9 in figure 2.) needs operating oil which is supplied by oil pump. The pump is driven by DC power.

In RCIC and HPCI systems there is test line. Some portion of injection water can be returned to the CWST by this line to control the amount of injection water. With this method, excessive increase of water level can be avoided.

All the valves in IC were closed by fail safe mechanism after the station black out in the present accident. This situation was produced by the control button being set to be "auto". All the valves in IC can be maintained in open state after the station black out by setting the button "open".

All the valves in RCIC and HPCI are maintained in "as is" state after the station black out. This is mentioned in NISA comments[6].

It is also assumed that switchboard (MCC) wetted by water is recovered within few hours.

##### **4.3. Component failure data**

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[7].

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

As the additional assumptions, following failure rates or probabilities are assumed considering the failure data shown in the procedures of Level 1 PSA[7] for the analyses.

Air operated valve(AOV)	
failure of open/close action	$3.6 \times 10^{-3}/D$
failure during usage	$2.0 \times 10^{-7}/\text{hour}$
Rapture disk of CV	$3.9 \times 10^{-2}/D$
Valves of IC is fixed open	$3 \times 10^{-3}/D$

#### 4.4. Event tree construction

In Unit 1, 72 hours continuous decay heat removal from the core requires two lines of IC and HPCI systems, because one IC has only 8 hours maximum operating time. After the 72 hours core cooling, it is assumed that an external fire water pump is connected and it injects cooling water into reactor core. The event tree for unit 1 is shown in Figure 4.

After the station blackout, it becomes very difficult to start HPCI. So, there is a selection to start HPCI before Tsunami arrival and do not use ICs. The valves in HPCI are fixed in open state before station blackout. The event tree for this case is shown in Figure 5.

In Unit 2, the core is initially cooled by the RCIC. During the core cooling by RCIC, DC power source is prepared and HPCI can be used as an alternative cooling system of RCIC. After the 72 hours core cooling, also an external fire water pump is connected and it injects cooling water into reactor core. The event tree for unit 2 is shown in Figure 6.

In Unit 3, fortunately the DC power is available. The Unit 3 has advantage over Unit 2, and HPCI is available at any time during initial cooling. The event tree for Unit 3 is similar to the one for Unit 2, except heading of "DC power preparation".

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.

#### 4.5. Event tree analysis

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, failure probabilities of safety systems (appeared as headings in Figs 4.-6.) are quantitatively evaluated by only considering random failure of components.

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

$$3.6 \times 10^{-3} \text{ (pump fails to start)} + 1.4 \times 10^{-4} \times 72 \text{h (failure of pump during operation)} \\ + 2 \times 3.6 \times 10^{-3} \text{ (MOV's fail to open)} + 2 \times 10^{-7} \times 9 \times 72 \text{h (failures of MOV valves during usage)} = 2.10 \times 10^{-2}$$

Success probability of HPCI's function =  $1.0 - 2.10 \times 10^{-2} = 0.979$

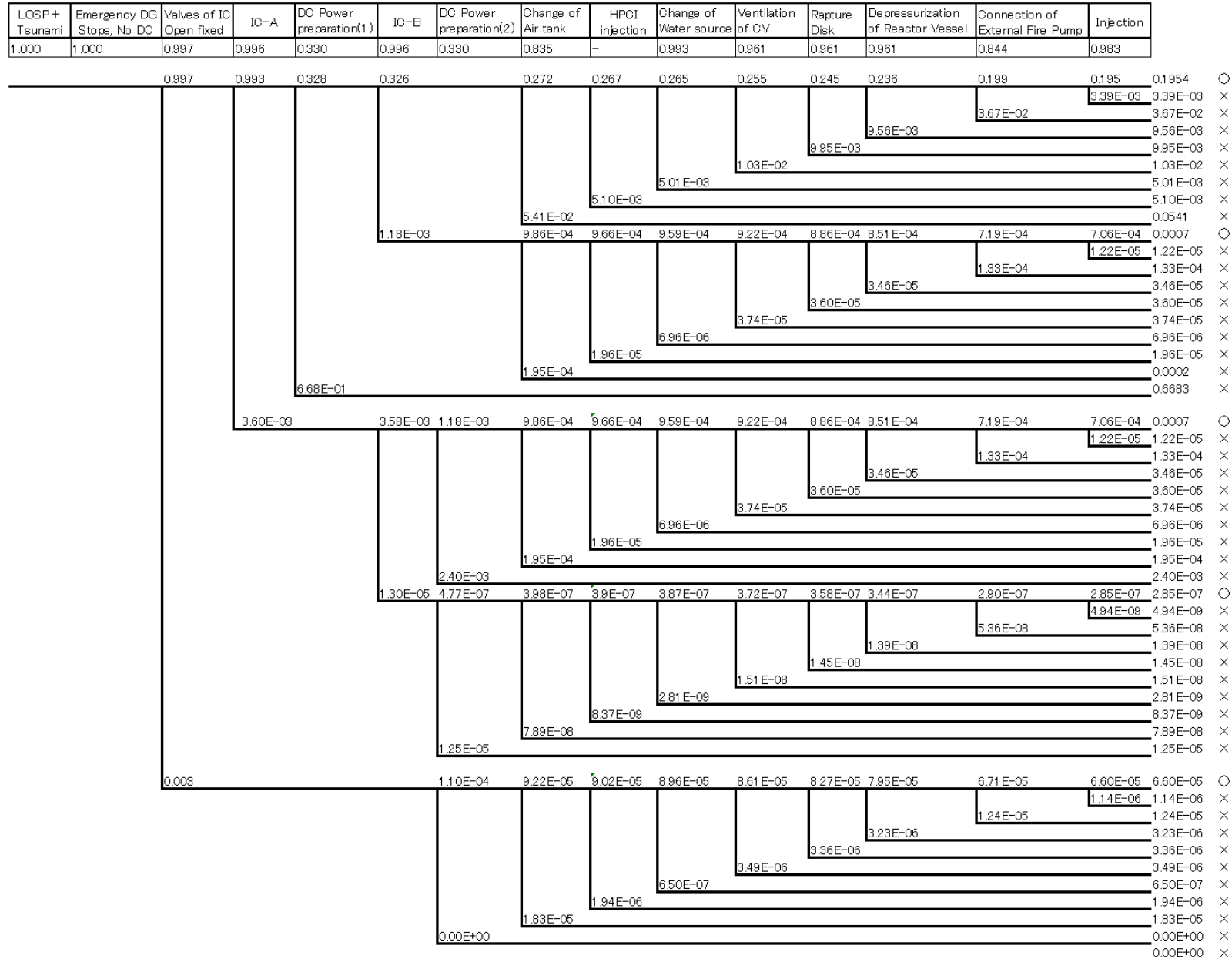


Figure 4. Event tree for Unit 1 (IC & HPCI).

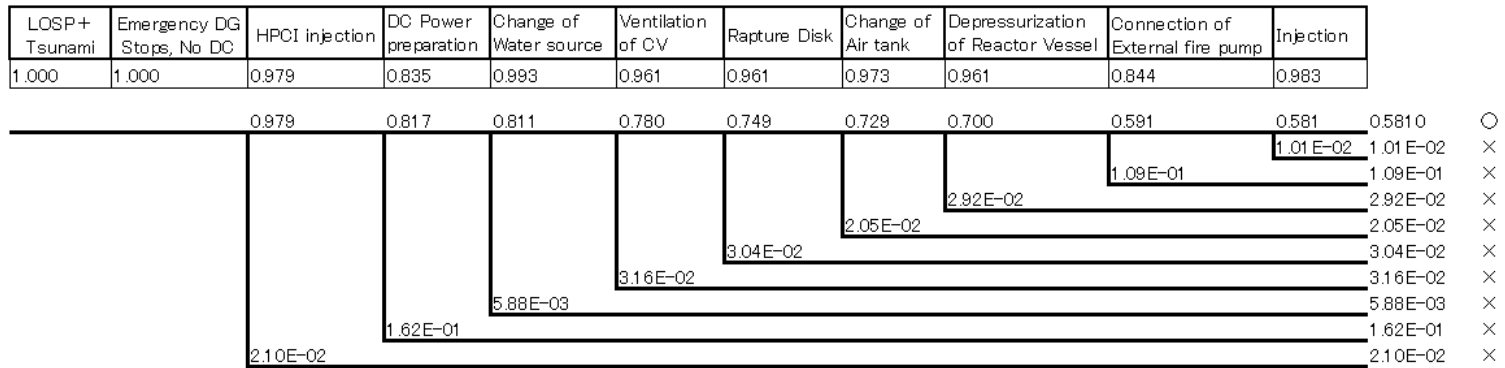


Figure 5. Event tree for Unit 1 (HPCI).

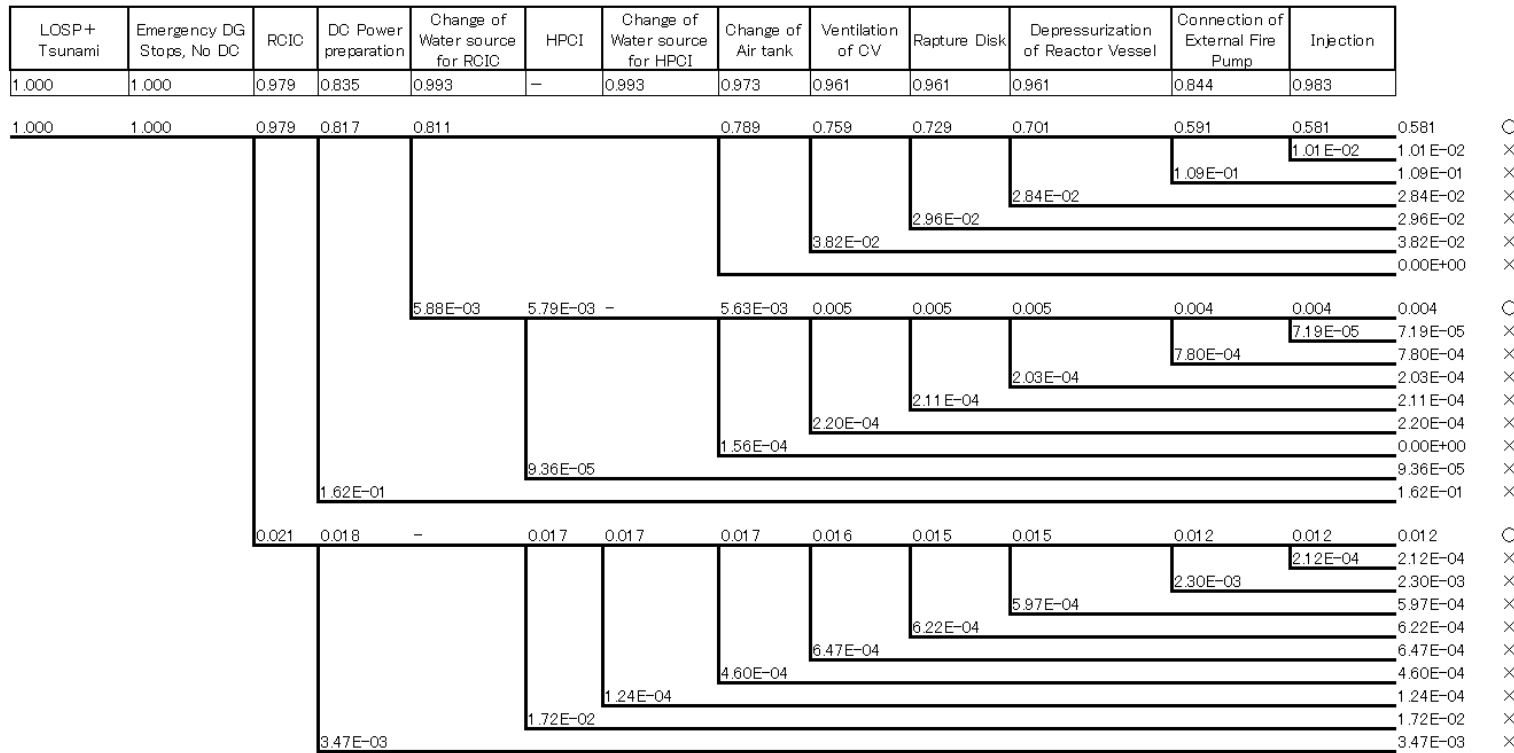


Figure 6. Event tree for Unit 2.



#### 4.6. Analysis results

The core damage probabilities are obtained as shown in Table 1, at 72 hours (3days) and 168 hours (7days) after the LOSP. The case in which IC is initially operated is indicated by "Unit 1 (IC & HPCI)", and the case without IC usage is indicated by "Unit 1 (HPCI)".

Core damage probability of Unit 1(IC & HPCI) has large value, but that of Unit 1(HPCI) has the value comparable to the values of Units 2 and 3. The selection of the strategy to use only HPCI is better than to use ICs and HPCI.

Table 1. Core damage probabilities of Fukushima-Daiichi nuclear power plant under the Tsunami attack.

	Unit 1 (IC & HPCI)	Unit 1 (HPCI)	Unit 2	Unit 3
at 72h (3days)	$7.53 \times 10^{-1}$	$2.71 \times 10^{-1}$	$2.51 \times 10^{-1}$	$7.71 \times 10^{-2}$
at 168h(7days)	$8.03 \times 10^{-1}$	$4.19 \times 10^{-1}$	$4.03 \times 10^{-1}$	$3.04 \times 10^{-1}$

#### 5. DISSCUSSIONS AND CONCLUSIONS

The analysis results are summarized as shown in Table 1. It is necessary to be taken notice that the core damage probabilities shown here are conditional probabilities.

As the CDP at station blackout, larger value is obtained for Unit 1 (IC&HPCI) comparing to other cases. The reason is the short time duration of IC's possible continuous operation. It could be said that the design of Unit 1 and selection of ICs were not adequate for the case in which long time was required for recovery of offsite power.

Almost the same value is obtained for Fukushima Unit 1(HPCI) and Unit 2 as the CDP at station blackout. There are two turbine driven cooling systems; RCIC and HPCI, in Fukushima units 2 and 3. It was expected small CDP because of this redundancy, but difficult conditions produced by the Tsunami yields the high CDP.

With the core cooling by external fire water pump, the CDP is kept under 0.5 for all three units even at 168 hours (7days) after Tsunami arrival. Simultaneous occurrence probability of core damage of three units is calculated as  $0.419 \times 0.403 \times 0.304 = 5 \times 10^{-2}$  based on the analysis results. But, actually the core melt of three reactors occurred in this accident. It is a little difficult to understand for this situation to be happened accidentally.

It is reported that there is no component failure due to the earthquake itself. But, it could be supposed that any degradation or failure of components was produced and the core melts occurred.

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 chapter 3). It could be said that operators' actions were not appropriate for the prevention of core melt in this accident.

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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