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## Original Article

# EVALUATION OF PLANT OPERATIONAL STATES WITH THE CONSIDERATION OF LOOP STRUCTURES UNDER ACCIDENT CONDITIONS

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## ABSTRACT

Nuclear power plants have logical loop structures in their system configuration.

This paper explains the method to solve a loop structure in reliability analysis. As examples of loop structured systems, the reactor core isolation cooling system and high-pressure core injection system of a boiling water reactor are considered and analyzed under a station blackout accident condition.

The analysis results show the important role of loop structures under severe accidents.

For the evaluation of the safety of nuclear power plants, it is necessary to accurately evaluate a loop structure's reliability.

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## 1. Introduction

Some complex engineering systems have loop structures in their system configuration, and sometimes their operation depends on functional loop relations. A typical example exists

in the automobile engine system. Electricity ignites an explosion of the fuel gasoline, and produces rotation of the engine, which drives the car and also makes electricity.

Nuclear power plants have other examples of logical loop structures in their system configuration. One is a power

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source system, that is, a nuclear plant generates electricity and it is used for the operation of pumps that supply water to the reactor core for the production of steam and electricity. Without an external power supply, a nuclear power plant can continue its operation with the internally generated electric power.

The second example is a component cooling water system. Without the cooling water, the main components cannot continue their operation and the generation of electricity has to be ceased. The cooling water is circulated by a pump driven by electricity.

Also, the reactor core isolation cooling system (RCIC) and the high-pressure core injection system (HPCI) of a boiling water reactor (BWR) show loop structures. In an accident condition, steam from the reactor core drives a turbine pump and this pump supplies cooling water to the reactor core to maintain the core at a controlled temperature.

The reliability of all these loop-structured systems formerly had to be solved by approximation. The simplest method was to just ignore the loop structure and replace it with a series structure. However, there is always anxiety about the analysis results, and many different analysis methods have been proposed as shown in the next section. The authors have solved this difficulty, and the present paper is based on the new findings [1].

First, we explain the exact method [1] for solving a logical loop structure in reliability analysis. Next, the special core cooling systems (RCIC and emergency core-cooling system) of a BWR plant are considered and essential parts of logical loop structures are modeled as relatively simple forms. The model has been analyzed by the generalized analysis method of loop structures [2] under the accident condition “station blackout”. The availability of these systems under accident conditions is calculated numerically.

The analysis results show the important role of loop structures for system availability or reliability, especially under severe accidents. For the evaluation of the safety of nuclear power plants, it is necessary to accurately evaluate a loop structure's reliability. Also the reliability analysis of a loop structure can be utilized in effectively designing highly reliable systems.

## 2. Method for solving logical loops in system reliability analysis

### 2.1. Problems in the loop structure

For systems that have logical loop structures, the Boolean relations have to be described with unknown variables. The number of unknown variables equals the number of essential logical loop structures existing in the system. If we try to solve a Boolean equation with unknown variables, we encounter infinite circulation of the unknown variables. Logical loops are not generally solved in terms of the arithmetic operators of Boolean algebra.

Many attempts [3–6] have been proposed. An exact method [1] has been proposed for solving this problem in reliability analysis, but it was effective only in a restricted analysis condition, that is, in the condition that almost all

the components are started at the same time. A more generalized method [2,7] has been presented that can treat complex analysis conditions.

### 2.2. Solution of Boolean equation with an unknown element

Consider a simple system as shown in Fig. 1, which is a generalized system configuration for a single loop structure. The U means upstream part against the loop structure. The D is placed downstream from the loop. Parts A and B are the elements of the loop, and only A directly connects to D.

Now, consider the probability that a loop structure is functioning. So, it is necessary to distinguish between sound state and operating state for components. A component does not enter its operating state without a start signal or support from an upstream component, even if it is in a sound state.

The set of operating states of part A is represented by the italic character *A*. Italic characters *X* and *Y* represent the sets of events in which outputs of B and D exist, respectively, that are equivalent to the operating states of parts B and D. Then, the following Boolean relations are obtained:

$$Y = (U + X)AD, \quad X = (U + X)AB. \tag{1}$$

Substitute the relation  $X = (U + X)AB$  into the first equation,

$$Y = (U + (U + X)AB)AD = (U + XAB)AD = UAD + XABD. \tag{2}$$

The unknown element *X* cannot be eliminated, and the last relation does not change after repeating the substitution of *X*. This is the situation in which infinite circulation of an unknown element appears.

Consider the next Boolean equation with unknown element *x*.

$$x = f(\alpha_1, \dots, \alpha_n)x + g(\alpha_1, \dots, \alpha_n). \tag{3}$$

where  $\alpha_i$  is an independent Boolean variable (fixed elements of a Boolean algebra). Equation  $G = H$  is equivalent to the following equation in Boolean algebra:

$$G\bar{H} + \bar{G}H = \phi. \tag{4}$$

Then, Equation 3 becomes as follows:

$$\begin{aligned} x(\bar{f}x + g) + \bar{x}(fx + g) &= \phi, \\ x \cdot \bar{f}x \cdot \bar{g} + \bar{x}(fx + g) &= \phi, \\ x(\bar{f} + \bar{x})\bar{g} + \bar{x}(fx + g) &= \phi. \end{aligned} \tag{5}$$

It is transformed to the next equation:

$$x\bar{f}\bar{g} + \bar{x}g = \phi. \tag{6}$$

The Boolean theorems [8] say that the Boolean equation  $xA + \bar{x}B = \phi$  has a solution if and only if  $AB = \phi$  has a

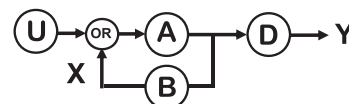


Fig. 1 – Basic loop structure.

solution, and the solution is  $x = m\bar{A} + B$ , where  $m$  is an arbitrary Boolean element.

The relation  $AB = \phi$  is equivalent to equation  $\bar{f}g = \phi$ , which always holds. Therefore the solution of Equation 3 becomes:

$$x = mf(\alpha_1, \dots, \alpha_n) + g(\alpha_1, \dots, \alpha_n). \quad (7)$$

The unknown element  $x$  can be expressed by  $\alpha_i$  and  $m$  without  $x$ , where  $m$  is an indefinite arbitrary element. Basically, a loop structure can be solved.

### 2.3. Indefinite element $m$

The solution of a Boolean equation with an unknown variable has indefinite constant  $m$  as shown in Equation 7. It is the reason that most people did not pay much attention to the fact that a Boolean equation with an unknown variable can be solved by algebraic operations [7]. The situation in which there exist indefinite constants is similar to that of differential equations. Indefinite constants ( $C_i$ ) appearing in the solution of differential equations are determined by boundary or initial conditions in solving an actual engineering system.

For Boolean equations, it is necessary to determine terms, including  $m$ , in order to obtain a solution, which correctly represents the reliability or availability of an actual engineering system.

In Section 3.4, it is shown that arbitrary Boolean element  $m$  must be unity or a universal set under the condition that Boolean elements represent operating states. With  $m = 1$ , the solution of Equation 3 correctly represents the operating state of an actual engineering system.

Therefore, the solution of Equation 1 becomes:

$$X = UAB + AB, \quad Y = UAD + ABD. \quad (8)$$

and the solution of Equation 3 becomes:

$$x = f(\alpha_1, \dots, \alpha_n) + g(\alpha_1, \dots, \alpha_n), \quad (9)$$

instead of Equation 7.

## 3. Key points for analysis of loop structure

### 3.1. Types of components

Two typical examples, a water supply system and an electric power supply system, are considered as systems with a loop structure, and fundamental aspects of loop characteristics and the role of components are discussed [7].

The discussion deduces that it is necessary to classify components into three different types. The information about component type is used in judging whether a loop system can continue its operation under isolated conditions, or not. There are three types of components: self-sustained (SS) type, generative (G) type, and transmitter (T) type [7].

#### 3.1.1. SS type component

A SS-type component is one that can start and continue its operation without any support by other components. The SS-type component does not require support. Examples of this

component type are batteries, radioisotopic powered generators, accumulator tanks, water tanks placed at high position, external electric power sources, and so on.

If a start signal or command is given to an SS-type component, it begins and continues its operation without any support (input) from outside.

#### 3.1.2. G-type component

A G-type component is one that can produce a driving force for loop operation. In other words, it supplies sufficient energy for the loop operation. Examples of this type of component are engines, electric motors, and pumps. For the production of its output, a G-type component requires support by other components.

If there is no support to a G-type component, it cannot start its operation even if the G-type component is in a sound state. An engine requires a fuel supply, an electric motor requires electricity, and a pump requires both water and electricity. These G-type components cannot start and cannot continue operation without these supports (inputs).

#### 3.1.3. T-type component

A T-type component is one that cannot produce a driving force for a loop operation. In other words, it does not produce sufficient energy for a loop operation.

Examples of this type of component are pipes, wires, an electric transformer, and an energy converter. These components just transfer input to output. Pipes and wires transmit their input, i.e., water or electricity, without changing its quality.

Electric transformers and energy converters modify inputs and produce some different quality of outputs, but they do not give driving force.

For the production of its output, a T-type component also requires input from other components. If there is no input to a T-type component, it cannot send its output even if the T-type component is in sound state.

Parts appearing in Fig. 1 are classified as follows: U is a SS-type, at least one of A or B is a G-type, and Part D can be G-type or T-type.

### 3.2. Concrete expression for component states

In this paper, irreversible change of a component's state is assumed, and variation with time is considered.

A set representing the sound state of component A in standby condition at time  $t$  is expressed by the notation  $S_A(t)$ . Then, the probability of component A's soundness becomes as follows, for the constant standby failure rate  $\lambda_{AS}$ :

$$\Pr(S_A(t - t_0)) = S_{A0} \cdot \exp(-\lambda_{AS}(t - t_0)), \quad (10)$$

where  $S_{A0}$  is the probability that component A is in sound state at time  $t_0$  (initial time).

The notation  $s_{A,t}$  is used for a set representing the event, in which the starting signal is given to component A at time  $t$ . The notation  $D_{A,t}$  is used for a set representing the event in which component A successfully starts its operation by a given starting signal. Then,  $\Pr(D_{A,t})$  equals the demand probability.

The notation  $O_A(t)$  is used for a set representing the operable state of component A (sound state of component A) which has already operated for time duration  $t$ . For a constant failure rate,  $\Pr(O_A(t))$  becomes:

$$\Pr(O_A(t - t_1)) = \exp(-\lambda_{AO}(t - t_1)), \quad (11)$$

where  $t_1$  is the time at which component A starts its operation. In this paper, consider the case in which the start signal is given only once. More general discussions are given in [2,7].

If component A is SS-type, a set representing the operating state of component A at time  $t$  is shown by Equation [12]. It is denoted by  $A_o(t)$ , where lower suffix  $_o$  means operating state.

$$A_o(t) = S_A(t_1 - t_0) \cdot \sigma_{A,t_1} \cdot D_{A,t_1} \cdot O_A(t - t_1). \quad (12)$$

If a component is G- or T-type, the set of its operating state contains the operating states of upstream components.

### 3.3. Takeover phenomenon

Fig. 2 shows a case in which G-type component C is supported by two SS-type components A and B.

Starting signals to the components are given at time  $t_i$ ,  $t_j$ , and  $t_k$ , respectively. Assume a time sequence for starting signals as shown in Table 1.

At time  $t_2$ , component C could start its operation by the support of component A, but it is not yet supported by component B. There is a support gap between B and C, that is, component B is started after the start of C, and B does not support the start of C. This situation is called a “support gap” between B and C. However, B begins to support the operation of component C after time  $t_3$ . Then, the operating state of component C at time  $t$ ;  $t_3 < t$  becomes as follows:

$$C_o(t) = A_o(t) \cdot C(t) + B_o(t) \cdot A_o(t_3) \cdot C(t); \quad t_3 < t. \quad (13)$$

where  $C(t)$  is an abbreviated expression of  $S_C(t_2 - t_0) \cdot \sigma_{C,t_2} \cdot D_{C,t_2} \cdot O_C(t - t_2)$ , which means that component C is started at time  $t_2$  and reaches operable state. However,  $C(t)$  expresses intrinsic characteristics of component C itself, and does not express the actual operating state of component C.

The second term in Equation [13] represents the contribution from the support by B, and this situation is called a “takeover” in this paper.

The factor  $A_o(t_3)$  is defined as a “takeover factor”, and this factor is a fixed value not a variable. Even if there is a “support gap” between B and C, the link B–C becomes a “connecting chain” by the “takeover” condition. The “connecting chain”

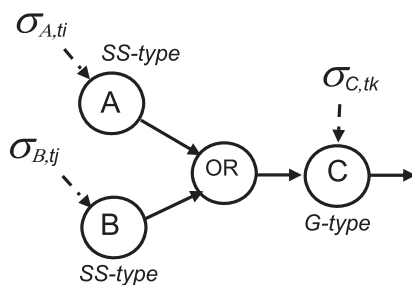


Fig. 2 – Supported by two components.

Table 1 – Timing of starting signals given to components in Fig. 2.

| Time  | A( $\sigma_{A,ti}$ ) | B( $\sigma_{B,tj}$ ) | C( $\sigma_{C,tk}$ ) |
|-------|----------------------|----------------------|----------------------|
| $t_0$ |                      |                      |                      |
| $t_1$ | ◆                    |                      |                      |
| $t_2$ |                      |                      | ◆                    |
| $t_3$ |                      | ◆                    |                      |

means that operation of component C is supported by component B placed in an immediately upstream position.

### 3.4. Operating state of loop structure

In Section 2, a basic loop structure is considered as shown in Fig. 1. Now, the operating state of the components in this loop structure can be obtained via a step-by-step method.

Assume each component is started in the order shown in Table 2.

The operating state of component A at time  $t_1$  is:

$$A_o(t) = U_o(t) \cdot A(t); \quad t = t_1. \quad (14)$$

Then, the operating state of component B at time  $t_2$  becomes:

$$B_o(t) = A_o(t) \cdot B(t) = U_o(t) \cdot A(t) \cdot B(t); \quad t = t_2. \quad (15)$$

Now consider the link B–A. In this order, there is a “support gap” between the components B and A. With consideration of the “takeover phenomenon”, the operating state of component A after time  $t_2$  becomes:

$$A_o(t) = U_o(t) \cdot A(t) + B_o(t) \cdot U_o(t_2) \cdot A(t) = U_o(t) \cdot A(t) + U_o(t_2) \cdot A(t) \cdot B(t); \quad t_2 < t. \quad (16)$$

Then the operating state of B after time  $t_2$  becomes:

$$B_o(t) = A_o(t) \cdot B(t) = U_o(t) \cdot A(t) \cdot B(t) + U_o(t_2) \cdot A(t) \cdot B(t); \quad t_2 < t. \quad (17)$$

Now, calculate the product of  $A_o(t) \cdot B_o(t)$ :

$$A_o(t) \cdot B_o(t) = \{U_o(t) \cdot A(t) + U_o(t_2) \cdot A(t) \cdot B(t)\} \cdot \{U_o(t) \cdot A(t) \cdot B(t) + U_o(t_2) \cdot A(t) \cdot B(t)\} = U_o(t_2) \cdot A(t) \cdot B(t). \quad (18)$$

The second term of Equation 17 corresponds to the second term of Equation 8 for the expression of X. This shows that arbitrary Boolean element  $m$  must be unity or a universal set.

The term  $U_o(t_2) \cdot A(t) \cdot B(t)$  represents the operating state of the loop structure, and the operation of the loop does not need the support of U [ $U_o(t_2)$  is a fixed value]. As elements of the

Table 2 – Timing of starting signals given to components in Fig. 1.

| Time  | U | A | B | D |
|-------|---|---|---|---|
| $t_0$ | ◆ |   |   |   |
| $t_1$ |   | ◆ |   |   |
| $t_2$ |   |   | ◆ |   |
| $t_3$ |   |   |   | ◆ |

loop structure, A and B have the same operating state  $U_O(t_2) \cdot A(t) \cdot B(t)$ .

System output, that is the operating state of D, becomes:

$$D_O(t) = U_O(t) \cdot A(t) \cdot D(t) + U_O(t_2) \cdot A(t) \cdot B(t) \cdot D(t); \quad t_3 < t. \quad (19)$$

The above results are obtained for the simple operational sequence. For more complex cases, please see [2,7].

#### 4. Engineering systems with loop structure

In a nuclear reactor system, many kinds of safety systems are prepared for the prevention of accidents. If the normal operational system fails its function, usually emergency core cooling systems are activated and heat is removed from the reactor core.

For example, a high-pressure core spray system, low-pressure coolant injection system, residual heat removal system, and so on, are utilized for cooling the core by injecting cooled water into the reactor core by electrical pumps.

If a severe accident happens and all AC power is lost (“station blackout”), as seen in the Fukushima Daiichi accident, these electrical pumps are stopped, and the emergency core cooling systems also cease their function.

Fukushima Daiichi Units 2 and 3 have special cooling systems, RCIC, and HPCI. These systems are driven by a steam turbine and do not require electricity to run. The steam is supplied from the reactor core itself, so these systems are a kind of loop-structured system.

Fig. 3 shows the layout of the RCIC of Fukushima-Daiichi Units 2 and 3 [9]. This system is driven by a steam turbine (RCIC turbine). 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).

The HPCI is also driven by turbine as shown in Fig. 4. The system configuration is almost the same as the RCIC except for one additional pump, the HPCI booster pump. Long-term operation of the HPCI requires ventilation of the containment vessel for the prevention of excess increase of temperature and pressure.

At the accident of Fukushima Daiichi Unit 3 on March 11, 2011, the RCIC was started manually after the earthquake, and stopped at 19 minutes after the start. It then started again 38 minutes later. Finally the RCIC stopped about 20 hours after the restart. The HPCI was started at 12:35 on March 12, 2011, 1 hour after the stop of the RCIC. The cooling by the HPCI continued for 14 hours and then stopped.

From Figs. 3 and 4, we can see that the components MO15, MO16, and condensate water storage tank are used by both systems. They could be considered as one system with a double loop structure, but their operations are demanded sequentially.

#### 5. Modeling and expression by Boolean equations

The functional relations between the components of the RCIC and HPCI systems are expressed as shown in Figs. 5 and 6, respectively. The arrows that connect components express

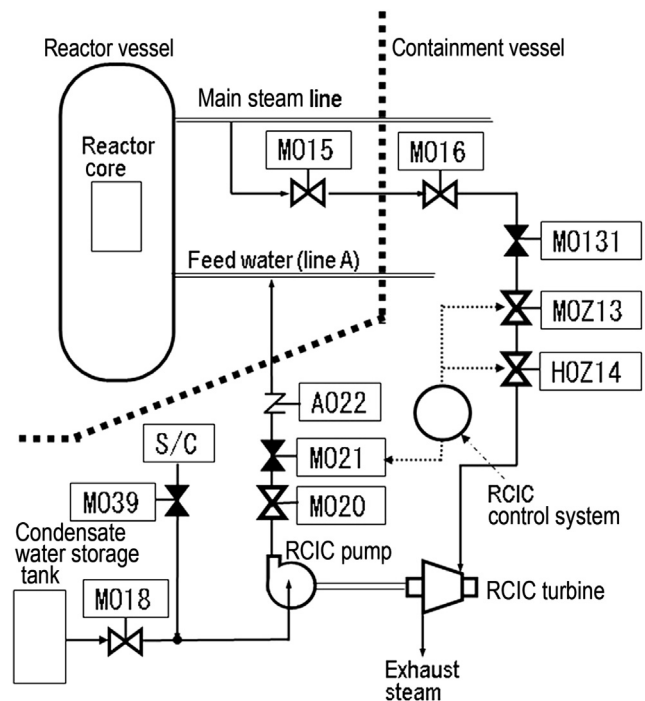


Fig. 3 – Reactor core isolation cooling system (RCIC) of Fukushima Daiichi Units 2 and 3.

the supporting relations. Red arrows indicate the demand signals to open valves M131 and M21; these valves are initially in a closed state. The main components and reactor core are indicated by red circles, and pumps are indicated by blue circles.

It is assumed that there is no adverse effect on the start of loop operation from outside of the loop structure, when the

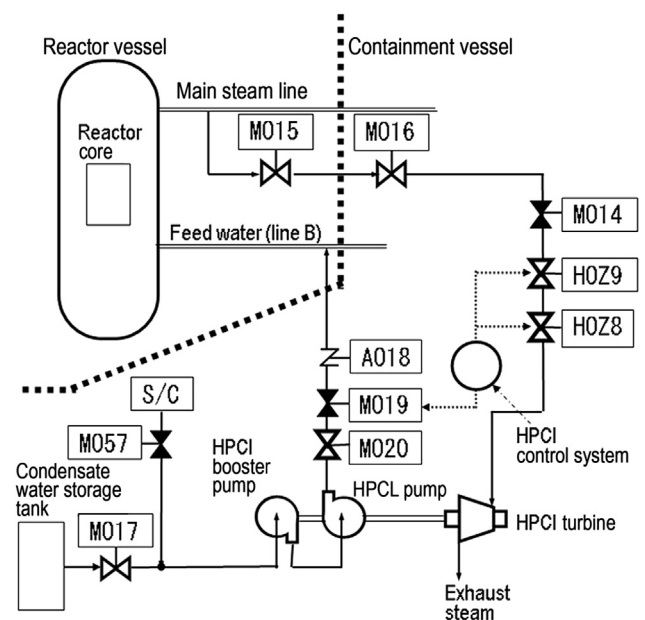


Fig. 4 – High-pressure coolant injection system (HPCI) of Fukushima–Daiichi Units 1–3.

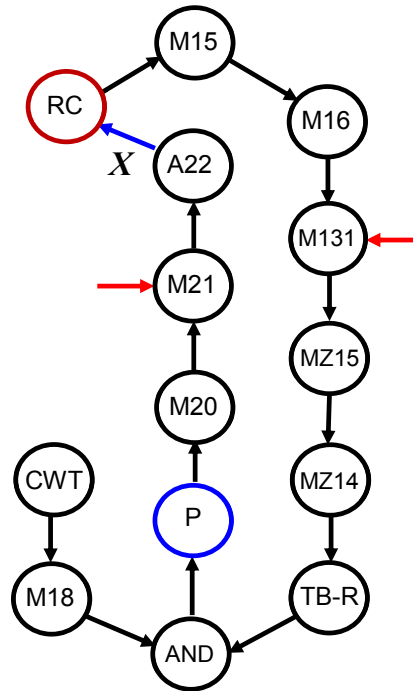


Fig. 5 – Functional relations between components of reactor core isolation cooling. X represents the state in which cooling water is injected into the reactor core (blue arrow). A18, A22, air-operated valve; BP, booster pump; CWT, condensate water storage tank; M14–M21, M131, MZ9–8, MZ13–14, motor operated valves; P, turbine driven pump; RC, reactor core; TB-H, steam driven HPCI turbine; TB-R, steam driven RCIC turbine.

station blackout accident occurs. Reliability of the RCIC and HPCI are evaluated after the successful start of RCIC. That is, initial support is perfect [ $U(t_2) = 1$  in Equation 16] and the valve open signal is correctly given ( $\sigma_{A,j} = 1$ ). This assumption simplifies the analysis procedure.

Output X in Fig.5 is expressed in the following Boolean equation:

$$X = \{RC \cdot M15 \cdot M16 \cdot M131 \cdot MZ15 \cdot MZ14\} \cdot TB - R \cdot \{CWT \cdot M18\} \cdot P \cdot \{M20 \cdot M21 \cdot A22\} \cdot X. \quad (20)$$

Equation 20 can be easily solved by the rule of Equation 7, as follows:

$$X = m\{RC \cdot M15 \cdot M16 \cdot M131 \cdot MZ15 \cdot MZ14\} \cdot TB - R \cdot \{CWT \cdot M18\} \cdot P \cdot \{M20 \cdot M21 \cdot A22\}. \quad (21)$$

and  $m = 1$ , according to the previous discussion.

Steam from the reactor core forms just after the reactor operation stops, then the RCIC successively starts with the opening of valves and starting of turbine and pump.

For the HPCI, the procedure is almost the same. Output X in Fig.6, representing the successful operation of the HPCI, is expressed in the following Boolean equation:

$$X = m\{RC \cdot M15 \cdot M16 \cdot M14 \cdot MZ9 \cdot MZ8\} \cdot TB - H \cdot \{CWT \cdot M17 \cdot TB} - H \cdot BP\} \cdot P \cdot \{M20 \cdot M19 \cdot A18\}. \quad (22)$$

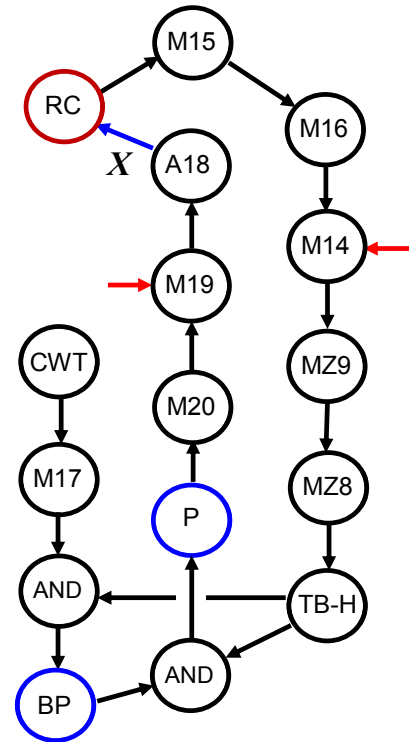


Fig. 6 – Functional relations between components of high-pressure coolant injection system. X represents the state in which cooling water is injected into the reactor core (blue arrow). A18, A22, air-operated valve; BP, booster pump; CWT, condensate water storage tank; M14–M21, M131, MZ9–8, MZ13–14, motor operated valves; P, turbine driven pump; RC, reactor core; TB-H, steam driven HPCI turbine; TB-R, steam driven RCIC turbine.

## 6. Analysis conditions and results

The reliability of successive operation of the RCIC and HPCI after the “station blackout” was evaluated. At 0 hours, just after the station blackout, it is assumed that motor operated valves M131 and M21 were demanded to be opened, and operation of the turbine and pump were started. The operation of the RCIC continued for 20 hours, then the HPCI was started and its operation also continued for 20 hours. The above assumption indicates that a small amount of electricity was available for the operation of motor operated valves.

Failure rates of components are assigned as shown in Table 3 based on the data shown in the standard for procedures of Level 1 probabilistic safety assessment [10] and component reliability data collected by International Atomic Energy Agency (IAEA) [11].

A GO-FLOW chart [12] is constructed as shown in Fig. 7. The RCIC part and the HPCI part are both included in this chart, because they have commonly used components. The RCIC and HPCI could be considered as one system with a double loop structure, and the reliability analysis becomes a phased mission problem [13].

With the aid of phased mission operators (Operators 24 and 41 in Fig. 7), the dependency between the two systems (RCIC and HPCI) is correctly treated.

**Table 3 – Failure rates of components.**

|                               |                        |
|-------------------------------|------------------------|
| Motor/air operated valve      |                        |
| Failure of open/close action  | $3.6 \times 10^{-3}/d$ |
| Failure during usage          | $2.0 \times 10^{-7}/h$ |
| Pump                          |                        |
| Fails to start                | $2.7 \times 10^{-2}/d$ |
| Failure during operation      | $1.0 \times 10^{-4}/h$ |
| Turbine                       |                        |
| Fails to start                | $2.7 \times 10^{-2}/d$ |
| Failure during operation      | $1.0 \times 10^{-4}/h$ |
| Condensate water storage tank |                        |
| Failure during operation      | $2.8 \times 10^{-8}/h$ |

Analysis results are shown in Fig. 8. The reactor core is cooled by RCIC and HPCI successively. So, this is a typical phased mission problem. In Phase 1, the RCIC is activated, and, in Phase 2, the HPCI is used. At 20 hours after the start of the RCIC, the next phase begins and the failure probability discontinuously increases, because of the failure of the start of the HPCI turbine, pump, and failure of the motor operated valves to open.

System failure probability is not so small, because relatively large values are assigned to component failure data for conservatively evaluating these two systems.

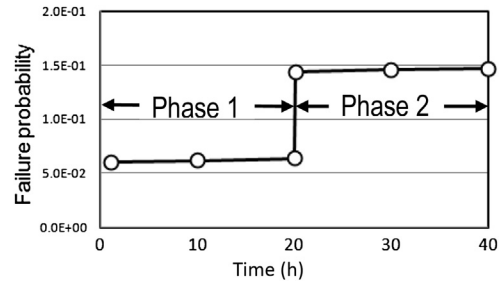
The system has the following characteristics. The steam used for driving the turbine is supplied from the reactor core and it always exists unless the reactor core cools down. The cooling systems, RCIC and HPCI, are loop-structured systems with relatively simple components and can continue their operation without external support.

These two emergency cooling systems can be said to be reliable systems in the case of an accident as severe as a “station blackout”, which actually happened at Fukushima-daiichi following a large tsunami.

## 7. Discussion

The exact method for solving a logical loop structure has been briefly explained. As examples of loop structured systems, the RCIC and HPCI of a BWR plant were described.

The severe accident “station blackout”, which actually occurred during the Fukushima Daiichi accident, has been considered. In this case, there is no electricity, neither



**Fig. 8 – Analysis result.**

external nor emergency diesel generator. Therefore, a self-sustained loop structured system becomes very important. The RCIC and HPCI can be operable under the condition station blackout.

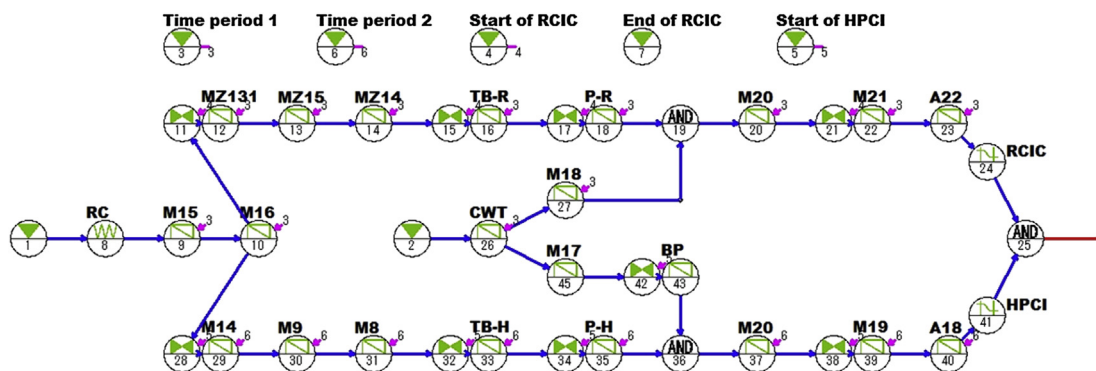
The RCIC and HPCI are successively utilized under severe accident conditions.

The loop structures have been solved by Boolean equations, and a double loop structure (RCIC and HPCI) has been modeled into one GO-FLOW chart. The analysis results indicate that at 40 hours of continuous operation after the occurrence of “station blackout”, the success probability of core cooling is about 85%.

In the Fukushima Daiichi accident, the reactor cores of Units 2 and 3 melted down at about 79 hours and 78 hours after the tsunami, respectively. The RCIC operated for 67 hours in Unit 2, and in Unit 3 the total operating time of the RCIC and HPCI was about 33 hours. In actual accident conditions, there were many difficult conditions and these factors would have affected the success probability for preventing the core meltdown.

The analysis results show the important role of loop structures for system availability or reliability, especially under severe accidents. For the evaluation of the safety of nuclear power plants, it is necessary to evaluate a loop structure’s reliability accurately.

The method presented here assures that reliability obtained for a loop-structured system is correct and there is no need to worry about the deviation from the true value. However, if the system configuration or the operational sequence becomes complex, the analysis procedure is tedious and needs much attention. There is no good software available for the handling of Boolean algebra.



**Fig. 7 – GO-FLOW chart for the reactor core isolation cooling and high-pressure coolant injection.**

If the system structure and operational sequence are simple, an approximate method as used in fault tree analysis gives almost the same results, that is, the deviations are small or negligible.

Also the reliability analysis of a loop structure can be utilized in effectively designing highly reliable systems.

### Conflicts of interest

The author declares no conflicts of interest

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