Estimation of dynamic behavior of nuclear power plant system state under severe accident conditions

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Abstract: Dynamic behavior of nuclear power plant system has been evaluated under accident conditions. Analyses have been performed by the GO-FLOW methodology, which is utilized as key technology in reliability monitoring system (RMS) or plant Did risk monitor, now being developed at Harbin Engineering University (HEU). A hypothetical sequence of accident conditions has been settled based on the Fukushima Daiichi accident. Success probabilities of system operation have been obtained with the progression of accident. The presented analyses show that dynamic behavior of nuclear power plant under accident conditions can be easily obtained.

Keyword: dynamic behavior; risk monitor system; severe accident condition

1 Introduction

In case of a nuclear power plant accident, especially in severe accident, the plant configuration drastically changes and required missions for safety operation of plant or prevention of escalation of accident also change. This situation typically shows dynamic behavior of plant states with the progression of accident.

The authors have developed a reliability analysis methodology, GO-FLOW [1], which is a success oriented system analysis technique, and is capable of evaluating a large system with complex operational sequences. The GO-FLOW methodology is a valuable and useful tool for system reliability analysis and has a wide range of applications, especially for evaluating the dynamic behavior of system state.

Now, Harbin Engineering University (HEU) is developing a reliability monitoring system (RMS) of nuclear power plants [2], which combines a dynamic reliability analysis system with an online fault management system. The HEU is also developing Plant Defense in-Depth (Did) Risk Monitor [3] by object oriented software system.

The RMS calculates the reliability over the lifetime of the system. The Did risk monitor provides an overview of system states and details about events that impact reliability. The GO-FLOW is utilized as key technology in these developments.

In this paper, the GO-FLOW is applied to estimate dynamic behavior of nuclear power plant system under severe accident conditions, such as Fukushima Daiichi accident. A hypothetical sequence of accident conditions is settled and availability or reliability of plant systems are analyzed under the varying accident conditions.

The GO-FLOW methodology is used for estimating the dynamical plant state. The results are expressed in graphical style which will correspond to a display window of risk monitor system, which visualizes risk state intuitively as "dynamic risk monitor”. It indicates that plant states with the progression of accident is easily obtained by the “reliability monitor” or “plant Did risk monitor” which are supported by the GO-FLOW methodology.

Received date: November 4, 2014

2 A hypothetical sequence of accident conditions

The following accident sequence is assumed in this paper.

Initially, nuclear power plant is in normal operational condition. At a certain point, offsite power is lost, but power generation is maintained with the start of emergency diesel generators. Next, one of two emergency generators fails, still the function of power generation is maintained. Finally, the second generator also fails. Even in this case, the plant is designed to be possible to continue its operation with loop structures as shown in Fig.1. In the actual operating procedure of nuclear power plants, the operation is immediately stopped if offsite power is lost.

In the next stage, reactor is shut down. There is no AC power source, that is, plant is placed in "station blackout" condition. The mission of the plant has changed from "power generation" to "core cooling".

The reactor core isolation cooling system (RCIC) and high pressure core injection system (HPCI) are successively used for core cooling. It indicates that small amount of DC power is available for the operation of motor operated valves.

After the failure of both systems (RCIC and HPCI), a fire protection pump is connected to the primary cooling system, and the core is cooled by the water from pure water tank. The fire pump is driven by diesel generator brought by a car. After the pure water tank is exhausted, the core is cooled by sea water, and waits to recover external power supply.

3 Systems analyzed under accident conditions

Figure 1 shows a general layout of BWR system. Only essential parts are expressed. Almost the same system has been analyzed [4] for evaluation of the effectiveness of loop structures. It is seen there are five essential loop structures, main steam and feed water loop, electric power supply, component cooling water supply, steam extraction, and lubricating oil system.

The details of analysis procedure of loop structure are explained in reference [5]. For a system which has logical loop structure(s), the Boolean relations between components' states have to be described with unknown variable(s). The Boolean relation can be solved with an indefinite arbitrary element (*m*). The *"m"* is determined by the condition how the loop operating state is established. It has been shown that arbitrary Boolean element "*m*" is unity or universal set ($m=I$) under the condition Boolean elements represent operating states of components [5].

In Fig. 1, red arrows indicate electric power supply. If components have red arrow, they require electricity for their operation. Blue arrows indicate cooling water, and components require to be cooled by water, when they have blue arrow. Green lines indicate extraction steam lines. Reactor feed water pump needs lubricating oil for its continuous operation.

Under the accident condition "station blackout", the mission of the plant is "core cooling". The reactor core isolation cooling system (RCIC) and high pressure core injection system (HPCI) are successively used for this purpose. The layout of the systems are shown in Figs. 2 and 3. The detailed procedures of reliability analyses of these two systems have been shown in reference [6] under accident condition.

These two systems have also loop structure. The analyses are also performed by using the method to solve loop structure.

From Figs. 2 and 3, we can see the motor operated valves (MO15, MO16) and condensate water storage tank (CWT) are commonly used for both systems. So, the successive operation of two systems becomes a phased mission problem.

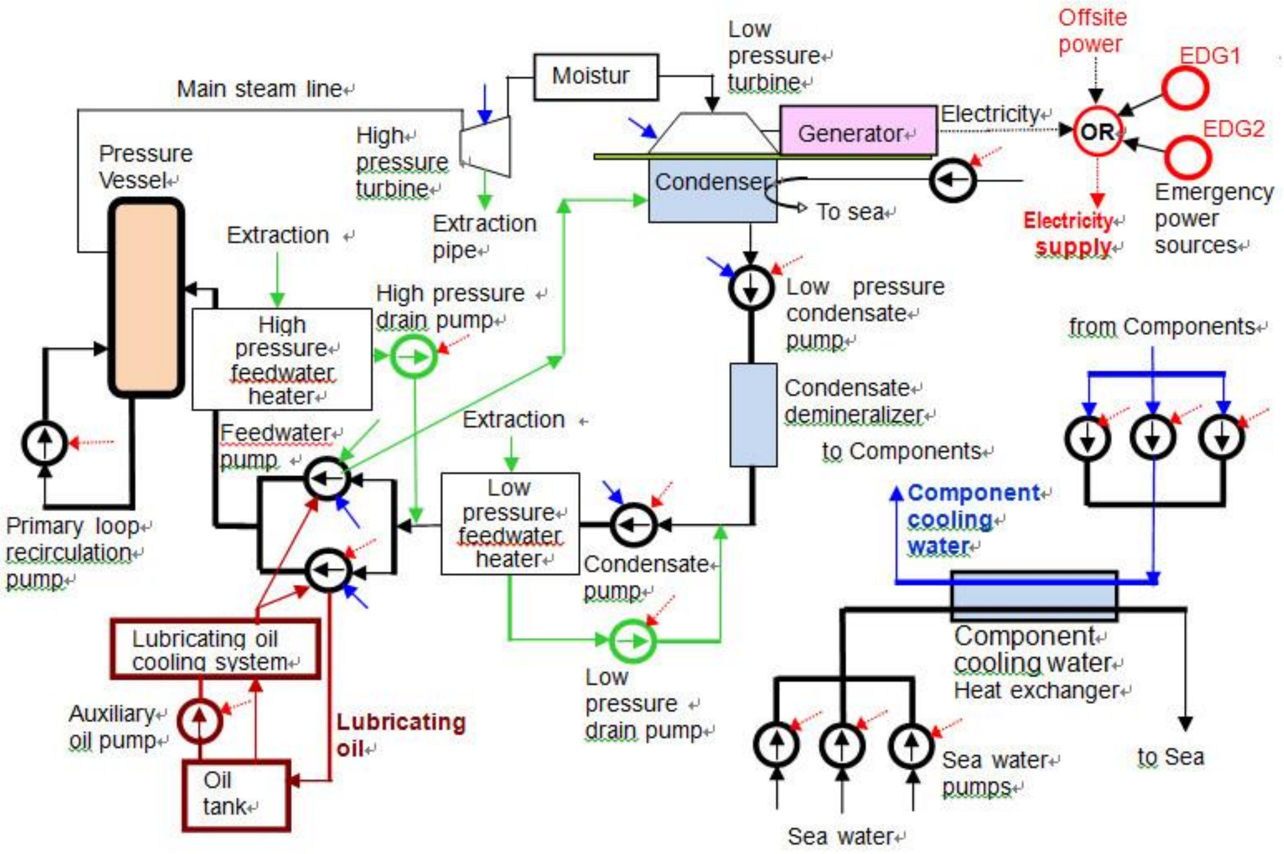

Fig.1 General layout of BWR nuclear power plant.

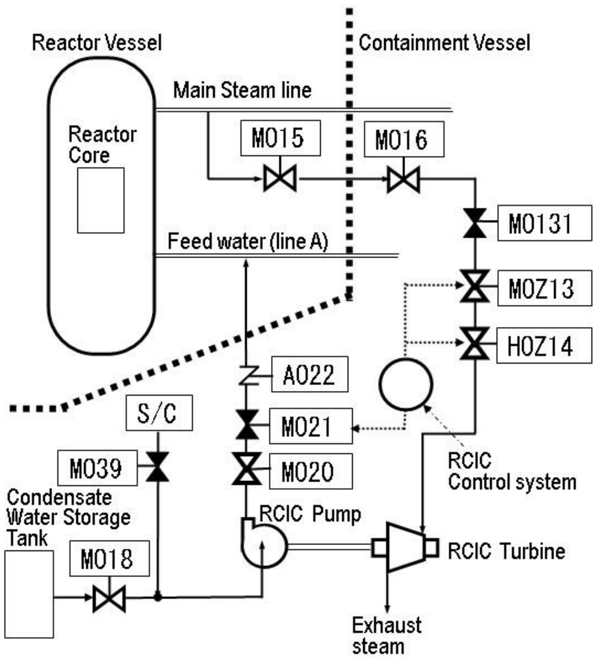

Fig. 2 Reactor core isolation cooling system (RCIC) of Fukushima Daiichi units 2 and 3.

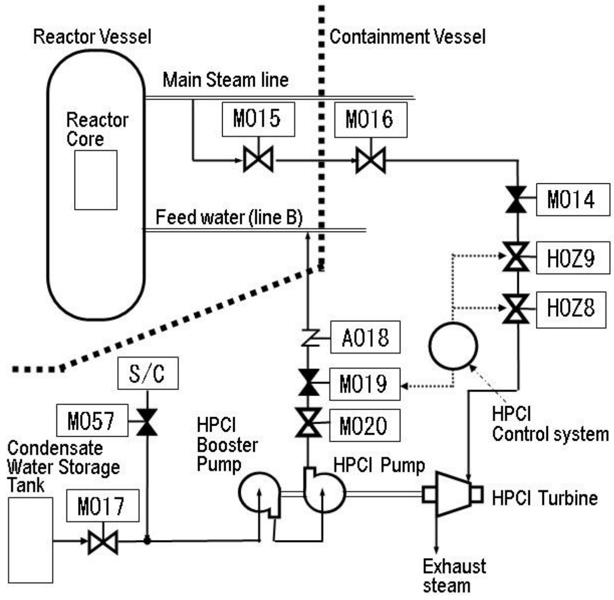

Fig. 3 High pressure coolant injection system (HPCI) of Fukushima Daiichi units 1, 2, and 3.

Also, these two systems have common components with the power generation system of BWR nuclear power plant (Fig.1). Common components are "main steam line", " pressure vessel (reactor vessel)" and "feed water line", but failure rates of these components are very small. Therefore, it is not necessary to consider phased mission condition for the operation change from "power generation" to "core cooling".

After the failure of two systems: RCIC and HPCI, fire engine is brought and fire protection pump is used for injection of pure water from a pit in the plant site.

The system layout is shown in Fig. 4, which is actually taken at the Fukushima Daiichi accident [7]. After the exhaust of pure water, sea water is used for core cooling.

In the analysis of water injection system by fire pump, it also need not consider phased mission condition with the power generation system, RCIC and HPCI.

4 Analysis by the GO-FLOW

Failure rates of components are assigned as follows based on the data shown in the standard for procedures of Level 1 PSA[8] and component reliability data collected by IAEA[9].

(1)Motor/Air operated valve
- failure of open/close action $3.6x10^{-3}$/D
- failure during usage $2.0x10^{-7}$/hour
- failure during standby $2.0x10^{-8}$/hour

(2)Pump
- fails to start $2.7x10^{-2}$/D
- failure during operation $1.0x10^{-4}$/hour

(3)Emergency diesel generator
- fails to start $1.0x10^{-2}$/D
- failure during operation $3.0x10^{-3}$/hour

(4)Fire engine
- Fails to connect $1.4x10^{-2}$/D

(5)Fire pump
- fails to start $2.7x10^{-2}$/D
- failure during operation $1.0x10^{-4}$/hour

(6)Turbine
- fails to start $2.7x10^{-2}$/D
- failure during operation $1.0x10^{-4}$/hour

(7)Condensate water storage tank
- failure during operation $2.8x10^{-8}$/hour

GO-FLOW charts are constructed as shown in Figs. 5, 6 and 7, for "BWR plant system", "RCIC and HPCI system", and "water injection system by a fire engine", respectively.

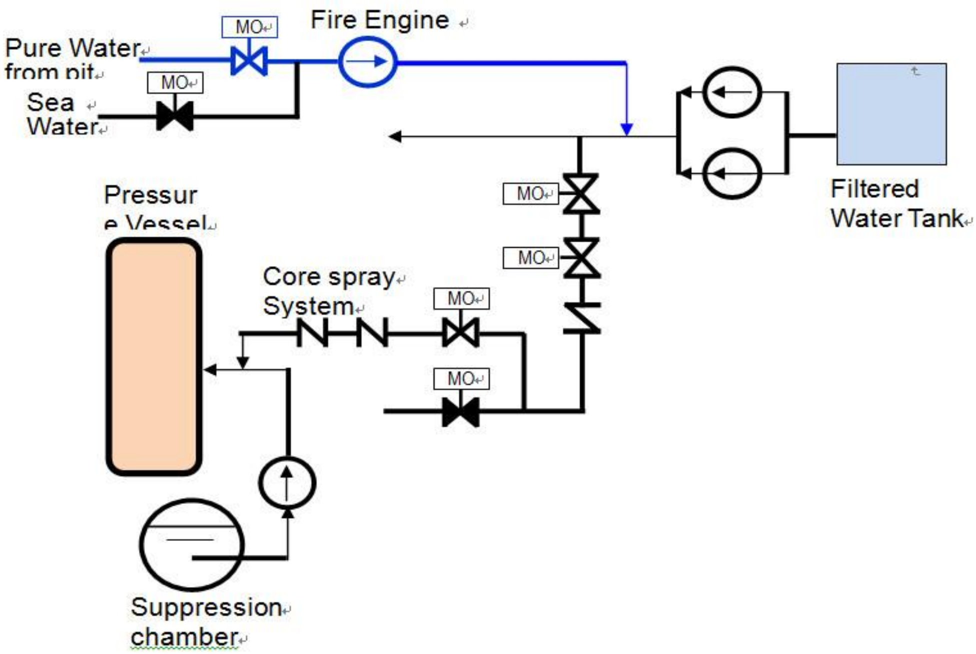

Fig.4 Water injection by fire engine.

The RCIC and HPCI could be considered as one system with double loop structures, and the chart includes both the RCIC part and HPCI part as shown in Fig. 6. With the aid of phased mission operators (operator number 24 and 41 in Fig. 6), the dependency between two systems (RCIC and HPCI) is correctly treated [10].

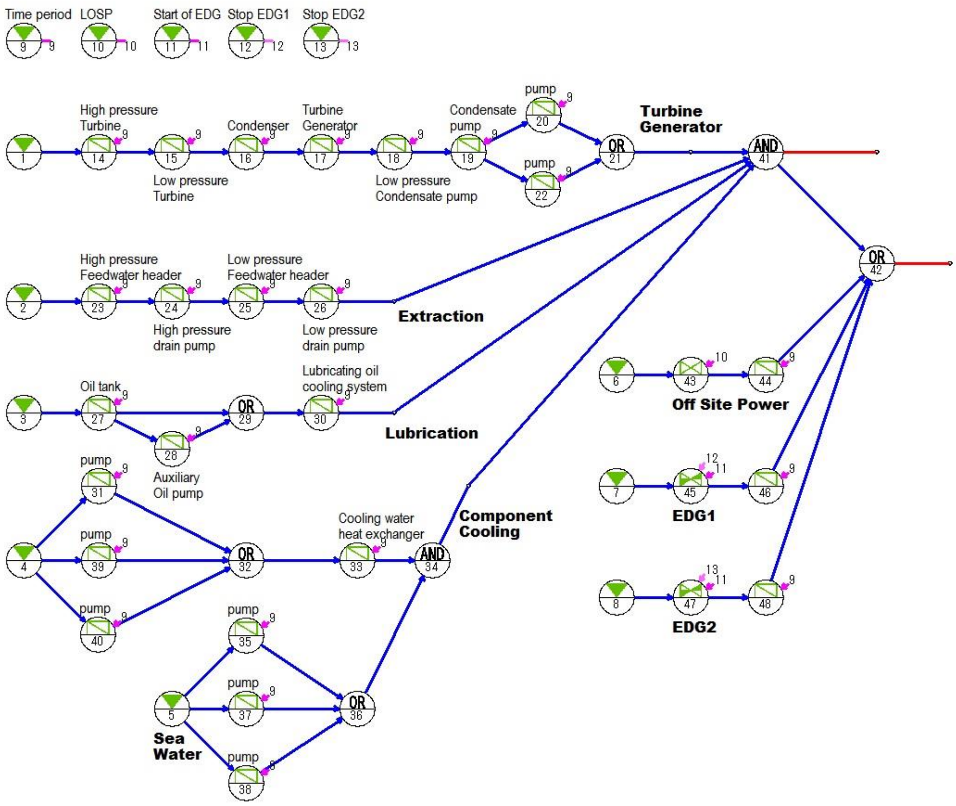

Fig.5 GO-FLOW chart for general layout of BWR nuclear power plant.

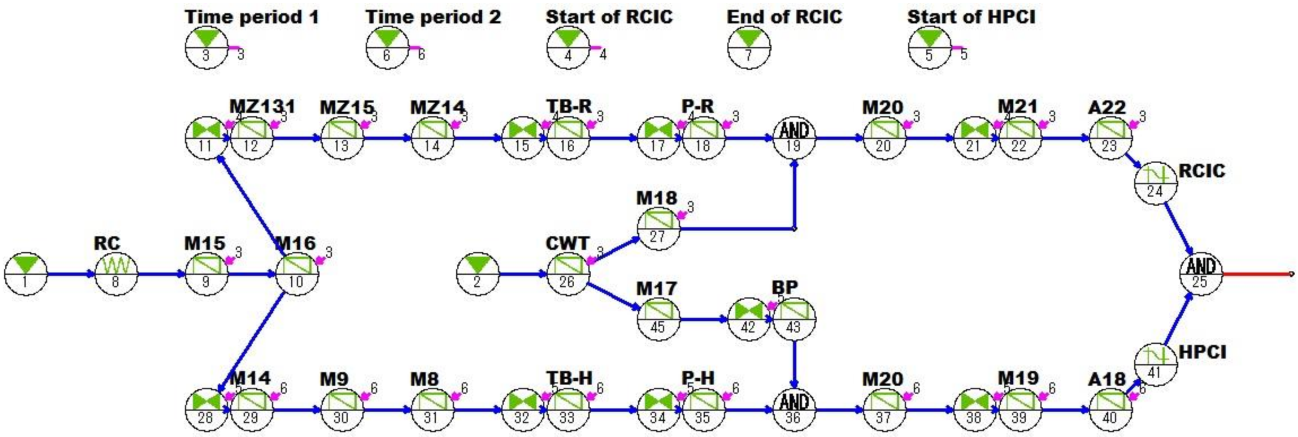

Fig. 6 GO-FLOW chart for the RCIC and HPCI.

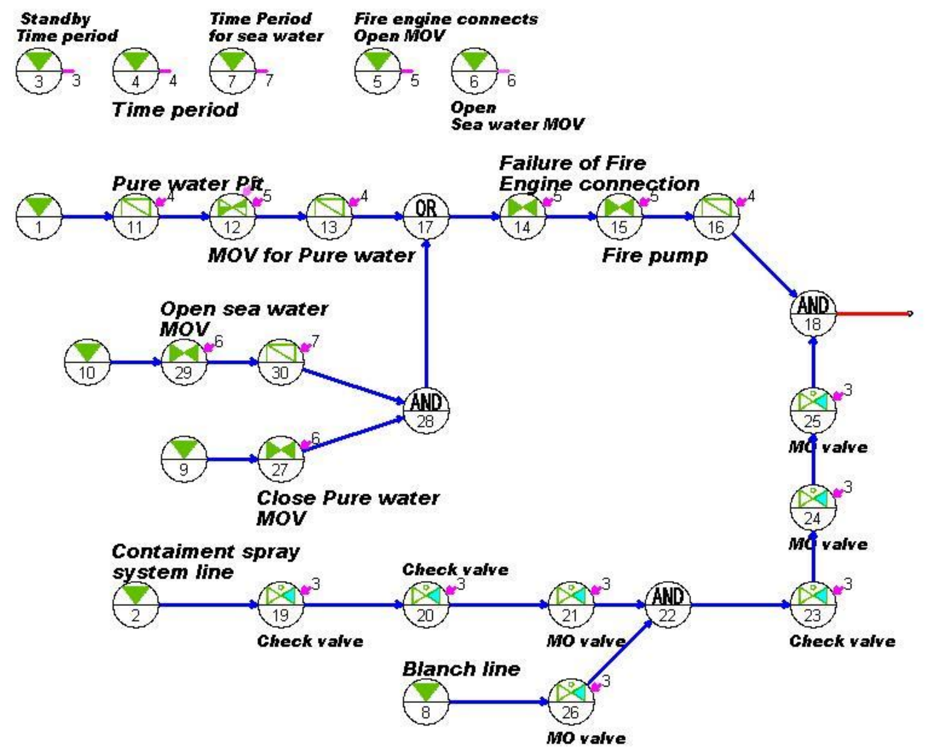

Fig.7 GO-FLOW chart for water injection by fire engine.

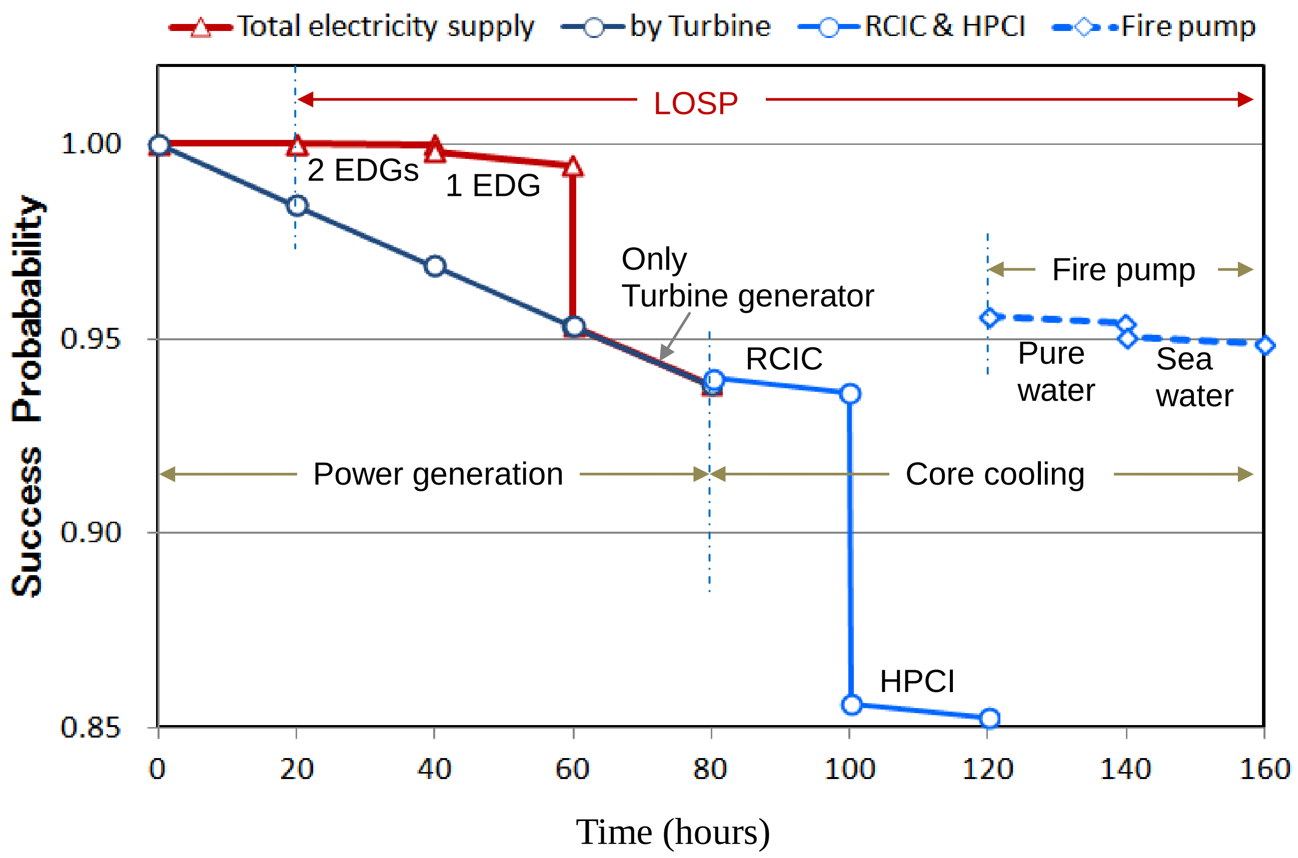

Fig.8 Analysis results.

Analysis results are shown in Fig. 8. From time 0 hour to time 80 hours, reactor is operated as normal, that is, continues to generate electricity. After 80 hours, the reactor is shut down and the main purpose becomes to cool the reactor core. The mission has been changed.

Success probabilities discontinuously change when operational condition changes. At 80 hours, success probability slightly increases but at this point the mission is also changed. Therefore it is no use to make a comparison of the success probabilities before and after the 80 hours.

From RCIC to HPCI, the success probability drastically decreases. This is because of failures of starts of HPCI turbine, backup pump and HPCI pump.

The water injection by the fire engine shows large success probability compared to HPCI. This is because of simplicity of the system, but the system is emergency and temporal equipment, and possible function is limited. Then, simple comparison makes misinterpretations.

5 Conclusions

In a severe accident, the plant configuration drastically changes and required missions for safety operation or prevention of accident also change. This dynamic behavior of plant states has been evaluated by the GO-FLOW methodology.

The analysis result presented in this paper is related to the two research activities on going at Harbin Engineering University (HEU), one is development of a reliability monitoring system (RMS) [2] while the other, Plant Defense-in Depth (Did) Risk Monitor [3], where the GO-FLOW is utilized as key technology to support the system function.

A hypothetical sequence of accident conditions has been settled based on the Fukushima Daiichi accident. Success probabilities of system operation have been obtained with the growth of accident.

Analysis results have shown us that success probability of system operation, reliability or availability are obtained with some boundary conditions, such as LOSP condition, unavailable equipment, possible resources, and so on. Furthermore, the mission as “power generation” or “core cooling” changes depending on a progression of accident.

The analysis results as shown in Fig. 8 could be utilized for visualizing risk state intuitively in "risk monitor” system. In this case, boundary conditions of the analysis should be properly presented to persons who are observing risk monitor. A value itself without additional information would sometimes make misreading.

The present analyses have shown that dynamic behavior of nuclear power plant with the growth of accident will be easily obtained by the “reliability monitor” which is supported by the GO-FLOW methodology.

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