

GO-FLOW: A New Reliability Analysis Methodology

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Abstract—A new reliability analysis methodology, GO-FLOW, is presented. Detailed explanations and two examples of GO-FLOW analysis are given.

The GO-FLOW is a success-oriented system analysis technique. The modeling technique produces the GO-FLOW chart, which is composed of operators and signal lines and represents a function of the system. A signal does not represent a "change of condition" but some physical quantity or information. The intensity of a signal represents the probability of actual or potential existence of a physical quantity, the probability that some information exists, or a time interval between two successive time points.

The examples of analysis show the applicability of the GO-FLOW method to a phased mission problem (a boiling water reactor emergency core cooling system) and to a time-dependent unavailability analysis (a pressurized water reactor auxiliary feedwater system).

The GO-FLOW has proved to be a valuable and useful tool for system reliability analysis.

I. INTRODUCTION

This paper presents a new reliability analysis methodology: GO-FLOW.

Since the completion of the Reactor Safety Study,¹ the use of probabilistic risk assessment (PRA) techniques has become more widespread in the nuclear community.^{2,3} Event trees and fault trees are the basic analytical tools that have been most frequently used for PRAs. Several system analysis methods can be used in addition to, or in support of, the event- and fault-tree analyses. The GO methodology, an alternative to fault-tree analysis, is one of these methods. The GO method is a success-oriented system analysis technique. It was originally developed to analyze the safety and reliability of nuclear weapons and missile systems, but it has been modified and refined for nuclear systems.⁴ At present, the GO methodology has some applications to a nuclear power plant.⁵

The GO method has some special features, but it also has disadvantages. In the GO methodology, the signal is "on" to "off" or "off" to "on." The GO method finds out the time when a system changes state but cannot treat a system that has multiple state changes, such as "on" to "off" and then to "on" again. Also, the GO method cannot easily perform a time-

dependent system analysis because it requires several computer runs with different input data.

These disadvantages are the motivation for developing a new analytical methodology⁶: GO-FLOW. In GO-FLOW, the modeling method (chart) and calculation procedure are similar to those of the GO method, but the meaning of the signal and the definitions of operators are essentially different.

The present logic model of a system is assumed as follows: (a) It is a coherent system, so every component is relevant to the system. (b) It is a binary system; i.e., a system can be in one of two states, the fail state or function state. (c) The lifetimes of various components are mutually independent. (d) Each component can, but need not, be repairable with specified repair times. (e) When repair of a component is complete, the component becomes as good as new.

In this paper, the GO-FLOW methodology is explained, and two examples of analysis by the GO-FLOW method are presented.

II. OVERVIEW OF THE GO-FLOW METHODOLOGY

The GO-FLOW methodology is capable of evaluating system reliability/availability. Like the GO method,

it is a success-oriented system analysis technique. The GO-FLOW procedure uses a set of standardized operators to describe the logic operation, interaction, and combination of physical equipment. Ten different types of operators are currently defined. They are numbered greater than 20 to avoid being confused with the operators in the GO method. The specific probabilities (point estimates) of component operations are given as input data to operators.

A system is modeled by selecting operators and interrelating their inputs and outputs. The modeling technique produces the GO-FLOW chart, which represents the engineering function of the components/subsystems/system. The operators in the GO-FLOW chart are connected by signal lines, which identify the inputs and outputs to the operators.

A finite number of discrete time values (points) are required for expressing the system operation sequence. The values do not necessarily represent real time but correspond to it and represent an ordering. The total number of time points is a user-defined parameter.

In most cases, only one or, at most, a few of all the defined signals are of interest, and these signals are called final signals. An analysis is completed when the intensities of final signals at all the time points are obtained.

The GO-FLOW methodology is applicable to a system that has a complex sequence of system operation or a change of system state with time. Therefore, a phased mission problem or a time-dependent unavailability analysis can be treated by GO-FLOW.

The GO-FLOW methodology possesses the following significant features: (a) The GO-FLOW chart corresponds to the physical layout of a system and is easy to construct and validate, (b) alterations and updates to a GO-FLOW chart are readily accomplished, and (c) GO-FLOW contains all possible system operational states.

III. SIGNAL

The connecting lines in the GO-FLOW chart are called signal lines, which identify the inputs and outputs to the operators. A signal represents some physical quantity or information, for example, a fluid flow in a pipe, an electric current in wire, pneumatic pressure, a demand signal for operation, an operating period, etc. It does not represent a "change of condition" or "occurrence," in contrast with the signals in the GO methodology. This is the major difference between the GO-FLOW and GO methodologies.

The "existence" of the signal necessarily means the existence of physical quantity or information. In GO-FLOW, the existence of physical quantity is interpreted as both the actual and potential existence of a physical quantity. In this case, "the potential existence" means physical quantity will exist when all the resis-

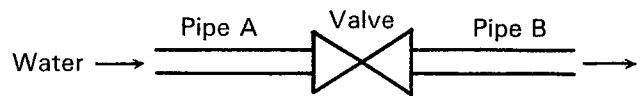


Fig. 1. Water flow through a valve.

tance "downstream" is removed. For example, consider a simple system as shown in Fig. 1, where two pipes and a valve are in an open state and water flows in pipes A and B. The signal is a water flow in a pipe, and the signals exist at sections A and B. If the valve is closed, the water does not flow either upstream or downstream from the valve. At section A, a water flow potentially exists; that is, the water will flow if the valve, which is located downstream, is opened. But, at section B, the water does not flow; nevertheless, there is no resistance downstream. Therefore, in GO-FLOW, we consider a signal to exist at section A but not at section B.

A quantity called "intensity" is associated with a signal. In most cases, the intensity represents the probability of signal existence. Therefore, intensity is the probability of the actual or potential existence of physical quantity or the probability that some information or mission exists.

If a signal is a subinput signal to the type-35, -37, or -38 operator (explained in Sec. V), the intensity is used for representing a time interval between the successive time points. In this case, the value of the intensity can be >1.0 because it does not represent a probability.

The summation of the intensity over all the time points needs not be unity. This is different from the likelihood defined in the GO methodology.

IV. TIME POINT

If a system alters its state with time, it is necessary to introduce "time" to express the changes of system state. In the GO-FLOW methodology, a finite number of discrete time values (points) is defined for expressing the system operation sequence.

The time points do not necessarily represent clock time. They represent an ordering, that is, time point 3 is one that comes after time point 2. If the intensities of final signals are obtained at every time point, the time-dependent characteristic of a system will be obtained.

Time points are numbered starting at 1. The smallest time point (1) is usually used to indicate a time before the system starts to operate. The total number of time points is determined by a user, depending on the system operation sequence or the purpose of analysis. In the GO method, the largest time point is always reserved to mean "never" or "infinity." In GO-FLOW, the time point that means "never" is not required.

V. OPERATORS

Generally, three types of signals are connected to an operator: the main input signal(s) S , subinput signal(s) P , and an output signal R . Each operator has a logic for combining the inputs properly and producing the output. The function of operators is governed by the following fundamental rules:

1. A main input signal $S(t)$ (a signal S at time point t) affects only the output signal $R(t)$.
2. All the subinput signals $P(t')$ ($t' \leq t$) affect the output signal $R(t)$.
3. A subinput signal $P(t'')$ ($t'' > t$) does not influence the output signal $R(t)$.

Operators in the GO-FLOW methodology can be used to model the operation and failure of physical equipment. There are also logical operators, such as AND, OR logic. Ten different types of operators have

currently been defined. Figure 2 shows the symbols of operators in the GO-FLOW chart. In Secs. V.A through V.J, the functions of the operators are explained in detail.

The functions of the GO-FLOW operators are different from those of the GO operators because the meaning of the signal in the GO-FLOW methodology is completely different from that in the GO methods. Table I summarizes the functions of the GO-FLOW operators.

V.A. Type-21 Operator

This operator models a "good/bad" component, such as a light bulb, resistor, or connector pin. This operator has one input and one output signal line and requires a probability for the good state of a component (P_g).

The intensity of the output signal becomes

$$R(t) = P_g \cdot S(t) \quad (1)$$

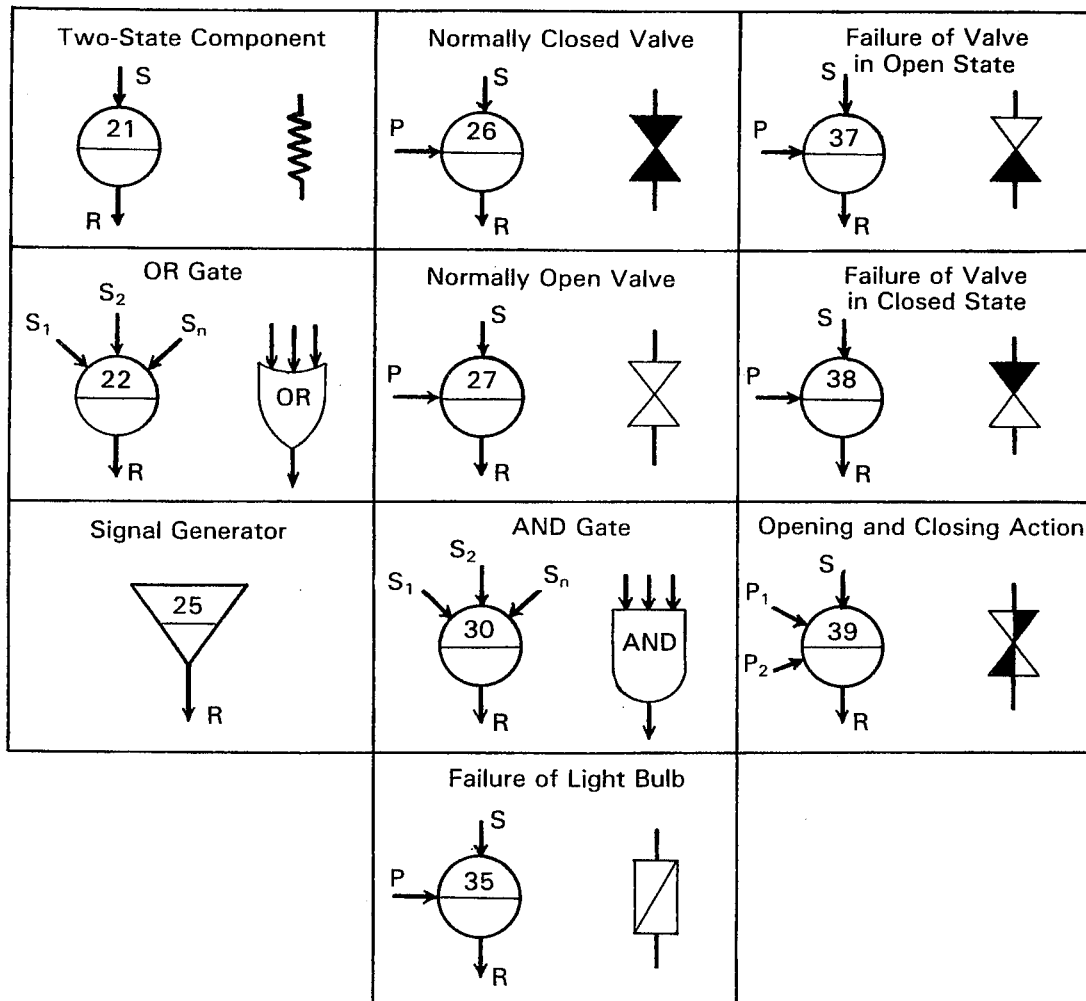


Fig. 2. Operators in the GO-FLOW methodology.

TABLE I
Summary of the Functions of GO-FLOW Operators*

Operator Type	Main Input Signal Intensity	Subinput Signal Intensity	Output Signal Intensity
21	$S(t)$	---	$R(t) = S(t) \cdot P_g$
22	$S_1(t), S_2(t), \dots, S_n(t)$	---	Probability that at least one input signal exists
25	---	---	Probability of a demand or time duration
26	$S(t)$	$P(t)$	$R(t) = S(t) \cdot O(t), O(t_1) = P_p,$ $O(t) = O(t') + [1.0 - O(t')] \cdot P(t) \cdot P_g$
27	$S(t)$	$P(t)$	$R(t) = S(t) \cdot O(t), O(t_1) = 1.0 - P_p,$ $O(t) = O(t') \cdot [1.0 - P(t) \cdot P_g]$
30	$S_1(t), S_2(t), \dots, S_n(t)$	---	Probability that all the input signals exist
35	$S(t_1), S(t_2), \dots, S(t)$	$P_1(t_1), \dots, P_1(t_n)$ $P_2(t_1), \dots, P_2(t_n)$...	$R(t) = S(t) \cdot \exp \left\{ -\lambda \sum_i \sum_{t_k \leq t} P_i(t_k) \min[1.0, S(t_k)/S(t)] \right\}$
37	$S(t)$	$P_1(t_1), \dots, P_1(t_n)$ $P_2(t_1), \dots, P_2(t_n)$...	$R(t) = S(t) \cdot \exp \left[-\lambda \sum_i \sum_{t_k \leq t} P_i(t_k) \right]$
38	$S(t)$	$P_1(t_1), \dots, P_1(t_n)$ $P_2(t_1), \dots, P_2(t_n)$...	$R(t) = S(t) \cdot \left\{ 1.0 - \exp \left[-\lambda \sum_i \sum_{t_k \leq t} P_i(t_k) \right] \right\}$
39	$S(t)$	$P_1(t)$ $P_2(t)$	$R(t) = S(t) \cdot O(t),$ $O(t) = O(t') + [1.0 - O(t')] \cdot P_1(t) \cdot P_o,$ $R(t) = S(t) \cdot O(t), O(t) = O(t') \cdot [1.0 - P_2(t) \cdot P_c]$

*In this table,

P_g = probability for successful operation

$O(t)$ = probability for valve in open state

P_p = probability for premature operation

t' = time point immediately before the time point t

P_o = probability for valve successfully open

P_c = probability for valve successfully close.

V.B. Type-22 Operator

This operator models an OR gate. The operator has more than one input signal line and does not require any data. The operator obtains the union of all the events represented by the input signals and makes it the output signal. The intensity of the output signal is the probability that at least one input signal S_i exists.

V.C. Type-25 Operator

This operator is a signal generator, having only one output signal line. The most common use of a type-25 operator is to generate a signal at only one

time point, but it can also successively generate signals at many time points. This operator is used to control the timing of component action and can also be used as a clock. In this case, the intensity of the output signal represents a period, and the signal line is connected to a type-35, -37, or -38 operator through a subinput signal P . The signals generated by type-25 operators and by different operators are mutually independent.

V.D. Type-26 Operator

This operator models a normally closed valve. The operator has one main input, one subinput, and one

output signal line. It requires probabilities for successful operation (P_g) and premature operation (P_p).

The output intensity is

$$\begin{aligned} R(t) &= S(t) \cdot O(t) , \\ O(t_1) &= P_p , \end{aligned}$$

and

$$O(t) = O(t') + [1.0 - O(t')] \cdot P(t) \cdot P_g , \quad (2)$$

where

$O(t')$ = probability for a valve in the open state at a time point immediately before the time point t

t_1 = initial time point.

This operator typically models a normally closed valve, which is opened by subinput signals. The valve will successfully open with probability P_g ; with probability P_p , it has been opened without any subinput signal. A normally open contact can be also modeled by this operator.

V.E. Type-27 Operator

This operator models a normally open valve. The operator has one main input, one subinput, and one output signal line. It requires probabilities for successful operation (P_g) and premature operation (P_p). The output intensity is

$$\begin{aligned} R(t) &= S(t) \cdot O(t) , \\ O(t_1) &= 1.0 - P_p , \end{aligned}$$

and

$$O(t) = O(t') [1.0 - P(t) \cdot P_g] , \quad (3)$$

where $O(t')$ and $O(t_1)$ have the same meanings as in Eq. (2). This operator typically models a normally open valve, which is closed by subinput signals. It can also model a normally closed contact.

V.F. Type-30 Operator

This operator models an AND gate. The operator has more than one main input signal line but only one output signal line, and it does not require any data. The operator obtains the intersection of the events represented by the input signals and makes it the output signal. The output signal intensity is the probability that all the inputs S_i exist.

V.G. Type-35 Operator

This operator models a light bulb failure while the bulb lights. The operator has one main input, more than one subinput, and one output signal line. A component failure probability per unit time duration (λ)

is required. The failure rate λ is assumed to be time independent.

The output intensity is

$$R(t) = S(t) \exp \left\{ -\lambda \cdot \sum_i \sum_{t_k \leq t} P_i(t_k) \times \min [1.0, S(t_k)/S(t)] \right\} . \quad (4)$$

The subinput signal represents a time duration, which must be measured by the same unit time by which the failure rate λ is expressed. The output signal $R(t)$ is affected by the main input signals $S(t_k)$, which arrive before time point t . This is an exception of fundamental rule No. 1, shown in Sec. V.

Equation (4) means that a failure of a component proceeds if and only if the main input signal $S(t)$ exists. This operator can model an operating failure of a component.

V.H. Type-37 Operator

This operator models a time-dependent valve failure in an open state. The operator has one main input, more than one subinput, and one output signal line. A component failure probability per unit time duration (λ) is required. The failure rate is also assumed to be a constant.

The output intensity is

$$R(t) = S(t) \exp \left[-\lambda \cdot \sum_i \sum_{t_k \leq t} P_i(t_k) \right] . \quad (5)$$

The subinput signal represents a time duration, which must be measured by the same unit by which the failure rate λ is expressed. If a standby failure rate is assigned for λ and a standby time duration is given to the intensity of subinput signal P , this operator models a standby failure of a component. Equation (5) means that a component failure proceeds whether the main input signal exists or not.

A repair of a failed component can be modeled by this operator. Consider the case in which a failed component is repaired at time point t_r and the component retains its good condition. This is modeled by giving the value

$$P_j(t_r) = -\sum_i \sum_{t_k \leq t_r} P_i(t_k)$$

to the intensity of a subinput signal at time point t_r . Then the output intensity at time point t_r becomes

$$\begin{aligned} R(t_r) &= S(t_r) \exp \left\{ -\lambda \cdot \left[\sum_i \sum_{t_k \leq t_r} P_i(t_k) + P_j(t_r) \right] \right\} \\ &= S(t_r) . \end{aligned} \quad (6)$$

The contribution from time-dependent failure becomes zero, and a repair action has been taken at time point t_r .

V.I. Type-38 Operator

This operator models a time-dependent valve failure in a closed state. The operator has one main input, more than one subinput, and one output signal line. A component failure probability per unit time duration (λ) is required.

The output intensity is

$$R(t) = S(t) \left\{ 1.0 - \exp \left[-\lambda \cdot \sum_i \sum_{t_k \leq t} P_i(t_k) \right] \right\} . \quad (7)$$

The interpretation of this operator is nearly the same as that of the type-37 operator, and it can model an isolation valve leak.

V.J. Type-39 Operator

This operator models the opening and closing action of a valve. The operator has one main input, two subinputs, and one output signal line. It requires probabilities for the valve being successfully opened (P_o) and successfully closed (P_c) upon demand.

If the subinput signal P_1 arrives, the operator takes opening action. Then the output intensity becomes

$$R(t) = S(t) \cdot \{ O(t') + [1.0 - O(t')] \cdot P_1(t) \cdot P_o \} , \quad (8)$$

where $O(t')$ is the probability for a valve in the open state at the time point immediately before time point t .

If the subinput signal P_2 arrives, closing action is taken. The output intensity becomes

$$R(t) = S(t) \cdot O(t') \cdot [1.0 - P_2(t) \cdot P_c] . \quad (9)$$

VI. TUTORIAL EXAMPLE CALCULATIONS

To understand the GO-FLOW analysis procedure, consider the simple electrical system, as shown in Fig. 3, which is treated in the review of the GO methodology.⁷ The system consists of a battery, two switches, and two lights. Initially, the battery is connected to the circuit, a little later S1 is actuated, and 10 h later S2 is actuated. The mean lifetime of the light bulbs is assumed to be 1000 h. Our interest is the probability that at least one light comes on.

The system was modeled in the GO-FLOW chart, as shown in Fig. 4. Each operator is represented by a compound number: The number above the horizontal line represents the operator type, and the number below the line designates each operator. The numbers on the connecting lines identify the signals. The final signal is signal No. 12, which corresponds to at least one light coming on.

In this example, we declare six time points. Time

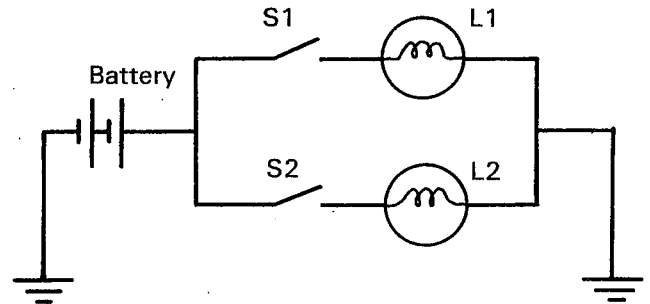


Fig. 3. Sample problem.

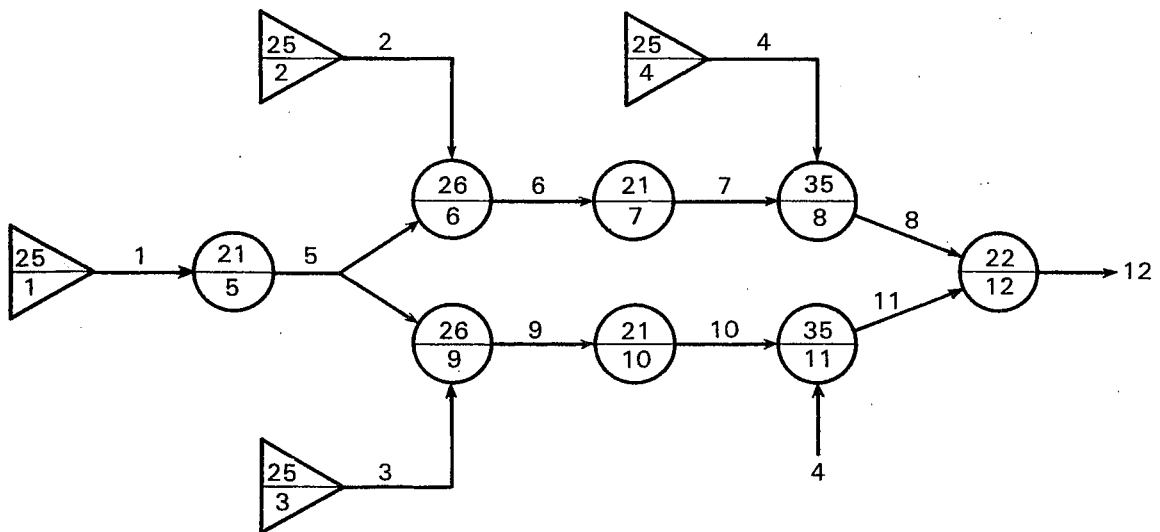


Fig. 4. GO-FLOW chart for the sample problem.

TABLE II
Operators Used in the Sample Problem

Operator		Data	Meaning
Type	Number		
25	1	$R(1) = 0.0, R(t) = 1.0 (t \neq 1)$	Battery is connected.
25	2	$R(3) = 1.0, R(t) = 0.0 (t \neq 3)$	Demand signal for switch S1 to close
25	3	$R(5) = 1.0, R(t) = 0.0 (t \neq 5)$	Demand signal for switch S2 to close
25	4	$R(4) = 10.0, R(6) = 10.0,$ $R(t) = 0.0 (t \neq 4, 6)$	Time duration
21	5	$P_g = 0.9$	Battery works with probability 0.9.
26	6	$P_p = 0.1, P_g = 0.7$	Switch S1 closes prematurely with probability 0.1 and closes normally with probability 0.7.
21	7	$P_g = 0.8$	Light bulb L1 works with probability 0.8.
35	8	$\lambda = 0.001/h$	Failure of L1 during lighting
26	9	$P_p = 0.1, P_g = 0.7$	Switch S2 closes prematurely with probability 0.1 and closes normally with probability 0.7.
21	10	$P_g = 0.8$	Light bulb L2 works with probability 0.8.
35	11	$\lambda = 0.001/h$	Failure of L2 during lighting
22	12		OR gate

point 1 is an initial time, and time point 2, the battery is connected. At time point 3, switch S1 is demanded to close, time point 4 is 10 h after time point 3, and time point 5 immediately succeeds time point 4. At time point 5, switch S2 is demanded to close, and time point 6 is 10 h after time point 5.

Twelve operators are used in this example. The explanations and the required data for these operators are shown in Table II, and the definitions of signals are given in Table III.

TABLE III
Signals Defined in the Sample Problem

Signal	Definition
1	Battery is connected.
2	Demand signal for S1 to close
3	Demand signal for S2 to close
4	Time duration
5	Battery provides sufficient power for both lights.
6	Power is available at L1.
7	L1 lights up (without operating failure).
8	L1 lights up.
9	Power is available at L2.
10	L2 lights up (without operating failure).
11	L2 lights up.
12	Either L1 or L2 or both are lit (final signal).

Table IV shows the steps of the analysis in the GO-FLOW methodology. In the table, input signal numbers in parentheses are subinput signal numbers. In the output signal column, No. 5 in parentheses means that the output signal exists under the condition that signal No. 5 exists. The signal that should be written in parentheses is the one in which the intensity is < 1.0 and is connected to more than one operator as an input signal. By adding this information for each output signal, we can obtain a conditional probability of a signal existence, for example, $\text{Prob.}\{I_6|I_5\} = I_6(t)/I_5(t)$. Then for the calculation of the type-22 operator (OR) or the type-30 operator (AND), it is possible to properly treat the dependencies of a shared component.

In step 1, type-25 operator No. 1 produces signal No. 1: intensity 0.0 at time point 1 and intensity 1.0 at time points 2 through 6.

In step 2, type-25 operator No. 2 produces signal No. 2: intensity 1.0 at time point 3 and intensity 0.0 at other time points. This is a demand signal for switch S1 to close.

In step 3, type-25 operator No. 3 produces signal No. 3: intensity 1.0 at time point 5 and intensity 0.0 at other time points.

In step 4, type-25 operator No. 4 produces signal No. 4: intensity 10.0 at time points 4 and 6 and intensity 0.0 at other time points. This represents that time point 4 is 10 h after time point 3, and time point 6 is 10 h after time point 5.

In step 5, type-21 operator No. 5 produces output

TABLE IV
Calculation Steps for the Sample Problem

Operator		Signal		Intensity of Output Signal for Time Points 1 Through 6					
Number	Type	Input	Output	1	2	3	4	5	6
1	25	---	1	0.0	1.0	1.0	1.0	1.0	1.0
2	25	---	2	0.0	0.0	1.0	0.0	0.0	0.0
3	25	---	3	0.0	0.0	0.0	0.0	1.0	0.0
4	25	---	4	0.0	0.0	0.0	10.0	0.0	10.0
5	21	1	5	0.0	0.9	0.9	0.9	0.9	0.9
6	26	5, (2)	6, (5)	0.0	0.09	0.657	0.657	0.657	0.657
7	21	6	7, (5)	0.0	0.072	0.526	0.526	0.526	0.526
8	35	7, (4)	8, (5)	0.0	0.072	0.526	0.5204	0.5204	0.5152
9	26	5, (3)	9, (5)	0.0	0.09	0.09	0.09	0.657	0.657
10	21	9	10, (5)	0.0	0.072	0.072	0.072	0.526	0.526
11	35	10, (4)	11, (5)	0.0	0.072	0.072	0.0713	0.5249	0.5197
12	22	8, 11	12	0.0	0.1382	0.5559	0.5505	0.7418	0.7374

signal No. 5 according to Eq. (1), where $P_g = 0.9$.
Then the intensity of signal No. 5 becomes

$$I5(1) = I1(1) \cdot P_g = 0.0 \times 0.9 = 0.0 ,$$

$$I5(2) = I1(2) \cdot P_g = 1.0 \times 0.9 = 0.9 ,$$

$$I5(3) = I1(3) \cdot P_g = 1.0 \times 0.9 = 0.9 ,$$

$$I5(4) = I1(4) \cdot P_g = 1.0 \times 0.9 = 0.9 ,$$

$$I5(5) = I1(5) \cdot P_g = 1.0 \times 0.9 = 0.9 ,$$

$$I5(6) = I1(6) \cdot P_g = 1.0 \times 0.9 = 0.9 ,$$

where $I5(t)$ is the intensity of signal No. 5 at time point t .

In step 6, type-26 operator No. 6 produces output signal No. 6 according to Eq. (2).

$$R(t) = S(t) \cdot O(t) , \quad O(t_1) = P_p ,$$

$$O(t) = O(t') + [1.0 - O(t')] \cdot P(t) \cdot P_g ,$$

where $P_p = 0.1$ and $P_g = 0.7$. Then the intensity of signal No. 6 becomes

$$I6(1) = I5(1) \cdot O(t_1) = 0.0 \times 0.1 = 0.0 ,$$

$$I6(2) = I5(2) \cdot O(t_2) = I5(2) \{ O(t_1) + [1.0 - O(t_1)] \cdot I2(2) \cdot P_g \} = 0.9 \times (0.1 + 0.9 \times 0.0 \times 0.7) \\ = 0.9 \times 0.1 = 0.09 ,$$

$$I6(3) = I5(3) \cdot O(t_3) = I5(3) \{ O(t_2) + [1.0 - O(t_2)] \cdot I2(3) \cdot P_g \} = 0.9 \times (0.1 + 0.9 \times 1.0 \times 0.7) \\ = 0.9 \times 0.73 = 0.657 ,$$

$$I6(4) = I5(4) \cdot O(t_4) = I5(4) \{ O(t_3) + [1.0 - O(t_3)] \cdot I2(4) \cdot P_g \} = 0.9 \times (0.73 + 0.27 \times 0.0 \times 0.7) \\ = 0.9 \times 0.73 = 0.657 ,$$

$$I6(5) = I5(5) \cdot O(t_5) = I5(5) \{ O(t_4) + [1.0 - O(t_4)] \cdot I2(5) \cdot P_g \} = 0.9 \times (0.73 + 0.27 \times 0.0 \times 0.7) \\ = 0.9 \times 0.73 = 0.657 ,$$

$$I6(6) = I5(6) \cdot O(t_6) = I5(6) \{ O(t_5) + [1.0 - O(t_5)] \cdot I2(6) \cdot P_g \} = 0.9 \times (0.73 + 0.27 \times 0.0 \times 0.7) \\ = 0.9 \times 0.73 = 0.657 ,$$

In step 7, type-21 operator No. 7 produces output signal No. 7 by Eq. (1), where $P_g = 0.8$. The intensity of signal No. 7 becomes

$$I7(1) = I6(1) \cdot P_g = 0.0 \times 0.8 = 0.0 ,$$

$$I7(2) = I6(2) \cdot P_g = 0.09 \times 0.8 = 0.072 ,$$

$$I7(3) = I6(3) \cdot P_g = 0.657 \times 0.8 = 0.526 ,$$

$$I7(4) = I6(4) \cdot P_g = 0.657 \times 0.8 = 0.526 ,$$

$$I7(5) = I6(5) \cdot P_g = 0.657 \times 0.8 = 0.526 ,$$

$$I7(6) = I6(6) \cdot P_g = 0.657 \times 0.8 = 0.526 .$$

In step 8, type-35 operator No. 8 produces output signal No. 8 according to Eq. (4), where $\lambda = 0.001$. The intensity of signal No. 8 becomes

$$I8(1) = I7(1) \cdot \exp(-0.0) = 0.0 \times 1.0 = 0.0 ,$$

$$I8(2) = I7(2) \cdot \exp(-0.0) = 0.072 \times 1.0 = 0.072 ,$$

$$I8(3) = I7(3) \cdot \exp(-0.0) = 0.526 \times 1.0 = 0.526 ,$$

$$I8(4) = I7(4) \cdot \exp[-\lambda \times I4(4) \times I7(4)/I7(4)] = 0.526 \exp(-0.001 \times 10.0 \times 1.0) = 0.5204 ,$$

$$I8(5) = I7(5) \cdot \exp[-\lambda \times I4(4) \times I7(4)/I7(5)] = 0.526 \exp(-0.001 \times 10.0 \times 1.0) = 0.5204 ,$$

$$I8(6) = I7(6) \cdot \exp[-\lambda \times I4(4) \times I7(4)/I7(6) - \lambda \times I4(6) \times I7(6)/I7(6)] \\ = 0.526 \exp(-0.001 \times 10.0 \times 1.0 - 0.001 \times 10.0 \times 1.0) = 0.5152 .$$

The above equations calculate the contributions from the operating failure of both prematurely and normally actuated bulbs.

Steps 9, 10, and 11 are similar to steps 6, 7, and 8, respectively. In step 12, the union of signals 8 and 11 is obtained. Note that signals 8 and 11 exist under the condition that signal 5 exists. Therefore,

$$I12(t) = I8(t) + I11(t) - I8(t)I11(t)/I5(t) . \quad (10)$$

Then,

$$I12(1) = 0.0 + 0.0 - 0.0 = 0.0 ,$$

$$I12(2) = 0.072 + 0.072 - 0.072 \times 0.072/0.9 = 0.1382 ,$$

$$I12(3) = 0.526 + 0.072 - 0.526 \times 0.072/0.9 = 0.5559 ,$$

$$I12(4) = 0.5204 + 0.0713 - 0.5204 \times 0.0713/0.9 = 0.5505 ,$$

$$I12(5) = 0.5204 + 0.5249 - 0.5204 \times 0.5249/0.9 = 0.7418 ,$$

$$I12(6) = 0.5152 + 0.5197 - 0.5152 \times 0.5197/0.9 = 0.7374 .$$

The intensities of final signal No. 12 are obtained at all the time points from 1 to 6. The result is interpreted as follows. When the battery is connected, at least one light comes on with the probability 0.1382 because one or two switches prematurely close. When switch S1 is actuated, at least one light comes on with the probability 0.559. At 10 h after the actuation of S1, at least one light comes on with the probability 0.5505. The probability decreases ($0.0054 = 0.5559 - 0.5505$) because of bulb failure during lighting. When switch S2 is actuated, at least one light comes on with the probability 0.7418. At 10 h after the actuation of S2, at least one light comes on with the probability 0.7374. Neither light comes on with the probability 0.2582 ($= 1.0 - 0.7418$).

VII. APPLICATIONS

Two examples are discussed here to illustrate the range of applications of the GO-FLOW methodology.

One is a phased mission problem and the other is a time-dependent unavailability analysis. Brief explanations and results of the analyses are given because the detailed procedure of the GO-FLOW has already been shown in Sec. VI.

VII.A. Phased Mission Problem

As an example of a phased mission problem, the emergency core cooling system (ECCS) of a boiling water reactor (BWR) is considered.⁸ The diagram of this system is shown in Fig. 5. It consists of eight subsystems: the high-pressure core spray (HPCS) system, low-pressure core spray (LPCS) system, three low-pressure core injection (LPCI) systems, the automatic depressurization system (ADS), and two heat exchangers.

One mission of the ECCS is to prevent excessive core heating as soon as possible after a large loss-of-coolant accident (LOCA) and then to keep water circulating to and from the reactor vessel until the core

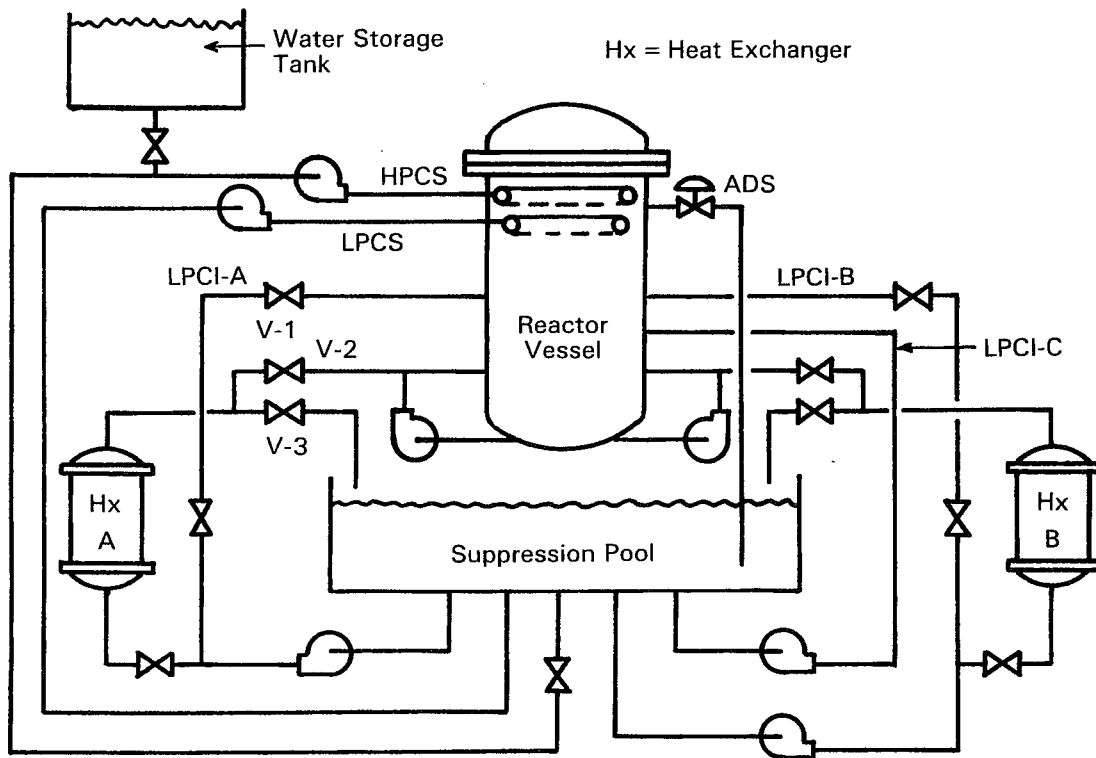


Fig. 5. BWR ECCS.

is cool. After a LOCA has occurred, three phases for the ECCS can be identified:

1. initial core cooling (0.0 to 0.5 h)
2. suppression pool cooling (0.5 to 36.5 h)
3. residual heat removal (36.5 to 120.5 h).

For phase 1, either the HPCS alone or the ADS and one of the low-pressure systems is needed. For phase 2, the ADS is required to limit pressure buildup in the reactor vessel. One heat exchanger and the corresponding LPCI are needed to cool the water within the suppression pool. Also, one of the two remaining low-pressure systems, LPCI or the LPCS, or HPCS is needed to circulate the water from the suppression pool to the reactor vessel. For phase 3, the break is assumed to be repaired or isolated so that the system can operate normally. Thus, one of the heat exchangers and the corresponding LPCI are needed. The zero-duration phase boundaries are assumed for the above phase changes, and all the components are assumed to be nonrepairable.

The GO-FLOW chart for this system is shown in Fig. 6. The names of subsystems are written by the side of corresponding operators. Table V shows the failure rates for the subsystems of the BWR ECCS. These values are the same as those used in Ref. 8. Failures of valves, pipes, and tanks are included in the

TABLE V

Failure Rates for Subsystems of BWR ECCS

Subsystem	Failure Rate per Hour
ADS	1.4×10^{-5}
LPCI	2.5×10^{-5}
HPCS	2.7×10^{-4}
LPCS	2.6×10^{-6}
Heat exchanger	2.8×10^{-6}

failures of the subsystems to which these components belong. The type-26 operators model valve-opening action. The type-21 operators show where the tank or suppression pool is located in the GO-FLOW chart, and $P_g = 1.0$ is given for these operators. The logic for the system operations in three phases is included in this chart. Final signals are Nos. 30, 38, and 27, which correspond to the operations of this system in phases 1, 2, and 3, respectively. Time points are defined in Table VI.

Having prepared the analysis as described above, the calculation was performed, and the intensities of the final signals were obtained at all time points. Table VI shows the results of the analysis, expressed by the mission unreliabilities. Values in parentheses are unreliabilities after the mission period, supposing that

TABLE VI
Result of the Analysis of ECCS Phased Mission Problem

Time Point	State	Unreliability			
		Signal No. 30 (Phase 1)	Signal No. 38 (Phase 2)	Signal No. 27 (Phase 3)	System
1	Standby	1.0	1.0	1.0	
2	Phase 1 Demand	0.0	1.0	1.0	0.0
3	30 min after	9.45×10^{-10}	1.0	1.0	9.45×10^{-10}
4	Phase 2 Demand	(9.45×10^{-10})	7.00×10^{-6}	1.0	7.00×10^{-6}
5	5 h after	(1.14×10^{-7})	7.70×10^{-5}	1.0	7.70×10^{-5}
6	36 h after	(5.01×10^{-6})	5.12×10^{-4}	1.0	5.12×10^{-4}
7	Phase 3 Demand	(5.01×10^{-6})	(5.12×10^{-4})	1.03×10^{-6}	5.13×10^{-4}
8	84 h after	(5.40×10^{-5})	(1.70×10^{-3})	1.12×10^{-5}	5.23×10^{-4}

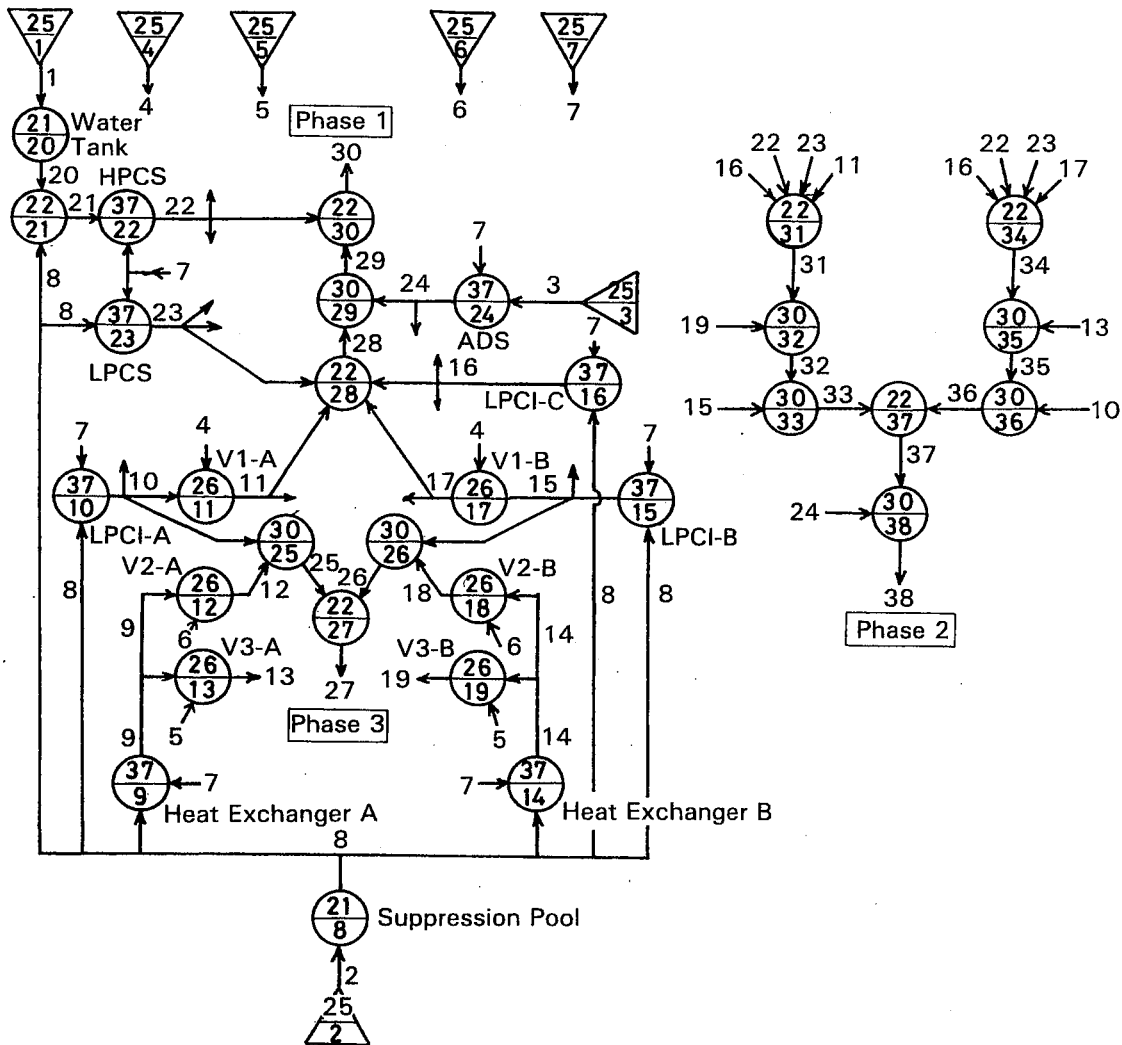


Fig. 6. GO-FLOW chart for BWR ECCS. (In the figure, V represents "valve.")

the function is required until phase 3. A plot of the time-dependent mission unreliability is shown in Fig. 7.

VII.B. Time-Dependent Unavailability Analysis

This example shows the applicability of the GO-FLOW methodology to an unavailability analysis of a system, which is periodically tested and repaired. The modeling of a periodic test includes the effects of test downtimes, test overrides, and repair contributions.

The system schematic⁹ is shown in Fig. 8. The system consists of two diesels parallel to a pump, and two valves are in a series with the pump. This system is a simplified system of the pressurized water reactor (PWR) auxiliary feedwater system (AFWS) given in WASH-1400 (Ref. 10).

The following test condition was assumed for the

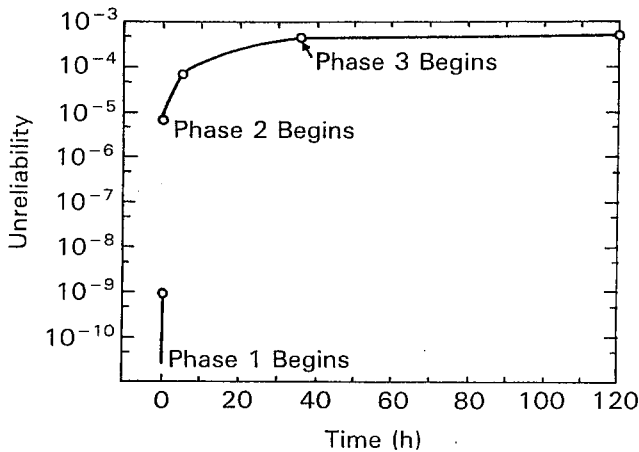


Fig. 7. ECCS phased mission problem unreliability graph.

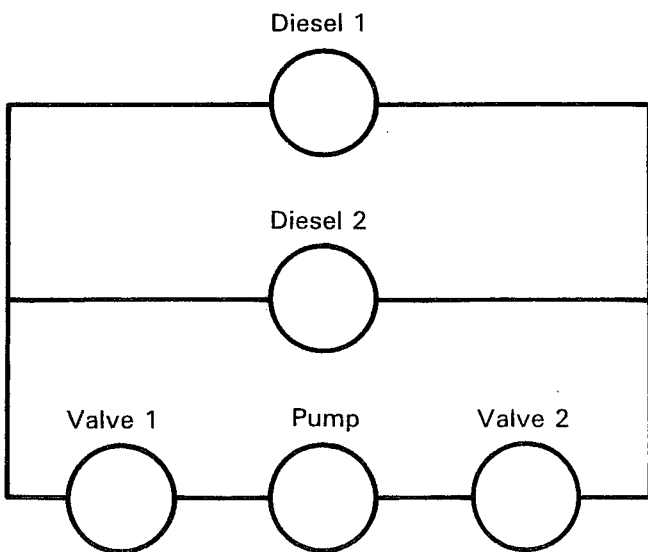


Fig. 8. Block diagram for PWR AFWS.

analysis. The pump test interval is 30 days, and the diesel test intervals are 60 days with the diesel test being staggered. The pump and diesel tests are also staggered. The valves are closed for the pump test, and the pump and valves are thus treated as being tested simultaneously. During the test, the pump and valves are unavailable for operation. The diesels are assumed to have a 90% probability of overriding the test and being placed in operation if demanded. Average test periods are 1.5 h for all the components, and average repair periods are 7, 19, and 21 h for valves, pumps, and diesels, respectively.

Standby failure rates, 3×10^{-7} , 3×10^{-6} , and $4.2 \times 10^{-5}/h$, are assigned to valves, pumps, and diesels, respectively.

The system was written in the GO-FLOW chart, as shown in Fig. 9. A type-37 operator models a standby failure and repair of a component. Type-39 operators are used for modeling the testing of valves, the pump, and diesels. The test override is modeled by giving $P_c = 0.1$ to the input data of type-39 operators (operator Nos. 5 and 7). Signal No. 16 gives the time intervals between the successive time points. Signal Nos. 17 through 20 give the intensities that cancel the standby failures of components, and then the repairs of valves, the pump, and diesels are modeled. Signals 21 through 26 are demand signals, which start or end the tests of components. The final signal is signal No. 15. Time points were defined, as shown in Table VII. The results of the analysis are shown in Fig. 10, in which a time-dependent, instantaneous unavailability is illustrated.

VIII. DISCUSSION

In this paper, the basic concept for the GO-FLOW methodology has been presented through detailed explanations and two examples of applications. Ten different types of operators have currently been defined, but these ten operators may not be sufficient for analyses of various kinds of systems. For example, a signal delay operator, an inhibit gate, and a complementary signal generator will be required for analyzing more complex systems. These operators are not defined in this paper, but the additional operators should be defined, when required, avoiding contradictions with the definitions of other operators or signals.

Although it is not shown in this paper, the effects of test inefficiency and test-caused failure could be treated only by the standardized operators in the time-dependent unavailability analysis (Sec. VII.B).

For operators 35, 37, and 38, the failure rate λ is assumed to be a constant; that is, the lifetime distribution of a component is a negative exponential. In general, the lifetime distribution will be expressed by Weibull or gamma distributions. At present, most failure data are given by a constant failure rate, so, in this paper, the failure rate λ is treated as a constant.

TABLE VII
Time Points with Testing and Repair Schemes

Time Points	Real Time (h)	Test and Repair	Intensity of Signal					
			16	17	18	19	20	
1	0.0							
2	360.0	Diesel generator 1 under test	360.0					
3								
4			1.5					
5	382.5	Diesel generator 1 under repair	21.0					
6								
7						-361.5		
8	720.0	Pump, valves under test	337.5					
9								
10			1.5					
11	721.5	Valves under repair	7.0					
12								
13						-721.5		
14	740.5	Pump under repair	12.0					
15								
16						-721.5		
17	1080.0	Diesel generator 2 under test	339.5					
18								
19			1.5					
20	1102.5	Diesel generator 2 under repair	21.0					
21								
22							-1081.5	
23	1440.0	Pump, valves under test	337.5					
24								
25			1.5					
26	1448.5	Valves under repair	7.0					
27								
28							-720.0	
29	1460.5	Pump under repair	12.0					
30							-720.0	
30	1800.0		339.5					

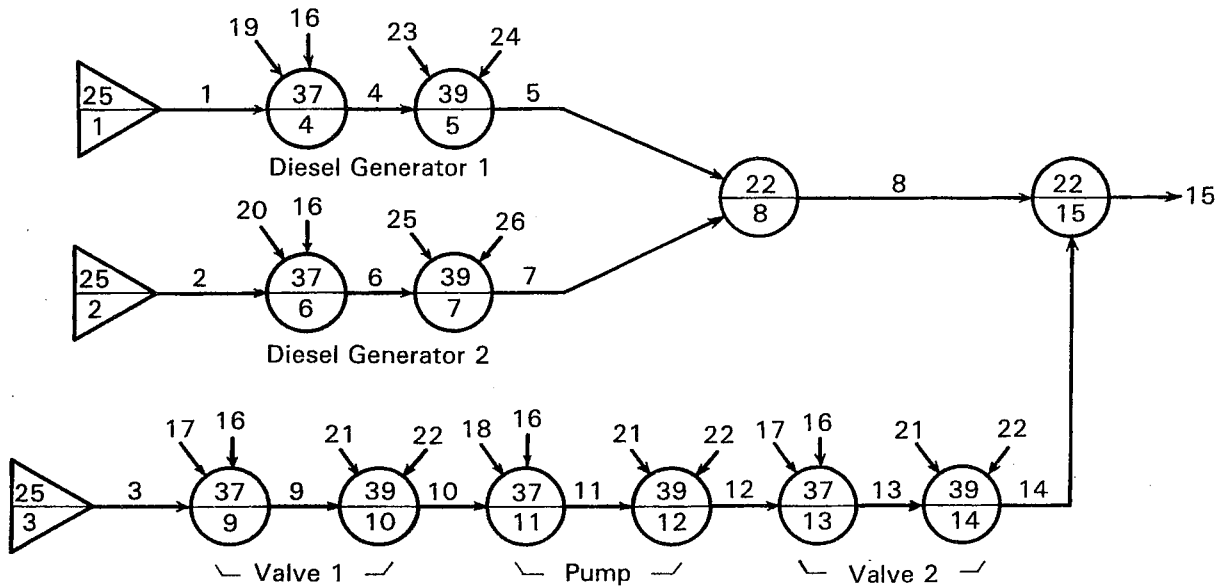


Fig. 9. GO-FLOW chart for PWR AFWS.

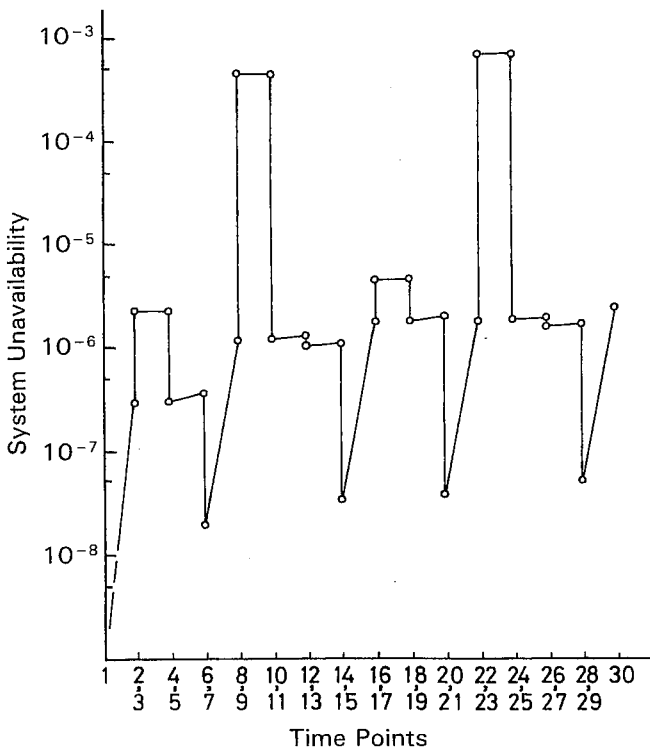


Fig. 10. Time-dependent unavailability for PWR AFWS.

For a large and complex system, the exact values of the intensities of final signals cannot be easily obtained due to large computer times and computer memory requirements. In the GO-FLOW methodology, the numerical calculation is performed at each operator, and the result is transferred to the successive

operator with the information on the dependencies between signals. If an input signal of an operator is composed of more than one minimal path distinguished by shared components, the operator handles them in parallel. The calculation of the intensity of the final signal is performed by the approximate method used in the fast fault-tree analysis (FFTA) program.¹¹ This method takes account of the sum of the occurrence probabilities of a twofold intersection of the minimal cut sets and gives accurate results with little computer time. The details of the treatment of a shared component and the cumulation of the unreliabilities at the successive phases are not shown in this paper. They are beyond its scope and will be presented in a future study.

The computer code of the GO-FLOW methodology is now being developed at the Ship Research Institute.

Sensitivity analysis is performed on the GO-FLOW method to determine which components have the largest effect on system failure. The analysis is done by changing the probability data for a single operator by a small amount and computing the change in the system results for one or more times. The ratio of change in the probability for an operator to change in system probability is defined as sensitivity.

To determine confidence limits on system results, Monte Carlo sampling from the probability distribution for the component can be used to provide the distribution of total system availability. This is basically the same approach taken by WASH-1400 (computer code SAMPLE).

Basically, the GO method can solve the phased mission problem and the time-dependent unavailability analysis, but, for the phased mission problem, the GO chart must be constructed for each phase to prepare

the input data and to calculate at all time points. For the time-dependent unavailability analysis, the input data must be prepared and all the time points calculated. The analysis requires much labor for making the GO charts and preparing the input data. On the other hand, GO-FLOW needs only one GO-FLOW chart and a set of input data for one analysis, and the analysis is performed with one computer run.

The GO-FLOW has nearly all the following significant features that the GO methodology has:

1. GO-FLOW charts are usually developed by following normal process flow, and the charts are constructed from engineering blueprints or flow diagrams. This makes it easy to validate and interpret the charts.

2. Alterations and updates to a GO-FLOW chart are readily accomplished. Adding or deleting operators or altering the logical combinations of signal lines can be accommodated without extensive alterations to the basic chart structure.

3. GO-FLOW methodology models system functions and operational logic. Thus, GO-FLOW contains all possible system operational states.

The GO-FLOW has the following specific features that the GO method does not have:

1. A time-dependent system analysis can be performed with one computer run.
2. A system that has a complex sequence of system operation can be easily analyzed.

Therefore, a time-dependent unavailability analysis and a phased mission problem can be easily analyzed as shown in Sec. VII.

The above specific features are accomplished by the definitions of a signal and operators, which are different from those of the GO method. That is, the signal represents some physical quantity or information and does not represent a "change of condition." The existence of a signal means the actual or potential existence of physical quantity or existence of information. The logic of an operator is constructed based on the meaning of a signal.

IX. CONCLUSIONS

This paper has presented a new reliability analysis methodology: GO-FLOW. The detailed explanations and the applications of GO-FLOW are given.

The GO-FLOW has proved to be a valuable and useful tool for system reliability analysis, especially for a time-dependent unavailability analysis and a phased mission problem.

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