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Reliability Analysis of Passive Containment Cooling System Using GO-FLOW Methodology

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Abstract: In the paper, the GO-FLOW methodology is used to characterize the dynamic operational profile of passive containment cooling system (PCCS) for phased-mission reliability evaluation. GO-FLOW method is a graphical modeling method that uses a series of GO-FLOW operators and signals to simulate the physical flow of water to fulfil the safety-related containment cooling function. The demonstration results show that the GO-FLOW method is applicable for describing the time-dependent characteristics of gravity driven drainage of water to the containment outer surface following the LOCA accident. The system reliability decreases over time due to the aging effects taking into account for the active components. The performance decrease in system reliability profile is consistent with the system configuration changes to align the passive containment ancillary water storage tank to the suction of the passive containment cooling system recirculation pump to replenish the cooling water supply to the passive containment cooling water storage tank.

Keywords: System Reliability Analysis, Passive Containment Cooling System, GO-FLOW Methodology, Thermal Hydraulic Reliability Model.

1. INTRODUCTION

Passive nuclear safety[1] is a design approach implemented for safety features that dost not require any active intervention but rely on natural forces of phenomena such as gravity, pressure differences or natural heat convention to bring the reactor to a safe shutdown state in the event of a particular type of emergency. With the promising benefits of high reliability and cost savings resulting from the absence of power supplies, passive safety features have been widely adopted in the newer advanced reactor designs[2]. However, the passive and inherent safety mechanisms with the engagement of little or no outside power or human control completely change the way the system works. The low driving forces can also pose significant challenges to performance effectiveness of passive safety systems.

A REPAS method was initially proposed by M. E. Ricotti and F. D. Auria [3] for reliability evaluation of passive systems in the late 1990s. Thereafter, a variant method of Reliability Evaluation of Passive Safety System (REPAS), which is known as Reliability Methodology for Passive Safety Systems (RMPS), is further developed within the 5th European framework programme[4]. An alternative Assessment of Passive System Reliability (APSRA) methodology is also presented by A. K. Nayak, *et al*.[5] for evaluation of reliability of passive systems. These methods require best estimate codes such as the Reactor Excursion and Leak Analysis Program (RELAP), Code for Advanced Thermal-Hydraulic Analysis of Reactors (CATHARE), etc. to find the Thermal-Hydraulic (T-H) model for passive system performance assessment. The passive systems reliability performance analysis is also strongly influenced by the deviations and uncertainties of process parameters involved with natural physical phenomena. Therefore, the series of REPAS, RMPS and APSRA methods should heavily rely on the simulation trials or experimental data. In order to reduce the T-H code runs, several alternative methods including variance reduction techniques, response surface methods, etc. have been proposed without resort to simplifying approximation[6]. T. H. Woo and U. C. Lee compared the non-linear fuzzy set and probabilistic expressions for failure explanation and failure probability estimation in Reference [7]. The quantitative dynamic reliability evaluation of passive safety systems is also investigated by A. Masood *et al*. using continuous time Markov chain (CTMC) and Monte Carlo simulation[8]. D. S. Samokhin *et al*.[9] discussed the different mathematical methods for reliability evaluation of passive systems. More review works and open issues for reliability evaluation of passive systems can be found in Reference [10-12].

It highlights that the reliability performance of passive systems is determined by physical components (such as valve, instrument, etc.) and functional component (passive phenomena)[13]. The contribution of the hardware failures can be assessed relatively simply by just taking into account the component configuration.

However, the reliability performance of passive systems is dynamic in nature. The classical probabilistic models such as fault tree and event tree are limited in handling the actual timing of events and the successive evolution of the scenarios. Moreover, the interactions between the dynamical evolution of the process variables (pressures, levels, etc.) and the behavior of the hardware components can hardly be taken into account from only the probabilistic perspective. Therefore, in this paper a novel framework is proposed for the dynamic reliability analysis of passive systems by taking into account the dependencies among events and component states as well as the phenomenal scenarios. Within the framework, the system physical configuration is modeled by GO-FLOW methodology. The existing and direction of working fluid flow can be also characterized by GO-FLOW in a phenomenological way. The actual timing of events coupled with the successive evolution of the scenarios are investigated by a simulation code.

The rest of the paper is organized as follows. Section 2 introduces the novel framework for quantitative reliability evaluation of passive systems. The GO-FLOW modeling and analysis of passive systems will be illustrated by the passive containment cooling system (PCCS) in AP1000 in Section 3. The conclusions are given in Section 4.

2. FRAMWORK FOR RELIABILITY EVALUATION OF PASSIVE SYSTEMS

In this framework, a novel framework for quantitative reliability analysis of passive systems is proposed as shown in Fig. 1. The framework consists of two parts: i) GO-FLOW method for system components reliability modeling; ii) simulation code/best estimate T-H codes (RELAP) for describing the phenomenological factors and dynamical accident scenarios.

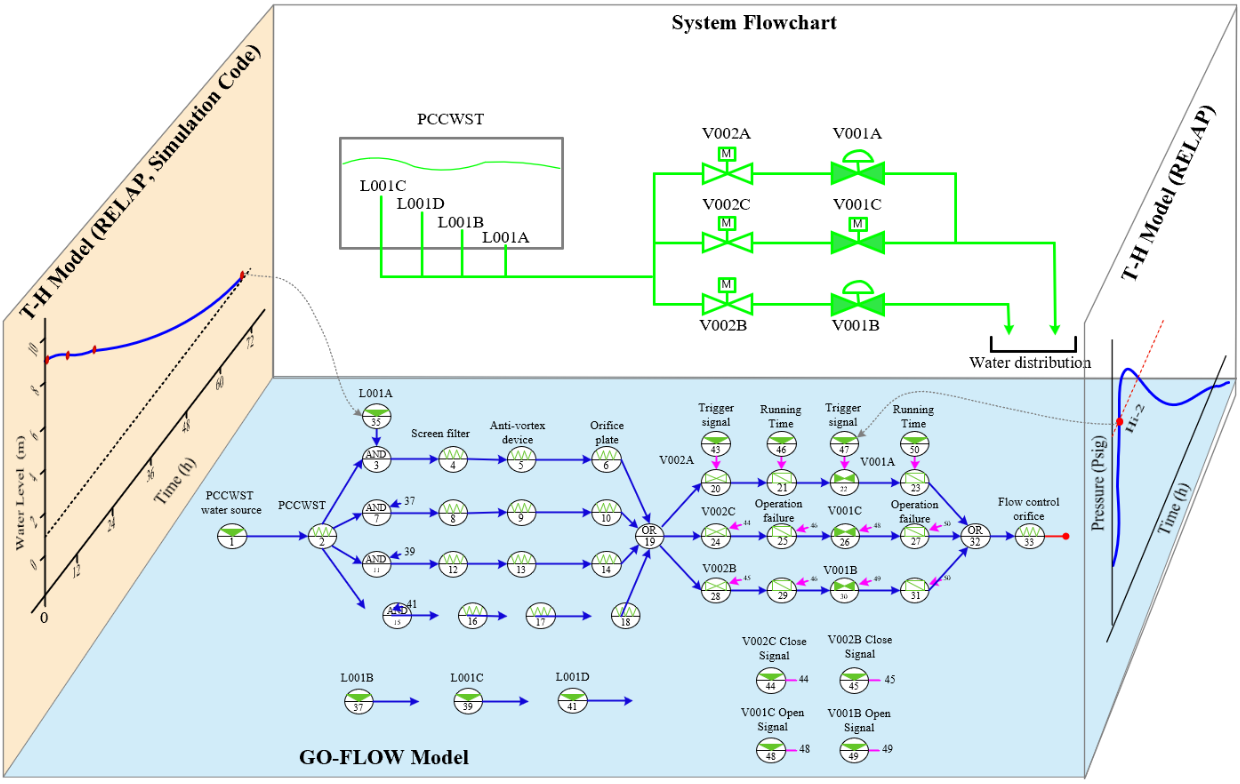


Fig. 1 Framework for relaibility evaluation of passive systems

GO-FLOW methodology is a success-oriented system reliability and safety analysis technique[14]. The GO-FLOW methodology was initially proposed by T. Matsuoka and M. Kobayashi for time-dependent and phased-mission problem solving[15]. GO-FLOW uses a series of GO-FLOW operators and signal lines to represent the actually existing or even potential existing of working fluid flow in a phenomenological and consistent way. The unique features of GO-FLOW method in handling time-dependent relationships and information flow control make it practical to interact with the dynamical evolution of the process variables as well as to account for the behavior of hardware components. In addition, the trigger mechanisms or conditions for natural circulation start-up and operational stability can be easily correlated by the trigger signals in GO-FLOW to capture the subtle phase changes or boundary condition changes suggest that the physical phenomena reliability can be obtained using simulation code or best estimate T-H codes (RELAP).

The framework supports integration and development of T-H codes or other pertinent simulation activities to estimate the evolution of the process parameters during the accident progress with uncertainty quantification. The transient processes calculated by T-H model are integrated into GO-FLOW modeling with the definition of time point. The timing of event occurrence along the successive evolution of the accident scenarios can be described with a set of discrete time points in GO-FLOW with synchronized simulation process.

3. GO-FLOW ANALYSIS OF PASSIVE CONTAINMENT COOLING SYSTEM

In the Section, the passive containment cooling system (PCCS) in AP1000 is taken as an example system to illustrate the GO-FLOW modeling process. The example PCCS system is first introduced in Section 3.1. Then the probabilistic GO-FLOW model is constructed for the PCCS system by mering with the hydraulic model in Section 3.2.

3.1. Passive Containment Cooling System

Passive containment cooling system[16] is an engineered safety feature designed in AP600 and AP1000 to reduce the containment temperature and pressure following a loss-of-coolant accident (LOCA) or main steam line break (MSLB) accident inside the containment by removing thermal heat from the containment atmosphere. The PCCS system also serves as the means of transferring heat to the ultimate heat sink for other design-basis events resulting in a significant increase in containment temperature and pressure. According to the Westinghouse AP1000 PCCS system design[16], the operation of PCCS system consists of two phases: Phase I of short-term containment cooling for nominal 72 hours and Phase II of long-term makeup water circulation for additional 4 days. Fig.2 shows the flowchart of PCCS system in AP1000.

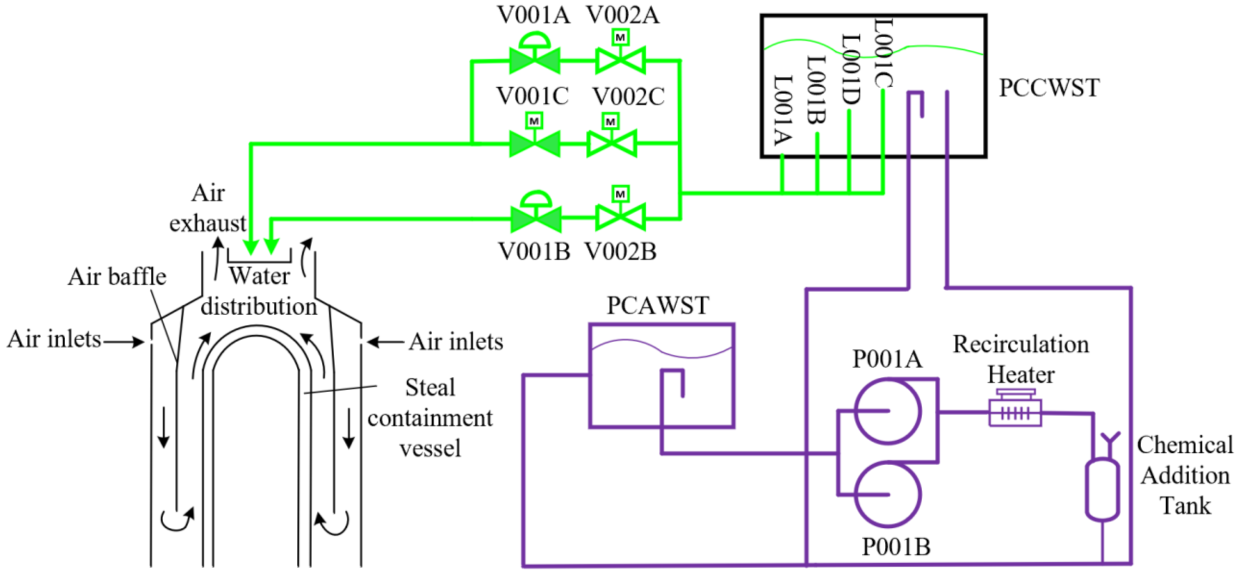


Fig. 2 Flowchart of passive containment cooling system

As shown in Fig.2, the PCCS system is consisted of a passive containment cooling water storage tank (PCCWST), redundant piping with fail-open isoluation valves (V001A, V001B), a water distribution bucket, an air baffle, air inlets and an air exhaust, passive containment cooling ancillary water storage tank (PCAWST), chemical addition tank, recirculation pumps, recirculation heater, and associated piping lines. In the passive containment cooling water storage tank, orifices are installed along with the different elevations of the four outlet pipes to control the flow of water as a function of water level. The flow rate change in phase I is dependent only upon the decreasing water level in the PCCWST. The active and passive components of PCCS system are summarized in Table 1.

Table 1. Category of PCCS system components

Category	Equipment	Function description
Active component	V002A, V002B, V002C	Allow for testing and mainteance of the downstream air-operated butterfly valves or motor-operated gate valves
	Recuirculation pumps P001A, P001B	Provide makeup flow to both the PCCWST and the spent fuel pool
	Motor-operated gate valve V001C	Isolate the cooling water when the upstream gate vavle is accidentally opened
	Air-operated butterfly valves V001A, V001B	Open upon receipt of a Hi-2 containment pressure signal
	Recirculation heater	Prvoide for freeze protection

Passive components	PCCWST	Filled with demineralized water
	PCAWST	Provide makeup flow to PCCWST and the spent fuel pool
	Flow control orifices (L001A, L001B, L001C, L001D)	Dependent on the water level (gravity)
	Chemical addition tank	Maintain water concentration
	Water distribution bucket	Deliver water to the outer surface of the containment dome
	Screen filters	Separate solid particles or suspended matter from water
	Anti-vortex devices	Suppress the submerged vortices
	Orifice plate	Control the flow rate

The outlet piping of PCCWST is configued with three trains of redundant isolation valves. In two identical sets, the discharge line consists of an air-operated butterfly valve and a motor-operated gate valve. The air-operated butterfly valves are normally closed and open upon the trigger signal of high contaiment pressure. The motor-operated gate valves are normally open and provided to allow for testing or maintenance of their upstream of the air-operated butterfly valves. The third discharge pipeline is equipped with two motor-operated gate valves in series with one normally open and the other one normally closed. The recirculatin pump is designed with a 100-percent capacity centrifugal pump to provide makeup flow to the PCCWST. The PCCS system performance parameters are given in Table 2.

Table 2. PCCS system performance parameters

PCCWST water level/m	**Nominal design flow/$m^3 \cdot h^{-1}$**
8.38	112.34
7.35	56.12
6.19	43.34
5.12	35.68
1.22	25.69

3.2. GO-FLOW Modeling of Passive Containment Cooling System

According to the flowchart of PCCS system, the GO-FLOW model can be directly constructed as shown in Fig. 3. The PCCWST tank is modeled with a Type-25 GO-FLOW operator (signal generator) to represent the water source signal. The source water is come from two parts: i) original water reservoir in PCCWST in Phase I; ii) makeup flow from PCCAWST in Phase II. An OR logic gate is added prior to the PCCWST to describe the two different water sources. The functional state of PCCWST being in good condition for water storage and supply is chararacterized by a Type-21 GO-FLOW operator. Type-21 GO-FLOW operator is a general functional opreator that is defined for binary state component modeling. The functional states (good or failure) of other passive or non-active components such as screen filters, anti-vortex devices, orifice plates, recirculation heater, chemical addition tank, etc. can be also modeled with Type-21 GO-FLOW operator in a similar way. The normally closed valves V001A, V001B, V003C and recirculation pumps P001A, P001B are represented by Type-26 GO-FLOW operators. In contrast, the Type-27 GO-FLOW opreator is used to model the normally-open or fail-open state of air-operated butterfly valves V002A, V002C, and normally-open motor-operated gate vavle V002B. Type-26 and Type-27 GO-FLOW operators are also functional opreators that are respectively designed for reliability modeling of normally closed component and normally open component. The definitions and explantions for general GO-FLOW opeartors and signal lines can be found in Reference [15].

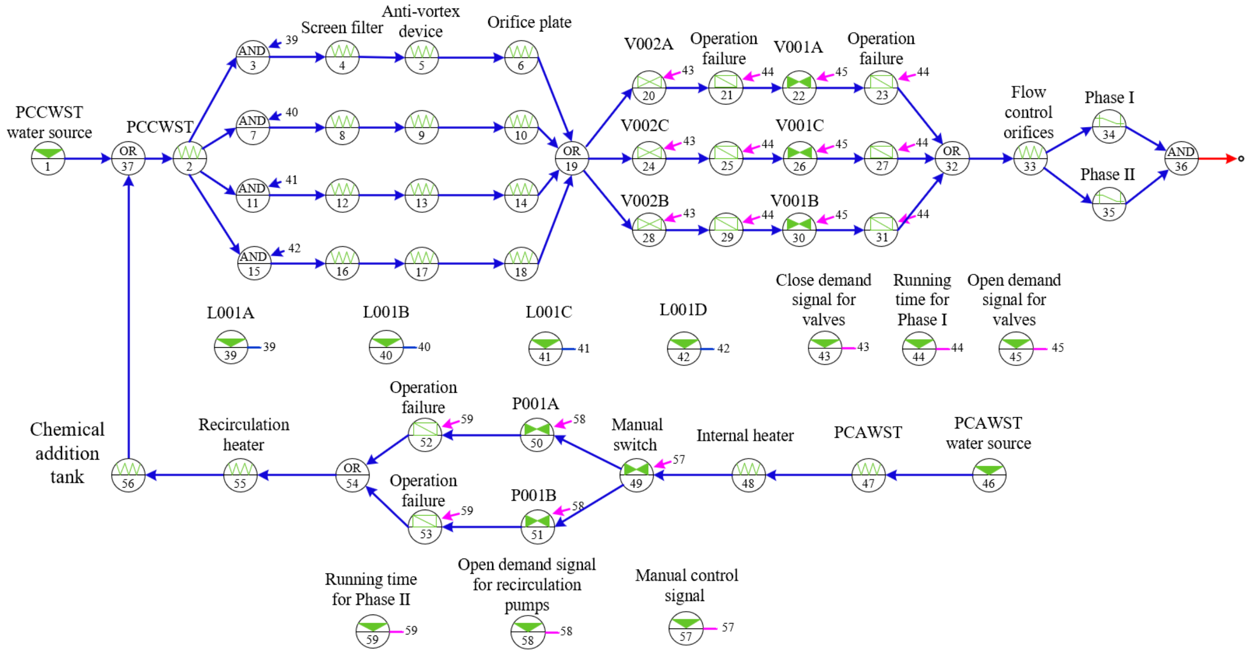


Fig. 3 GO-FLOW model of PCCS system

In essence, the logical relationships among the redundant PCCWST outlet pipes are dependent on the timing of when the pipe orifice is uncoverd by the water. The logic timing of water level changes in PCCWST is simulated by the T-H model. Since the flow rate change is primarily dominated by the descreasing water level in the PCCWST, only the hydraulic model is preliminarily developed in the study for providing the timing of events along the water level decreases. A logical clock composed by an AND logic gate together with a Type 25 GO-FLOW operator is inserted in each set of discharge line for capturing chronological and causal relationships among the distributed flow control orifices. The phased mission characteristics are expressed in terms of Type-40 GO-FLOW operators.

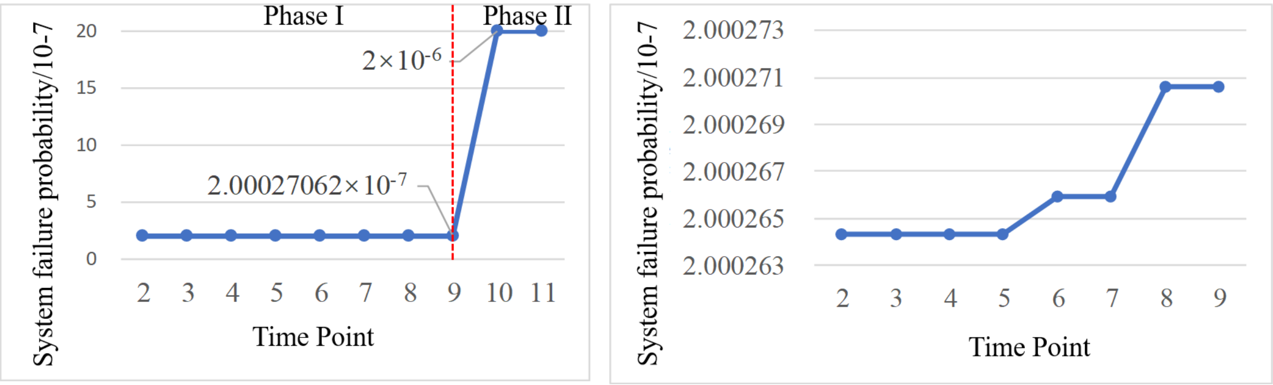
3.3. GO-FLOW Analysis

Assuming that the PCCS system is initiated upon the emergence of Hi-2 containment pressure signals during a large break loss of coolant accident (LB-LOCA). One of the air-operated butterfly valves will be opened immediately after the LB-LOCA accident, which allows the demineralized water to be delivered to the top and external surface of the steel containment shell for decay heat removal. Following a LB-LOCA, the water level in PCCWST decreases with a desired flow rate to reduce the post-accident containment pressure and remove decay heat. Upon completion of the first stage (Phase I) of containment cooling in 72 hours, manual actions are required to align the PCCAWST tank to the suction of the recirculation pumps to deliver the makeup water to the PCCWST for continuous cooling. Sufficient inventory is available within the PCAWST to maintain the minimum flow rate for additional 96 hours. The reliability data used for GO-FLOW analysis is presented in Table 3. It should be noted that the reliability data used here are for illustrative purposes only.

Table. 3. Reliability data used for GO-FLOW analysis

No. of GO-FLOW operator	Type of GO-FLOW operator	Reliability Parameters	Physical meaning or component
1	25	—	Water source originated from PCCWST tank
2	21	P_g=9.99999×10^{-1}	PCCWST tank
4, 8, 12, 16	21	P_g=9.99998×10^{-1}	Screen filters
5, 9, 13, 17	21	P_g=9.99998×10^{-1}	Anti-vortex devices
6, 10, 14, 18	21	P_g=9.99999×10^{-1}	Orifice plate
20, 24, 28	27	P_c=9.9971×10^{-1} P_p=1.98×10^{-8}	V002A, V002B, V002C
21, 25, 29	35	λ=3.58×10^{-8}/h	Failure rate of motor-operated gate valves
22, 30	26	P_o=9.99678×10^{-1} P_p=4.5×10^{-8}	V001A, V001B
26	26	P_o=9.9971×10^{-1} P_p=1.98×10^{-8}	V001C
23, 31	35	λ=1.76×10^{-7}/h	Failure rate of air-operated butterfly valves V001A, V001B
27	35	λ=3.58×10^{-8}/h	Failure rate of motor-operated gate valve V001C

33	21	P_g=9.99999×10^{-1}	Flow control orifices
46	25	—	Water source originated from PCAWST tank
47	21	P_g=9.99999×10^{-1}	PCAWST
48	21	P_g=9.9999×10^{-1}	Internal heater
49	26	P_o=9.999×10^{-1} P_p=0	Manually-opened flow path switch
50, 51	26	P_o=9.9981×10^{-1} P_p=0	P001A, P001B
52, 53	35	λ=4.25×10^{-6}/h	Failure rate of recirculation pumps P001A, P001B
55	21	P_g=9.9999×10^{-1}	Recirculation heater
56	21	P_g=9.99999×10^{-1}	Chemical addition tank
43	25	—	Trigger signal for the normally-open valves V002A, V002B, V002C
44	25	72 h	Running time for Phase I
45	25	—	Trigger signal for the normally-close valves V001A, V001B, V001C
57	25	—	Manual signal to align the PCAWST
58	25	—	Open demand signal for recirculation pumps
59	25	96 h	Running time for Phase II
39	25	—	Trigger signal for stopping L001A
40	25	—	Trigger signal for stopping L001B
41	25	—	Trigger signal for stopping L001C
42	25	—	Trigger signal for stopping L001D
37, 19, 32, 54	22	—	OR gate
3, 7, 11, 15, 36	30	—	AND gate
34	40	—	Phase I
35	40	—	Phase II



a) Overall system reliability

b) Reliability level changes in Phase I

Fig. 4. Analysis results

The phased mission reliability obtained for PCCS system is shown in Fig. 4. The reliability level is slightly decreased in each phase due to the aging effects of active components. Meantime, a sudden decline can be found in the phase shift point when the additional makeup water line is considered for replenishing the cooling water supply to the PCCWST tank. The time-dependent reliability characteristics of system subject to phase-shift configuration changes and degradation processes are described by a set of discrete time points in GO-FLOW methodology. In principle, the very subtle changes in system reliability profile can also be mapped out when there is enough time points are considered for components degradation modeling.

4. CONCLUSION

In the paper, a novel framework for reliability evaluation of passive systems is proposed based on GO-FLOW methodology and T-H model. The T-H model is used to simulate the accident scenarios and physical phenomena that are interacted with the behaviors of system components. The GO-FLOW model is then constructed for quantitative reliability evaluation. The GO-FLOW is supportive for capturing structural and behavioral characteristics of passive systems.

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