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Reliability analysis of phased mission system with loop structures

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Contents of the presentation

- *Phased mission system*
- *Reliability analysis method for loop structured system*
- *An analysis example*

This presentation is based on the following paper.

- *"Reliability analysis of a BWR plant system at startup stage - analysis by the GO-FLOW methodology with consideration of loop structures and phased mission problem –", Reliability Engineering & System Safety, Volume 233, May 2023, 109086*

Introduction

- With the development of technology, many systems become more sophisticated and complex.
- Many of these systems, such as nuclear power plants or aerospace systems, perform different tasks in multiple, consecutive duration, called phased mission systems (PMSs).
- Mission reliability is of crucial importance for these engineering systems, particularly for those designed to support critical missions, for instance, safety or accident prevention systems.
- In complex engineering systems, some part of system configuration has a loop structure, and it is necessary to carry out reliability analysis that correctly evaluates the logical loop structure.

How to deal PMSs(1)

- Burdick et al. [1, in1977] have presented an efficient approximation technique for unavailability estimates for phased mission systems of Boiling Water Reactor (BWR).
- Extensive research efforts have been expended in the reliability assessment of PMS after Burdick et al.
- Existing methodologies can be categorized into two types:
  - Simulation-based methods [13]
    - Simulation methods have been shown to be faster to solve than analytical methods [13].
  - Analytical methods. There are three groups:

    (1) combinatorial methods, fault tree (FT), binary decision diagram (BDD), etc.;

    (2) state-space model-based methods, the Markov process, Bayes network (BN), etc.;

    (3) the modular method, a combination of the two previous methods.

How to deal PMSs(2)

- In recent years the BDD —a combinatorial method — has become more widely used in reliability analysis of PMSs.
  - But this approach has been only suitable for small-scale systems.
- A modular method for the reliability analysis of large PMS has been performed to many engineering systems.
  - One example of a modular method was an application to autonomous vehicles, in which phase fault trees were simplified prior to the conversion to BDDs [14].

How to deal PMSs(3)

- Numerous studies have focused on PMS with special features. and applied to practical engineering systems.
  - multistate components [15],
  - non-exponential repairable components [16, 17],
  - common-cause failures [18, 19], etc.
- Analysis examples.
  - A BDD based method has been applied with the consideration of common cause failures (CCF) for small system with 3 phases [18].
  - A recursive and analytical method for reliability evaluation has been performed with the propagated failures for relatively large example of 12 binary elements with 6 phases [19].
  - A universal generating function-based method has been developed to analyze PMSs considering the imperfect fault coverage [16].

How to deal PMSs(4)

- Analysis examples (continue).
  - The redundancy allocation problem (RAP) of PMSs has been studied by the modular method and BDD, and applied to the propulsion system of a spacecraft [17].
  - A Markov model has been established to solve the dependence problem of multi-state components among different phases [15].
  - A multi-attempt, multi-unit scenario of missions' execution has been considered with the external shocks [20].
  - A new reliability model for the multi-state PMS with k-out-of-n(G) subsystems has been developed and applied to a power generating system which were connected to a common bus power line [21].

How to deal PMSs(5)

- Analysis examples (continue).
  - By using multi-state multi-valued decision diagram (MMDD), consideration of the multi-state behaviors in the PMSs and mission back-up design have been treated and applied to a propulsion system in a spacecraft [22].
  - The phased mission reliability of unmanned aerial vehicle (UAV) swarm has been taken up and analyzed by the BDD. The target system was 6 phases with number of UAV max 50 [23].
  - As more complicated situation, conflicting phase redundancy has been analyzed by modular method for space tracking, telemetry, and control (TT&C) systems [24].

Logical loop structure in a system

Reliability analysts have been long suffered to solve a problem of logical loops in reliability and/or availability analysis.

- Many attempts [3-7] have been made as breaking the logical loops at the points where the dependencies among the support systems are relatively weak and developing new logic without loops.
- Vaurio [8] suggested iterative method to solve the logical loop. The proposed methodology is quite intuitive because the repeatability of the loop structure is considered through iterative calculations.
- An approach to obtain exact solution has been proposed by the author [9] for solving this problem. It gives a formal solution with arbitrary set for a Boolean relation with logical loop.

Analysis by exact method

- The solution without logical loop structure can be obtained by exact method.
- The solution can be used in any analytical method, for example in fault tree (FT) or in graph-based reliability analysis methods.
- The solution is obtained with arbitrary set, and this arbitrary set has to be determined by engineering considerations for the loop establishing processes.

Approach to analyze logical loop structure

There still continues the efforts to solve logical loops in reliability and/or availability analysis.

- An attempt to use Dynamic Flowgraph Methodology (DFM) has been made [10]. The DFM does allow to handle logical loop structure with time lags, but it does not use analytical solution. The method has been limited to small-medium sized systems, because of “combinatorial explosion of states”.

Approach to analyze logical loop structure (2)

- A highly functional method [11] has been proposed for repairable loop structured system. A closed-loop probabilistic reliability assessment (CPRA) method has been developed for the dynamic reliability assessment of loop systems by integrating cyclic Bayesian network (CBN) modeling and dynamic Bayesian network (DBN). Numerical solution has been obtained by CPRA.
- Factor graph-based approach[12] has been proposed for the analysis of logical loop structure. It is applied for intuitively grasping logical loop problem. The method has been applied to 3-systems-in-loop and 4-systems-in-loop situations, and solutions have been obtained by iterations.

Reliability analysis of phased mission system with loop structures

- In this presentation, PMS with loop structures (PMS with special features) has been taken up.
- If non-analytical method is applied to solve loop structured system, iterations or numerical calculations are required in each phase. This makes it very difficult to handle dependencies between different phases.
- For this reason, reliability analysis of PMS with loop structures has not been common in literatures.

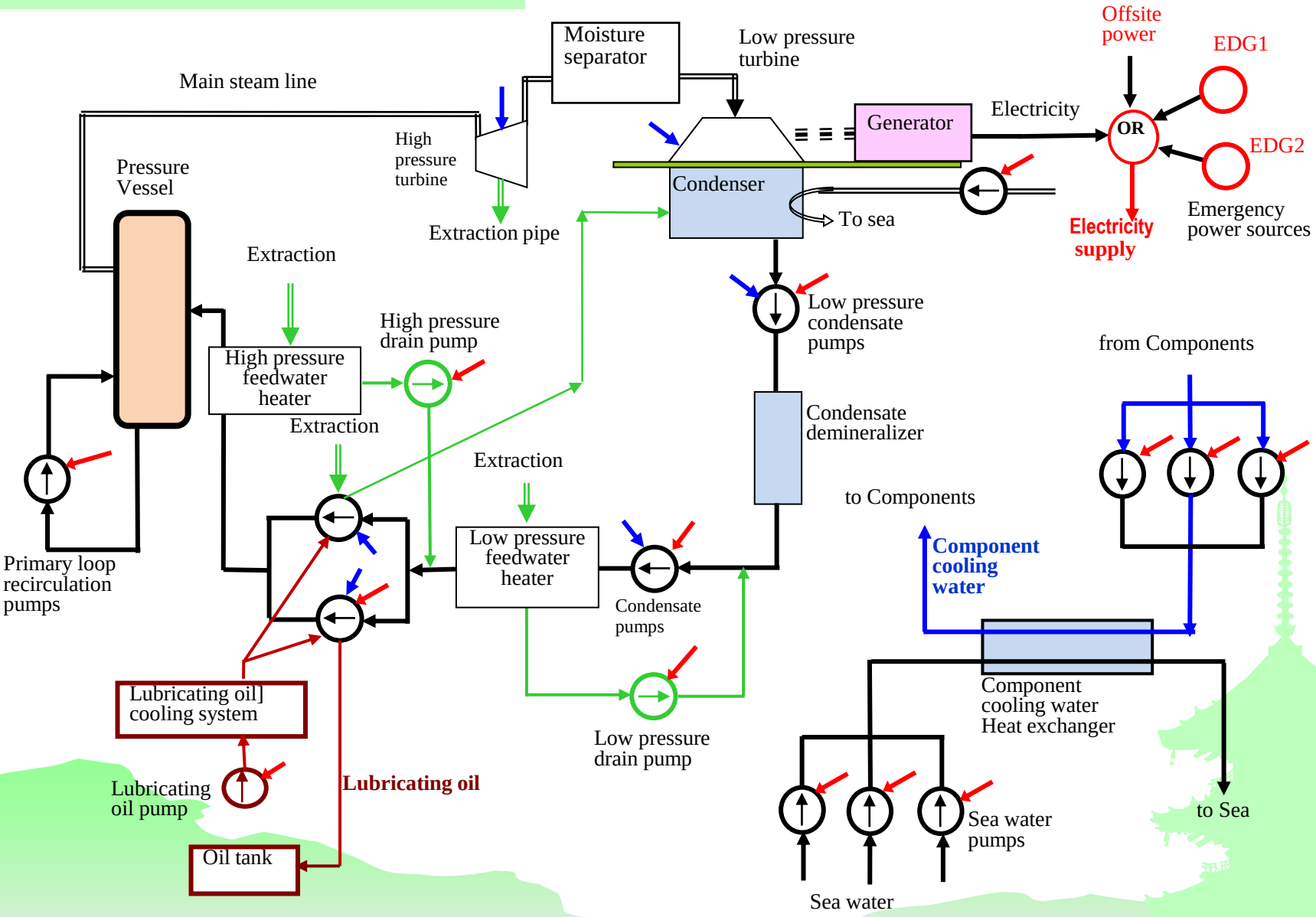
Analysis procedure for phased mission system with loop structures

- The logic of loop structure has been directly modeled on a GO-FLOW chart with the help of exact solution.
- The PMS of a BWR system has been also modeled on the same GO-FLOW chart by using the phased mission operator which is prepared in the GO-FLOW analysis framework.
- The GO-FLOW is a combinatorial method, and numerical calculations are performed for independent components in an early stage of the analysis. This makes reliability analysis of PMS with loop structures easy, efficient, and fast.
- Both the logic of loop structures and the logic of PMS have been modeled on the same GO-FLOW chart. This allows PMS with loop structures to be easily solved.

Analysis example for phased mission system with loop structures

- Nuclear power plants establish a stable power generating state through transient unstable conditions from cooled state.
- During this startup stage, many components and sub-systems are sequentially started and placed in operating state.
- The function and system configuration of the plant will change during startup stage, and it shows a phased mission problem.
- Some part of system configuration has a loop structure, and it is necessary to carry out reliability analysis that correctly evaluates the logical loop structure.
- a BWR system is taken up as the example system.

BWR plant system



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startup sequences

Time（hour）	0	6	22	25	32	33	35	72	720	2160	4368	8760
Phase	0	1	2	3	4	5	6					
Off site power	Connected					Disconnect						
Main steam condensor	Vacuum established											
Control rods	Withdrawn（Criticality in 2 hours）											
Turbine	Starts（10% of full power）											
Generator	Provisional	Parallel with off site power										
Low- pressure condensate pumps	Starts											
High-pressure condensate pumps	Starts											
Electric main feed water pumps	Start					Stop						
Turbine driven main feedwater pumps	Start											
Related pumps	Start											
Sea water system	Starts											
Cooliing system for main feedwater pumps	Starts											
Lubrication system	Starts											

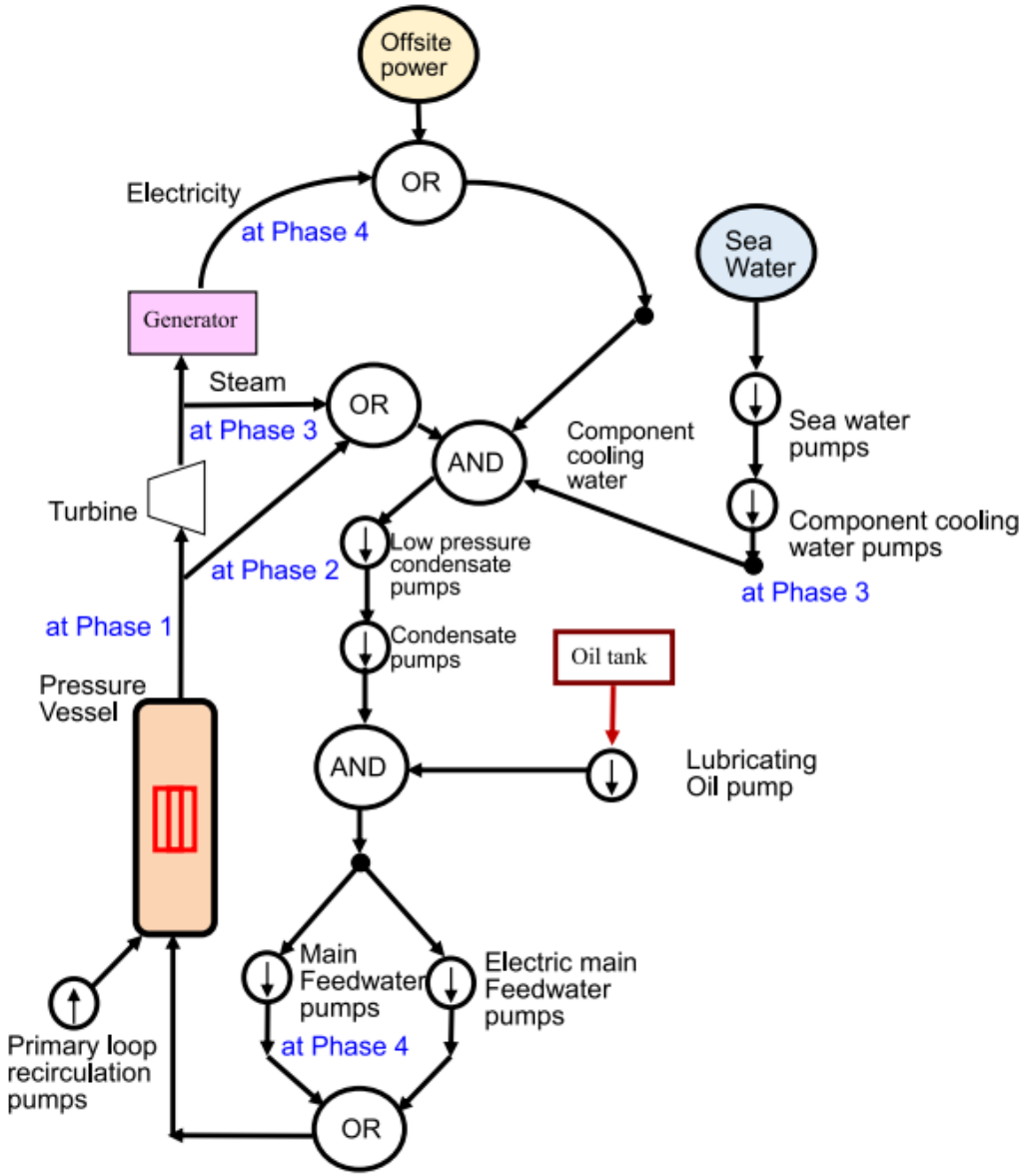


Fig. 2. Topological relation of a BWR plant system.

Phase 4

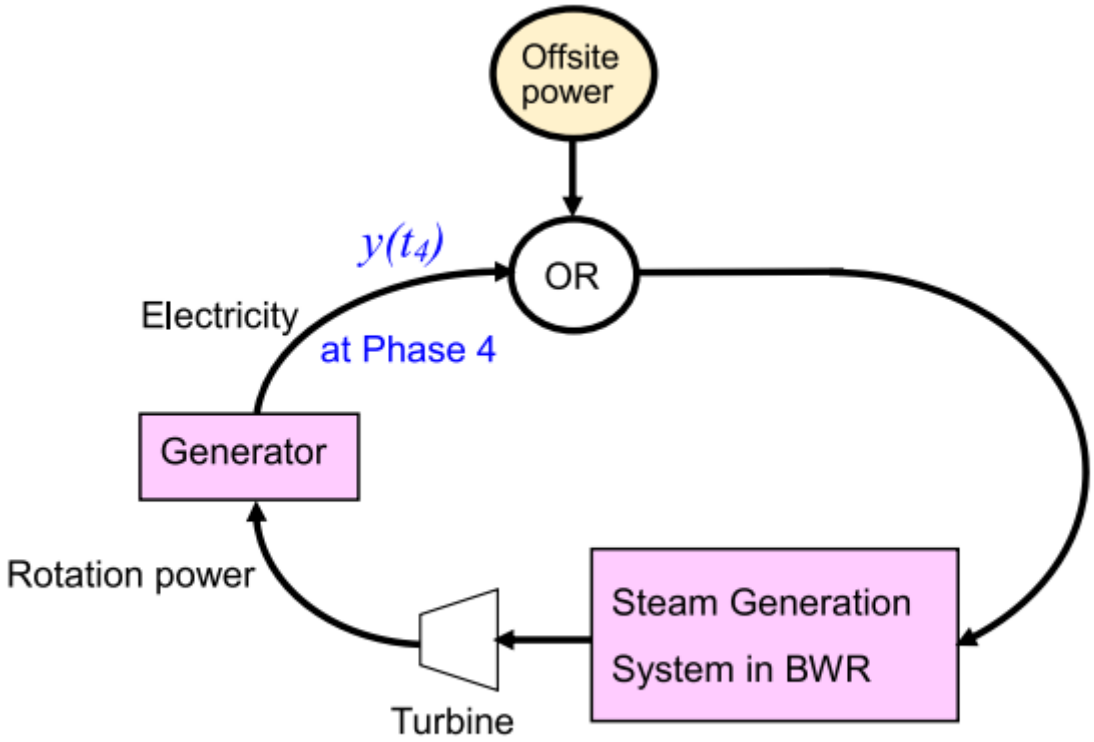


Fig. 8. Operating state at phase 4.

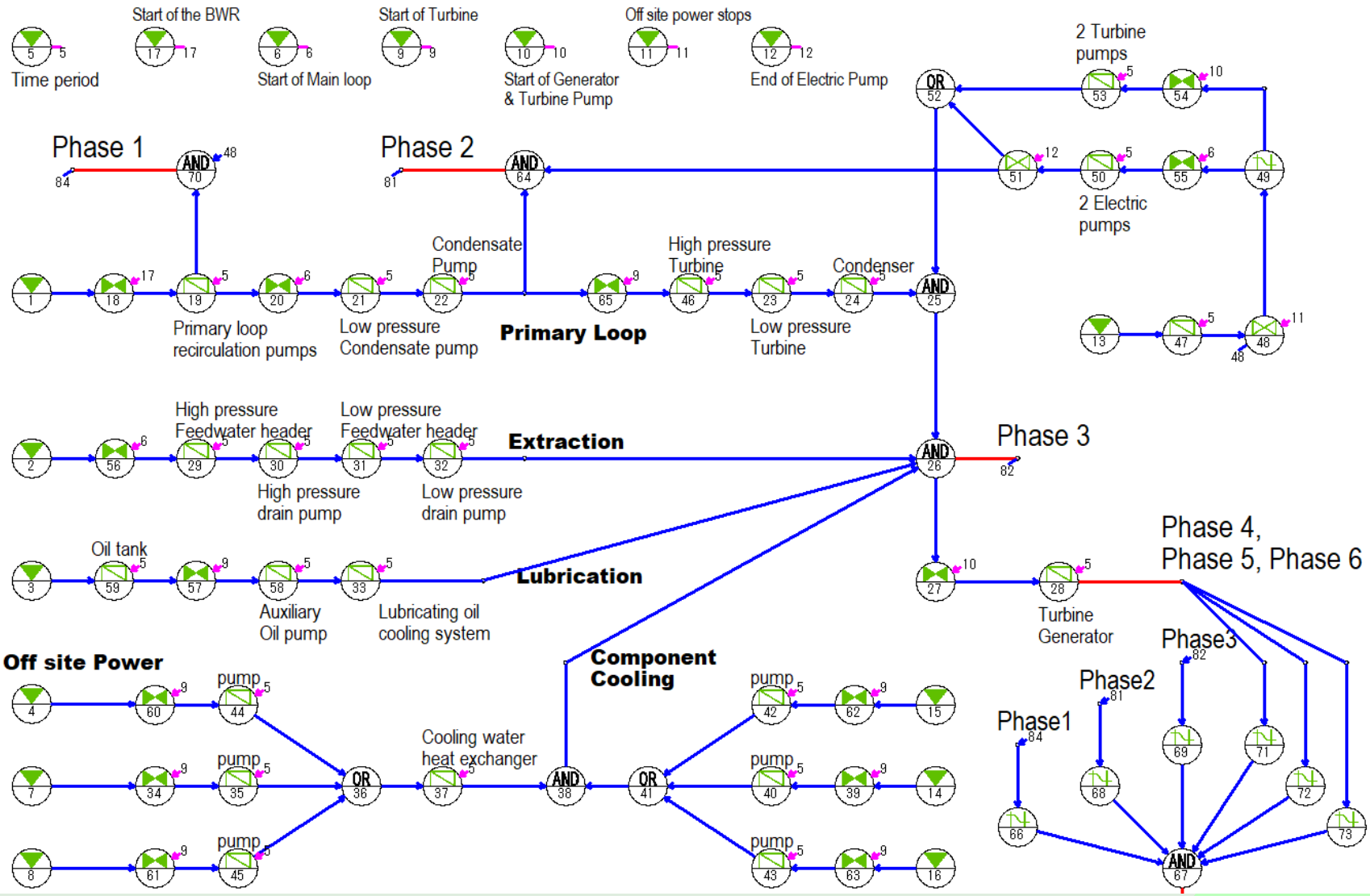
$$y(t_4) = \{OSP(t_4) + y(t_4)\} \cdot SGS(t_4) \cdot TRB(t_4) \cdot GEN(t_4)$$

$$y(t_4) = OSP(\tau_4) \cdot SGS(t_4) \cdot TRB(t_4) \cdot GEN(t_4)$$

Mechanism of establishing a loop operation

- A SS-type(Self Sustained type) component preexists and acts as a starting point of operations of series of components along loop line.
- After the loop is closed, the role of the SS-type component finishes and leaves its vestige or disappears.
- If a SS-type component is outside of the loop structure, the vestige is left as a fixed value of a SS-type component's reliability or availability at the time that loop structure is established.
- If a SS-type component belongs to a loop structure, no vestige is left.

Modeling into GO-FLOW chart



analysis results

Phase	0	1	2		3		4			5		6				
time(hour)		0	6	22	22	25	25	32	33	33	35	35	72	720	2160	8760
Mission	Preparation	Steam	Main feed water		Turbine operation		Electricity generation			Electricity generation		Electricity generation				
Success Probability	0	0.99927	0.997805	0.997771	0.995510	0.995485	0.996113	0.996056	0.996048	0.996048	0.996032	0.995295	0.994961	0.989117	0.976253	0.938039
Successive mission success probability	0	0.99927	0.997804	0.997771	0.995509	0.995485	0.995385	0.995329	0.995321	0.995321	0.995305	0.994568	0.994234	0.988394	0.975540	0.937354

Analysis results

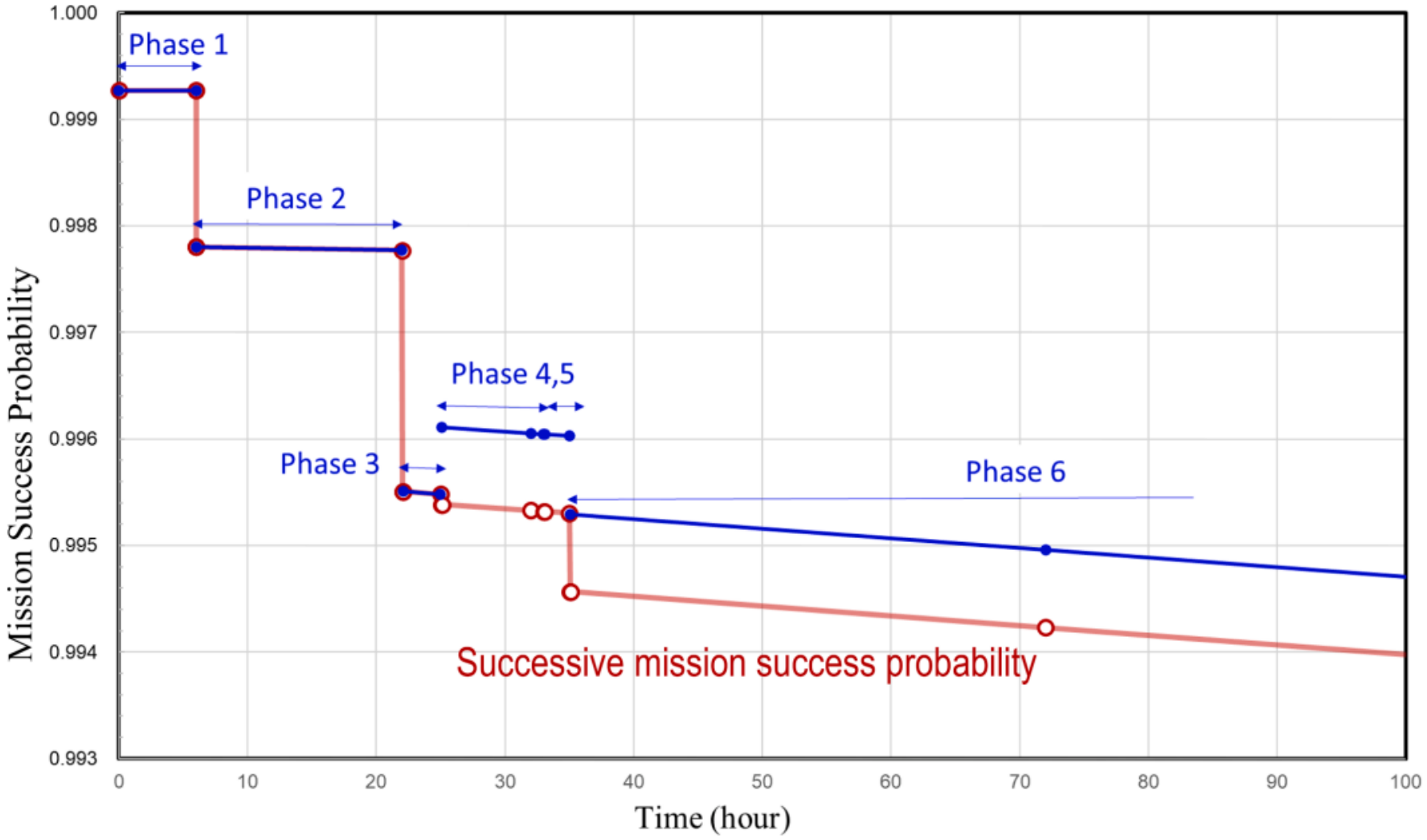


Fig. 12. Mission success probability for phases 1 to 6.

Summary

- Review the methods to solve the phased mission systems (PMSs).
- Existing methodologies can be categorized into two types:
  - Simulation-based methods
  - Analytical methods :
    - (1) combinatorial methods
    - (2) state-space model-based methods
    - (3) the modular method
- Review the approach to analyze logical loop structure.
- The difficulty is shown for reliability analysis of PMS with loop structures.
- As a real engineering system, BWR nuclear power plant system has been taken up and analysis has been performed for startup stage.

Summary (continue)

- How the GO-FLOW methodology performs reliability analyses in considering logical loop structure and phased mission problem.
- The system has been modeled on a GO-FLOW chart. The chart suggests a way to model logical loop relations in a diagram without loop structure.
- It has been also shown that phased mission problem is adequately treated by using type 40 operators.
- Both the logic of loop structures and the logic of PMS have been modeled on the same GO-FLOW chart. This allows PMS with loop structures to be easily solved.
- The proposed modeling method for logical loop structure and phased mission problem is applicable to any engineering systems.
- The method is particularly useful in evaluating reliability and/or availability of large complex engineering systems.

Thank you for your kind attention !