Dynamical reliability analysis for ECCS of pressurized water reactor considering the large break LOCA by GO-FLOW methodology

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Abstract: Reliability is the ability of a system or component to perform its required functions under a certain prescribed conditions for a specified period of time. It is a probability of failure or a measure of availability. The GO-FLOW methodology, which is a success-oriented system analysis technique, is able to evaluate the system reliability and availability. The analysis is made on phased mission problem in which system configuration is altered such that the failure logic model changes one or more times. In this paper, an exemplar of dynamical reliability analysis is conducted by GO-FLOW for ECCS of four-loop PWR that undergoes phased mission problem by considering the behavior of an ECCS component in case of a large break LOCA. The GO-FLOW methodology has proved to be a suitable tool for dynamical reliability analysis of phased mission problem
Keyword: dynamical reliability; GO-FLOW; phased mission problem; large break LOCA; PWR

1 Introduction

Reliability engineering deals with modeling, analysis, and evaluation on "reliability" of an engineering system for its life-cycle management. In reliability engineering, the word "reliability" is defined as the probability that a device will perform its required function under stated conditions for a specific period of time, or a collection of planned activities that are effectively working collectively to prevent loss of system function [1]. It is often measured as a probability of failure or a measure of availability. On the other hand, "maintainability" is also an important part of reliability engineering and is an ability of an item, under stated conditions of use, to be retained in, or restored to a state in which it can perform its required function. Maintaining reliability in complex systems requires diverse and more elaborated systems approach than that for non-complex systems / items[2].

Nuclear power plant is so complex engineering system that it requires special arrangement for high reliability of system performance. There are empirical considerations for reliability of the nuclear power plants such as determining the slope of the failure rate and calculating the activation energy, as well as environmental factors, such as temperature, humidity, and vibration and also electrical stressor such as voltage and current [1].

Reliability engineering focuses on (i) reducing the maintenance requirements, (ii) utilizing technology analysis to achieve reliability and maintenance task improvements, and (iii) improving the uptime and productive capacity of important equipment using formalized problem-solving techniques. For maintaining high reliability of any complex systems, an important issue is to establish "reliability database" which contains the statistical data of all important systems and components comprising the whole engineering system.

For the case of a nuclear power plant, the improvement of its reliability can also be performed through daily or periodic activities such as testing, inspections, maintenance and quality assurance activities to maintain the quality of the nuclear power plants operation[3]. In order to evaluate or predicate a system's reliability, the effective system reliability model is ultimately required. The reliability modeling approaches are largely based on statistical methods. Typical examples of these methods are reliability block diagrams (RBD) [4], fault tree analysis (FTA) [5], Failure Modes and Effects Analysis (FMEA) [6], Job

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Hazard Analysis (JHA), system and Subsystem Hazard analysis (SHA, SSHA)[7], GO-FLOW analysis [8], Operating and Suport Hazard analysis (O& HA). These methods can provide the system reliability models where individual system components must be defined as either active or failed [9]. The author of this paper has considered the GO-FLOW methodology to evaluate the dynamical reliability of ECCS system of conventional four-loop pressurized water reactor (PWR) by considering the large break LOCA in the clod leg.

The GO-FLOW is a new success-oriented reliability analysis technique. The explanation has been started from the overview of GO-FLOW, phased mission problems, description of ECCS and behavior of ECCS components under a large break LOCA and followed by the evaluation of dynamical reliability of ECCS system by GO-FLOW and finally discussion of a reliability result.

2 Overview of GO-FLOW methodology

The GO-FLOW method is a reliability analysis method based on success-oriented system analysis technique. It is capable of evaluating system reliability and availability by describing the target system using what is referred to as a GO-FLOW chart, which is composed of signal lines and operators. It is worthy to mention that "operator" is named for the functional elements defined in GO-FLOW methodology, and does not mean a person in the reactor control room. The operator represents the function of the system and failure of physical equipments, logical gates and a signal generator.

There are a total of 14 different types of operators, as shown in Fig. 1. These operators are used in making GOFLOW chart by modeling a subject system. The signal does not represent a “change of condition”, but rather some physical quantity or information. A physical quantity called “intensity” is associated with a signal line. The intensity represents the probability of signal existence. In this case, the “Existence” includes “Potential existence” which means that a physical quantity exists when all the resistance “downstream” is removed. The sub-input signal can be given to operators 35, 37 and 38, and its intensity represents a time interval between the successive time points.

The operators 35, 37 and 38 are light bulb failure, valve failure in an open state and valve failure in the close state, respectively. These operators require component failure rates (λ). The sub-input signal represents the time duration, having the same units as λ [10]. A finite number of discrete time values (points) are given to express the system operational sequence. It is important to mention that the values of time points do not represent the real time. They however correspond to the ordering of time for event occurrences. The GO-FLOW methodology possesses the following significant features: (i) GO-FLOW chart corresponds to the physical layout of a system and is easy to construct and validate, (ii) Alterations and updates of a GO-FLOW chart are easily made, (iii) The GO-FLOW chart contains all possible systems operational states, and (iv) The analysis is performed by one GO-FLOW chart run by one computer. If the system to be analyzed becomes large-scale, then the

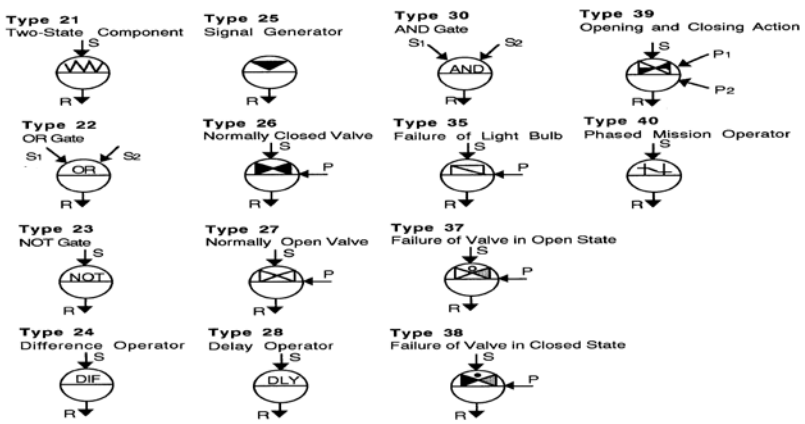

Fig. 1 Operators defined in GO-FLOW methodology.

construction of GO-FLOW chart and preparation of input data for GO-FLOW program requires great efforts. With this regard, an integrated analysis framework called ELSAT has been developed for easy handling of robust and complex systems [11].

The GO-FLOW methodology, as aforementioned, is a success-oriented system analysis technique, and can be used as a quantitative reliability evaluation method in Risk monitor. GO-FLOW methodology assembles and analyzes all the information, which is given in the form of failure data for individual subsystems and equipment.

3 Description of phased mission problem

The phased mission system (PMS) is subject to multiple, consecutive and non-overlapping phases (time periods) of operation, in which the system configuration, failure criteria and component's behavior (*e.g.* failure rate) may be different[12]. In phased mission problems, a system is operated in several phases and must operate successfully during each of the phases for complete execution of the mission.

An example of a phased mission problem includes an aircraft flight that involves take-off, ascent, level flight, descent, and landing. Many military operations for both aircraft and ships are also exemplars of phased mission problems. During the execution of the task, the configuration of the system is altered such that the failure logic model or a system's failure characteristics may change to accomplish a different objective.

The phase number, time interval, system configuration, tasks to be undertaken, performance measure of interest and maintenance policy can be used for the expression of a mission. This type of mission can be epitomized as a sequence of discrete events required to accomplish a task [13]. The reliability of a PMS is, in principle, the probability that the mission successfully achieves all the submission objectives in each phase. The condition of components may be critical for one particular phase and transition from one phase to another is the critical event leading to mission failure. Failures of the components can occur at any point during the mission [12].

In light of such considerations, a method to express how the combinations of component failures (basic events) can occur during the phases throughout the mission and cause system failure is required [13]. These failure events then require quantification to enable the likelihood and frequency of mission failure to be determined. For the solution of a phased mission problem, there are techniques that have previously been implemented such as fault tree analysis (FTA), Markov analysis and simulation as well as new techniques as GO-FLOW methodology.

The technique of fault tree analysis is a widely-used tool to assess the probability of failure of an industrial system [12]. The concept is to begin with a failure event and trace its influences back until the basic influence factors are attained. The fault tree analysis (FTA) is a top-down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine the series of lower level events. The events whose causes have been further developed are called intermediate events; the top event of the fault tree which is the intermediate event is the system's failure. The fault tree has some difficulties in phased mission problem: (i) The fault trees may reveal human error (They hardly can determine the underlying causes *vide infra*). (ii) Analysis can lead to the generation of a plethora of failure trees if the analysis has very wide scope[14]. (iii)The fault trees need detailed knowledge of the operation, construction and design of the system. (iv)Fault trees may become very robust and intricate. (v)Significant training and experience is necessary to use this technique properly; and hence explains why it is time-consuming. (vi) The tree does not represent the transition routes between the states of any events (vii) Different fault trees must be developed for different top events[14]. (viii)The same event may appear in different parts of the tree, leading to some initial confusion[15]. Mindful of these difficulties the author has considered the GO-FLOW methodology for analyzing the dynamical reliability of non-repairable ECCS systems of conventional PWR that undergo phased missions. Owing to the fact that the GO-FLOW can easily make logic for each phase

freely, logic models in different phases can mutually use the same component's failure. The probability of the system successively operating in the series of phase is automatically calculated by carefully considering the dependencies with the aids of phased mission operator (type 40). Automatic consideration of components' dependencies is the feature of GO-FLOW methodology.

There are two phases in ECCS system, that is, injection phase and recirculation phase. In GO-FLOW reliability analysis, the results of the analysis are the system failure modes in each phase, the failure probability and the total mission unreliability. The success of the mission depends on the performance of the non-repairable components used in each phase, and the probability of this success is referred to as the mission reliability.

4 Description of ECCS of PWR nuclear power plant

Emergency core cooling system (ECCS) is an important safety feature that supplies boric acid water urgently into the reactor core to cool the core and maintain the integrity of fuel shielding under abnormal conditions, and also keep the core sub-critical to prevent fuel damage. Worthwhile to mention is that the design of the ECCS (based on safety analysis) is sufficient to make the maximum temperature of cladding tubes below 1200ºC, which is in line with the Single Failure Criteria.

The emergency core cooling system is a highly important system which is designed with sufficient redundancy and independency. The ECCS has two full capacity subsystems to perform the specified functions on the assumption of a single failure of any active component during a short term, or assuming either a single failure of any active component or a postulated single failure of any passive component during a long term after the Loss of Coolant Accident. The ECCS of Japanese nuclear power plant consists of three interconnected subsystems, which include accumulator injection system, High-Pressure Injection System and Low-Pressure Injection System[16]. The Accumulator Injection System (AIS) is composed of accumulator tanks, piping and valves, and one accumulator subsystem is provided for each loop.

At the event of loss of a coolant accident (LOCA) (when the pressure of the reactor coolant system decreases below the accumulator tank pressure), it will automatically supply boric acid water to the core to prevent damage of the fuel and cladding. The AIS is a passive system, and thus, no particular impetus such as external power supply is required. In accumulator tanks, borated water is stored and pressurized with nitrogen gas. The High Pressure Injection system (HPIS) is composed of High Pressure Injection pumps (HPIP), piping and valves. HPIP is automatically actuated upon reception of the ECCS actuation activation signal (i) Low Reactor Pressure, (ii) Low Main Steam Pressure (iii) High Containment Pressure and Manual. HPIP starts and injects borated water

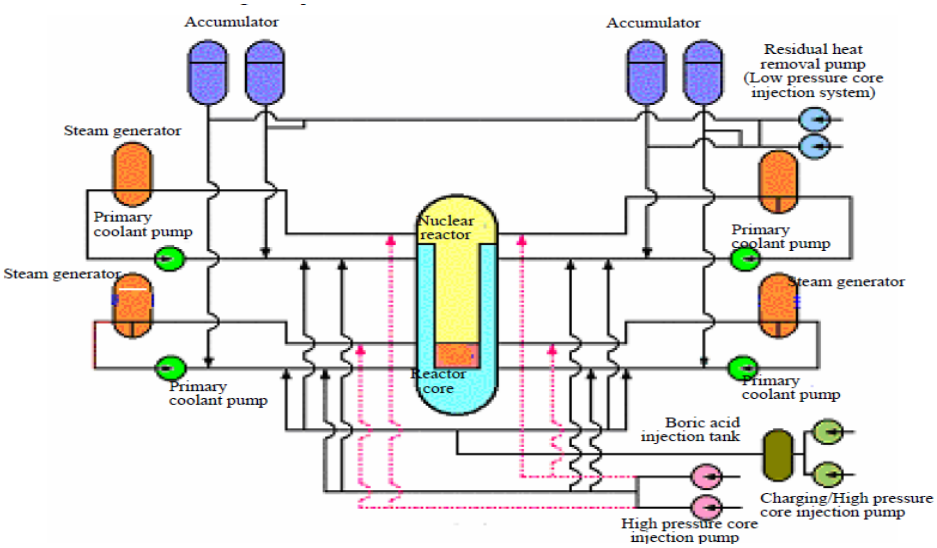

Fig. 2 Emergency core cooling system.

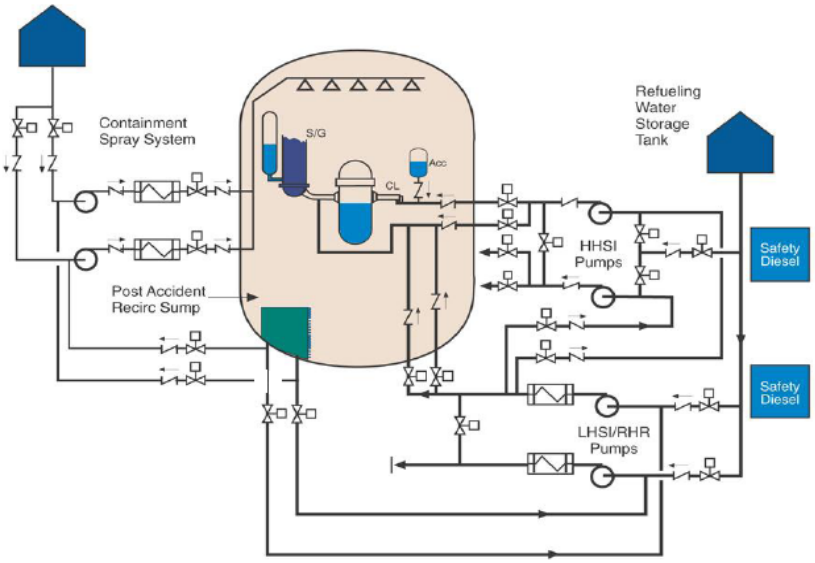

Fig. 3 ECCS of a four-loop PWR (recirculation mode).

(phase one) of the Refueling Water Storage Tank (RWST) into the core through the cold leg of the Reactor Coolant Pipe on ECCS actuation signal. When RWST water level becomes low, HPIP is then switched to the Containment Recirculation Sump (phase two) as shown in Fig. 2. Likewise, Low Pressure Injection System (LPIS) is comprises two Residual Heat Removal Pumps (RHR, pump), two Residual Heat Removal Heat Exchangers (RHR HX) and related piping and valves. LPIS injects borated cooling water from RWST to the core through the heat exchanger and the cold leg of the reactor cooling pipe on ECCS actuation signal (phase one). LPIS switched to the Containment Recirculation sump and operation is switched to the recirculation mode on a low level of RWST water (phase two) as shown in Fig. 3[16]. ECCS systems have many motor-operated valves, air-operated valves and check valves for emergency bus bar and emergency diesel generators. As for GO-FLOW analysis, the valves related to emergency bus and diesel generators are neglected *vide infra*.

5 Behavior of ECCS component under the large break LOCA.

The hypothetical large break LOCA is the classical design-basis accident for the PWR reactor concept. To describe its phenomenology, the assumption that represents the worst accident that could be conceived to happen in the event of a water circuit, are as follows: (i) one of the inlet pipes from the circulating pump is completely non-fractional, and (ii) free discharge of the primary coolant from the both broken end. A double-ended guillotine or 200 percent break as shown in Fig. 4[17]. In this paper, the author has considered the large break LOCA in a cold leg of RCS for GO-FLOW analysis. The sequence of an event during the large break LOCA in cold leg and behavior of ECCS components are given in Table 1.

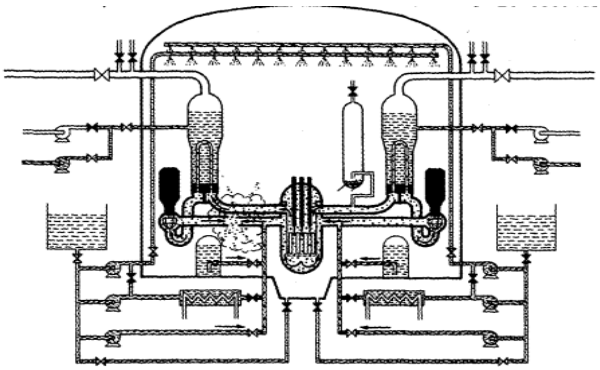

Fig. 4 Large Break LOCA in cold leg of PWR.

6 Modeling of four loops ECCS for GO-FLOW analysis

Let us consider a simplified ECCS of a four-loop system PWR; one of the loops includes a pressurizer, while the other three loops are devoid of pressurizers. Large break LOCA is assumed at the outlet of the main primary pump in the cold-leg piping system, which has a pressuriser. The simplified ECCS system consists of three sub-systems:

Table 1 Sequence of Events of LOCA and behavior of ECCS components[18, 19]

Phenomena	Time	Condition	Mitigate systems actuating, reactor core status
Reactor scram	before 4sec	Core Depressurization	Movement of control rods, In light water reactors this is achieved by inserting neutron-absorbing control rods into the core
Containment spray system	after LOCA	Containment high pressure sensor signal	CSP will start at containment high pressure and spray the water in containment to washout the reactive iodine (radioactive material). First CSP take the water from RWST and then switched to sump at low level of RWST water.
Blow down	0 to 600 sec	Accumulator =40 bar, HPIS =100 bar	Break occurs, Reactor trip, Pumped safety Injection signal (high containment pressure and low reactor core pressure), Accumulator injection system begins. HPIP and RHR pump system start by taking water from RWST, Pump ECCS injection commences
Bypass	600 to 1200 sec	HPIS = 100 bar, Accumulator = 40 bar.	HPIS and RHR pump is automatically actuated upon the receipt of the ECCS actuation signal. AIS are continuously started on ECCS signal. *i.e.* low reactor pressure ,low main steam pressure , high containment pressure,
Refilling	1200 to 1800 sec	LPIS = 30bar	Accumulator empty, End of blow down, End of bypass, Switch to cold leg recirculation on RWST low level alarm, Pumped ECCS injection begins, RHR HX
	1800 to 2400		and Containment heat removal system starts on the receipt of ECCS signal. Bottom of core recovery.
Reflooding	2400 to 3000sec	Fuel temperature 1000ºĊ	Core quenched, Steam binding phenomena will occur in this phase,
Long term cooling	after 3600sec	RCS temperature less than 100ºC	Cold leg recirculation is progressing steadily. Switch to cold / hot leg recirculation, HIPP and RHR pump taking water from sump, RHR HX start continuously.

Accumulator Injection System (AIS), High Pressure Injection System (HPIS) and Low Pressure Injection System (LPIS). One function of the ECCS is to prevent excessive core heating as much as possible after a large break LOCA and keep the reactor water circulating to and from the reactor vessel until the core is cool[19]. In the real four-loop ECCS systems, there are many motor-operated valves, air-operated valves, check valves for emergence bus bar and emergency diesel generators. They are, however, omitted in simplified ECCS systems for GO-FLOW modeling. The functions of ECCS can be identified in two phases *i.e.* injection phase and recirculation phase in case of a large break LOCA and time of these phases for GO-FLOW analysis are as follows:

(i) Phase one (injection phase: 0 sec to 1800 sec)

(ii)Phase two (recirculation phase: 1800sec to 3600sec)

For phase one (injection phase), four accumulators (*i.e.* HPI-pump1, HPI-pump2, RHR pump1, RHR pump2) and valves from M1 to M8 are required. For phase two (which is the recirculation phase) HPI-pump1, HPI-pump2, RHR pump1, RHR pump2, RHR HX A and B and valves from M7 to M14 are needed and an operation of all these components is given in Table 2.

Table 2 Operation of passive and active components

Components	Phase 1 (injection mode)	Phase2 (recirculation mode)
HPI-Pump1&2	on	on
RHR-Pump1	on	on
RHR-Pump2	on	on
RHR-HX A	off	on
RHR-HX B	off	on
M1	on	off
M2	on	off
M3	on	off
M4	on	off
M5	on	off
M6	on	off
M7	on	on
M8	on	on
M9	off	on
M10	off	on
M11	off	on
M12	off	on
M13	off	on
M14	off	on

For phase one, four accumulators supply the borated water urgently after the loss of a coolant accident. There is no necessity for power source of actuation as these are passive systems. The check valves from M3 to M6 actuate on low pressure ECCS actuation signal. Furthermore HPI pump 1 and 2 take the borated water from RWST when the motor-operated valves M1 and M2 open.

Similarly, RHR pump 1 and 2 take borated water from RWST when the motor-operated valves M1, M2 and M7, M8 are open as shown in Fig. 5 (injection mode). For recirculation phase, when the water level in RWST becomes low at certain value then HPI (pumps1 and 2) and RHR pump (pumps 1 and 2) take the water from the sump when the motor-operated valves M7 to M10 are open. In recirculation mode, RHR HX (A and B) and motor-operated valves from M11 to M14 are also in an operational state to cool the borated water taking from a sump as shown in Fig. 6 (recirculation mode).

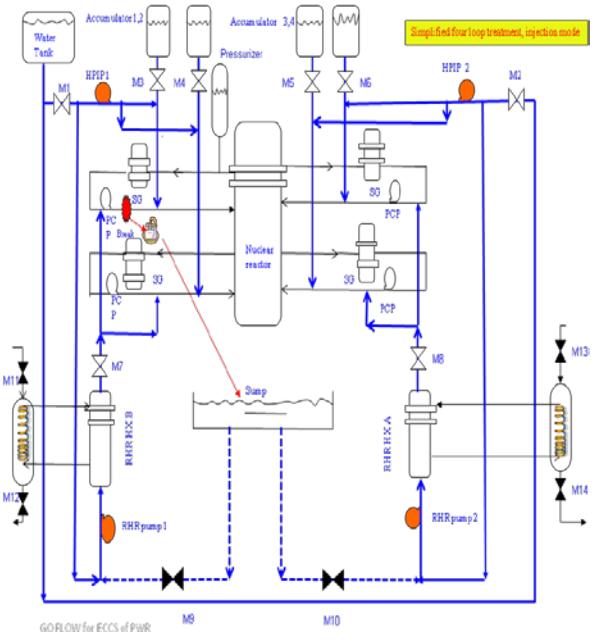

Fig. 5 Simplified ECCS system (injection Mode).

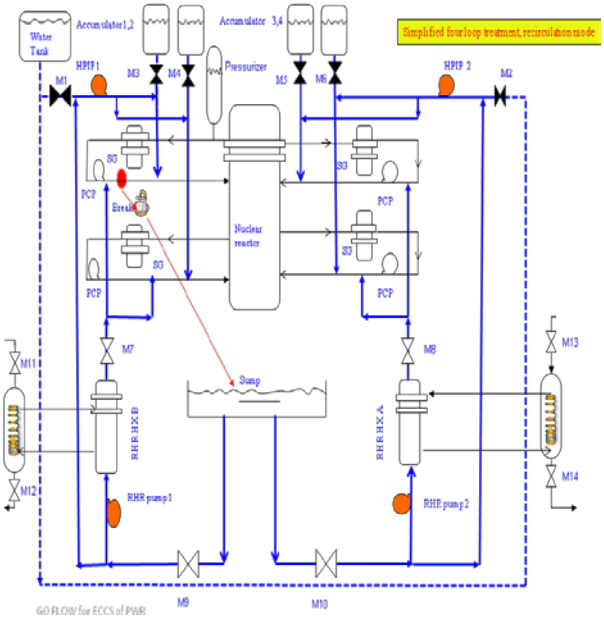

Fig. 6 Simplified ECCS system (Recirculation Mode).

7 Reliability analysis of four loops ECCS by GO-FLOW methodology

The author has conducted the GO-FLOW analysis to obtain the dynamical reliability of ECCS system for conventional four-loop PWR. The GO-FLOW chart of four loops ECCS is shown in Fig. 7 where each operator represents a component number. The names of subsystems are written by the side of corresponding operators. According to GO-FLOW chart, there are two phases. For phase 1, four accumulators corresponding to each loop, RWST, HIP pumps 1 and 2, RHR pumps 1 and 2 and valves from M1 to M8 are in operational states and are represented by corresponding operators according to their functions.

Likewise, for phase 2 Sump, HIP pumps 1 and 2, RHR pumps 1 and 2, RHR HX A and B and valves from M7 to M14 are in operational states and represented by corresponding operators. In GO-FLOW chart the connecting lines between the every operator identifies the signals. Every valve is assigned a sub- input signal for close and open state on the basis of demand. Final signals are 48 and 100 for phase 1 and 2 respectively, and 49 operators who correspond to the final GO-FLOW reliability analysis result for both phases.

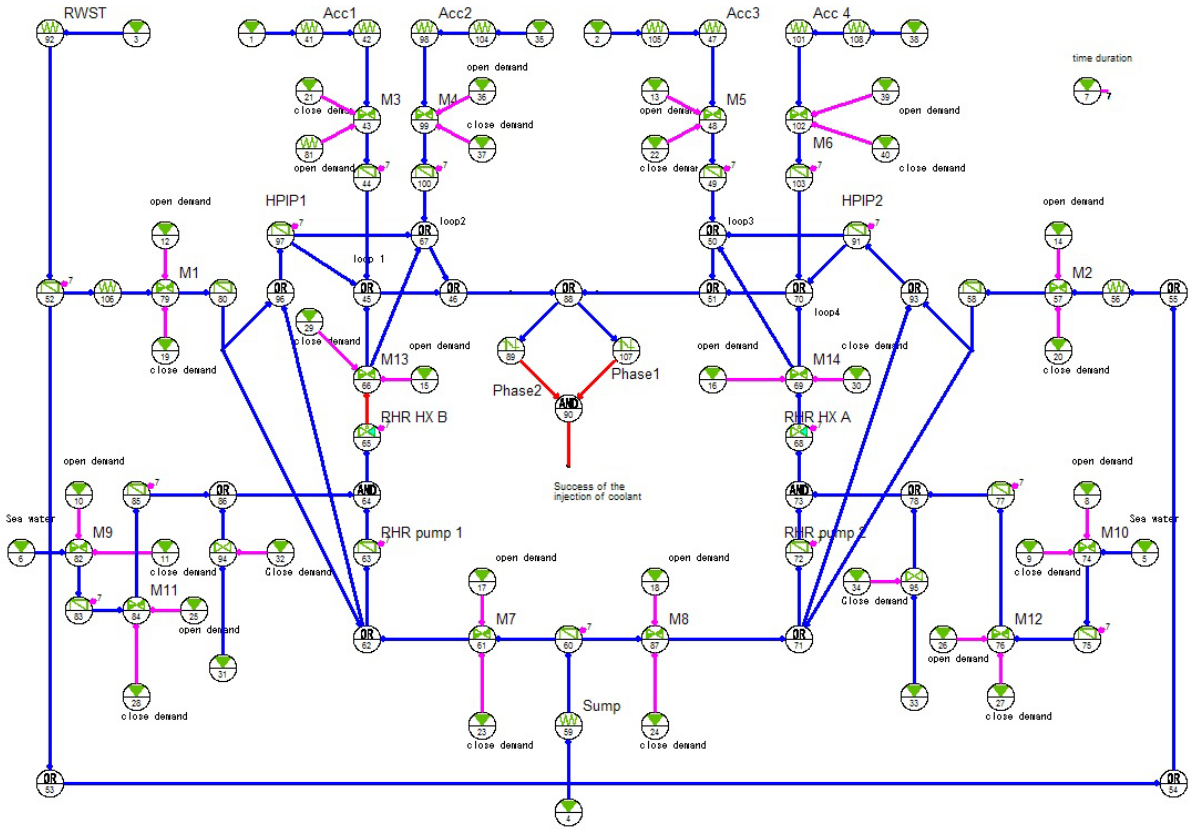

Fig. 7 GO-FLOW chart of four loop ECCS of PWR

Time duration for each phase is given by operator 7. Having prepared the analysis as described above, the calculation was performed and intensities of the final signals were obtained at all time points. The reliability data assigned to each component is furnished in Table 3. In Table 3, four accumulators and check valves from M3 to M6 are passive components, which essentially do not need any power source for operation and are in an open state in a phase 1 and close state in a phase 2 but However, the other components *i.e.* HPI pumps 1 and 2, RHR pumps 1 and 2 are in operating condition in both phases, and motor-operated valves from M1, M2 and M7 to M14 have open and close states. In the phased mission problem, during the execution of the task, the system configuration is altered such that the failure logic model changes at one or even more times. The mission reliability is defined as the probability that the system functions in successive phases. It is therefore necessary to calculate the product of success probabilities among different phases and to treat correctly the inclusion or exclusion relation between the failures of shared components.

Table 3 Failure rate of components

Components	Kind	Successful probability and failure rate
Accumulator 1 to 4	Passive	Pg =0.9
M3 to M6	Passive Open in initial state	Po=0.96, Pc= 1.0, Pp= 0.96, $\lambda o = 1\times10^{-08}$/sec, $\lambda c = 1\times10^{-08}$/sec
RWST	Passive	Pg= .999999, $\lambda o = 1\times10^{-05}$/sec
HPIP 1 and 2	Active	$\lambda o = 1\times10^{-08}$/sec
RHRP 1 and 2	Active	$\lambda o = 1\times10^{-05}$/sec
M1 and M2	Active	Po=0.96, Pc= 1.0, Pp= 0.96, $\lambda o = 1\times10^{-08}$/sec, $\lambda c = 1\times10^{-08}$/sec
M7 , M8	Active	Po=0.96, Pc= 1.0, Pp= 0
M9 to M14	Active	Po=0.96, Pc= 1.0, Pp= 0,$\lambda o = 1\times10^{-08}$/sec, $\lambda c = 1\times10^{-08}$/sec
RHR HX A and B	Passive	$\lambda o = 1\times10^{-08}$/sec
Sump	Passive	Pg= .999999 λo =1*10-5/sec

8 Discussion on GO-FLOW reliability analysis result

The failure probability result of a four-loop ECCS which is conducted by GO-FLOW is given in Table 4. The failure probability curve against time for the ECCS system of a four-loop PWR is depicted in Fig. 8. The time for phased mission ECCS of a typical four-loop PWR is 0～1800 and 1800～3600 sec for phases 1 and 2, respectively.

Table 4 Failure probability result

Real Time (sec)	Failure probability
0	0.00
0.1, phase 1 start	5.47×10^{-07}
600	2.59×10^{-06}
1200	4.62×10^{-06}
1800, phase 1 end	6.64×10^{-06}
1800, phase 2 start	1.94×10^{-02}
2400	2.53×10^{-02}
3000	3.11×10^{-02}
3000	3.11×10^{-02}
3600	3.69×10^{-02}

The failure probability of the four loops system is subtle in phase 1 owing to each component functioning correctly after the large break LOCA. There is also a redundancy of four accumulators, but failure probability increases with time in phase two due to the fact that the availability or reliability of the nuclear power plants has been adversely affected by the failure of the components and also the redundancy of four accumulators is reduced only into a recirculation mode in this phase, which is the responsible for a reliable power production. This GO-FLOW result can be utilized for the safety evaluation since the analysis result by GO-FLOW is qualitatively reasonable, correct, and easy to recalculate. It has been found out from the GO-FLOW analysis that the key components due to which failure probability in phase 2 increases are valves M7, M8 and recirculation sump. If we increase the open probability say from Po=0.96/sec to Po=0.99/sec for M7 and M8, and decrease the failure rate of sump from λo =1*10-5/sec to λo =1*10-7/sec, then, level of failure probability will almost be the same in both phases. Sufficient information is not obtained at the present analysis for the failure rates or probabilities as the input parameters. These values have to be based on failure statistics, which are neither abundant nor adequate for this purpose. Although the values obtained from the present analysis are not real values, the analysis results clearly reveal the system's behavior during phase change.

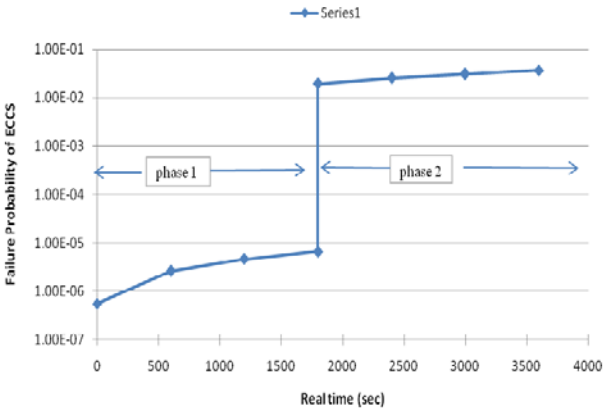

Fig. 8 Failure probability versus real time.

9 Concluding remarks

In this paper the dynamical reliability analysis has been developed for ECCS of a four-loop PWR by utilizing the GO-FLOW reliability analysis methodology. The authors begin his discussion by first giving an overview of the GO-FLOW methodology, a description of phased mission problem, explanation of ECCS and finally the GO-FLOW analysis result.

A reliability analysis is performed by GO-FLOW methodology in order to determine which components have the largest effect on system failure, and 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. By changing the small amount of failure data of key components in phase 2, the reliability result has the same level as in phase 1. As the GO-FLOW analysis results is qualitatively reasonable, correct and easy to recalculate, the GO-FLOW methodology is suitable for solving the dynamical problems. In the application of reliability engineering; an improvement can be achieved by the establishment of a reliability database which should contain the failure statistic with respect to the failures in all critical systems and components of a nuclear power plant.

The above study of evaluating the dynamical reliability for ECCS of four-loop PWR does not give high reliable values due to the lack of accurate input parameters. Further study can be conducted by considering common mode failure analysis, uncertainty analysis and Bayesian method to failure data in order to make pragmatic evaluation of dynamical reliability for ECCS of PWR.

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