Availability Analysis of Heliotron J Water-cooling System by the GO-FLOW methodology

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Abstract: Heliotron J is a magnetically confined fusion research device, designed to study high temperature plasma confinement. It is located at the Institute of Advanced Energy, Kyoto University. The first plasma has been produced in 1999. For the successful operation of the system, availability of the water-cooling systems in the Heliotron J is essential matter. Reliability/availability analysis of the cooling systems have been performed by the GO-FLOW methodology for possible maintenance schedules and methods. There are so many components in the cooling systems, and it is very difficult to maintain all the components at every year. Components are divided into multiple groups. Important active components are checked and repaired every year. Less important components are checked once every two years. Some components are not subjected to maintenance. Failure rates of components are assigned based on the operational records of Heliotron J. Also, the data shown in nuclear industry are referred. The water-cooling system is modeled into GO-FLOW chart and failure data and analysis conditions are given to this chart. Analyses are performed for different maintenance schedules. Analysis results could be utilized for the decision of the strategy of maintenance schedule and method.

Keywords: Availability Analysis, Maintenance schedule, GO-FLOW, Risk Informed decision.

1. INTRODUCTION

Heliotron J is a magnetically confined fusion research device, specifically with a helical axis heliotron magnetic configuration designed to study high temperature plasma confinement. It is located at the Institute of Advanced Energy, Kyoto University. The first plasma has been produced in 1999. The purpose of the device is to demonstrate its improved helical confinement property in the helical axis heliotron line [1].

Experiments by Heliotron J are continuously performed during half year and rest of the period is used for the maintenance of the system. For the successful operation of the system, availability of the water-cooling systems in the Heliotron J is essential matter. Reliability/availability analysis of the cooling systems have been performed by the GO-FLOW methodology [2] for possible maintenance schedules and methods.

There are so many components in the cooling systems, and it is very difficult to maintain all the components at every year. Components are divided into multiple groups. Important components as Heliotron main part are checked and repaired every year. Other main components are maintained once every two years in some cases. Less important components as passive components like tanks, pipes are not subjected to maintenance. Modeling of the effects of different maintenance method is considered in this study. One is the perfect maintenance; after the repair, components become as good as new. Less perfect maintenance is applied only to the phenomena for operating failure mode.

Failure rates of components are assigned based on the operational records of Heliotron J. Also, the data shown in nuclear industry [3], [4], [5] are referred.

The water-cooling system is modeled into GO-FLOW chart and failure data and analysis conditions are given to this chart. The GO-FLOW can analyze time dependent availability by one GO-FLOW chart with a single calculation [2]. Analyses are performed for different maintenance schedules. Analysis results could be utilized for the decision of the strategy of maintenance schedule and method.

2. WATER-COOLING SYSTEM

2.1. System Configuration

The following two diagrams can be created as a configuration diagram with the main equipment taken from the water-cooling system design drawings kept at the Institute of Advanced Energy, Kyoto University.

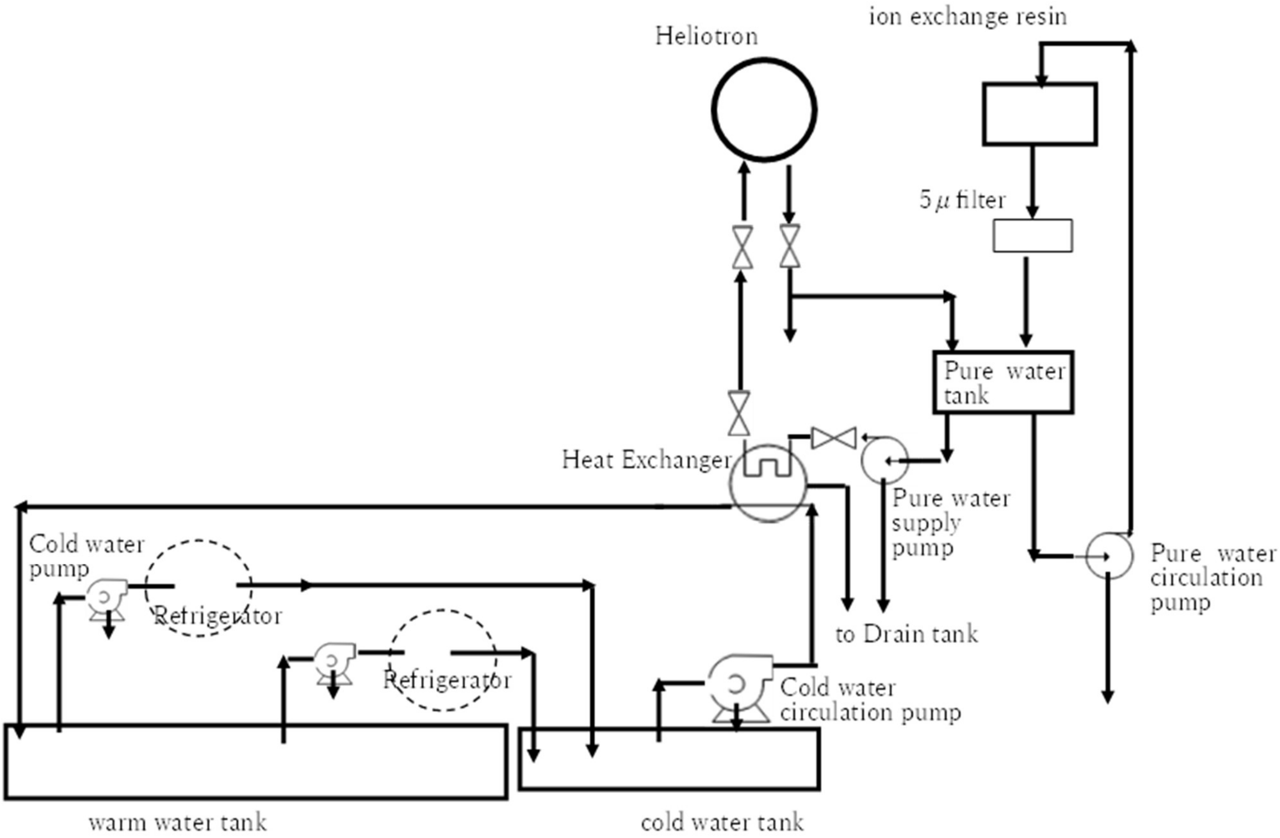

Figure 1. Heliotron J Water-cooling system Part 1

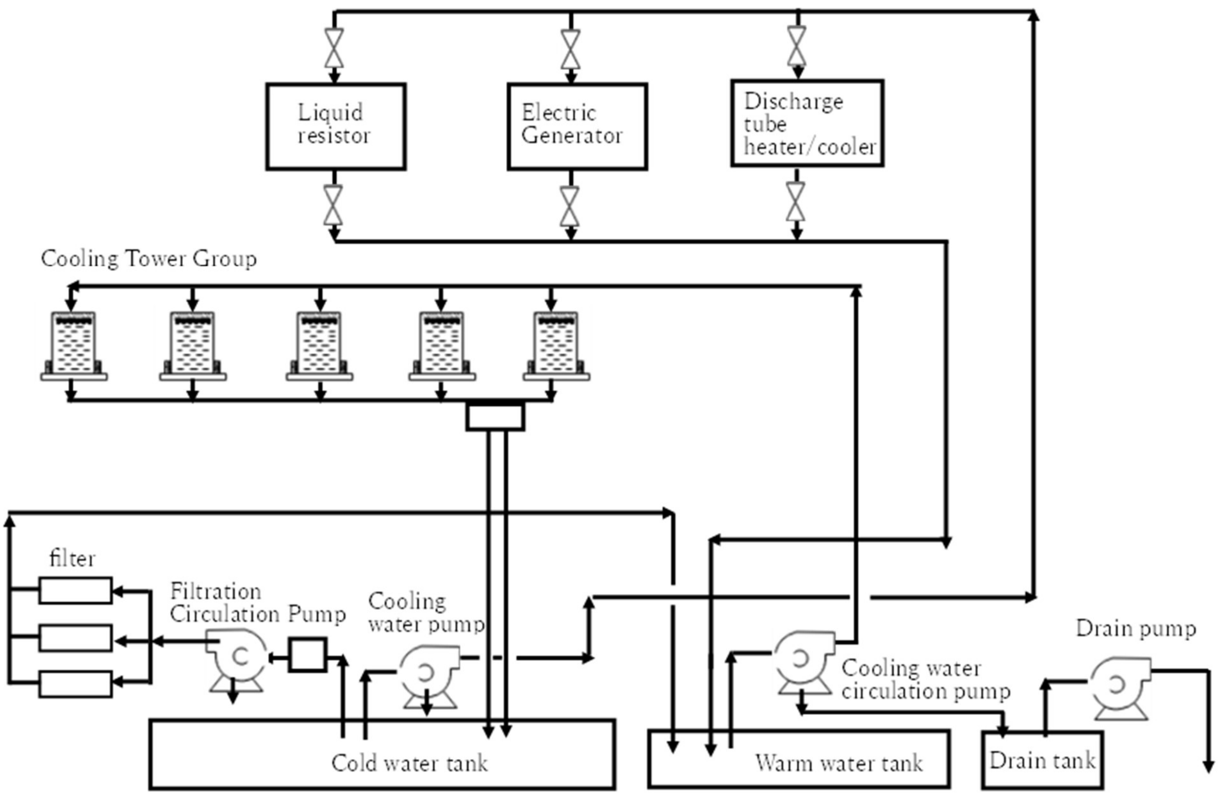

Figure 2. Heliotron J Water-cooling system Part 2.

2.2. System Operational schedule

Since 1999, the system has been in operation for 24 years (with a few years of inactivity), so the actual operating time is about 20 years. The experiment was conducted for approximately 6 months per year, 28 hours operation per week, about 5hours per day.

The annual operating hours would be 28h/week x 6 months = 28x26 weeks = 728h/year. Hence, the total operating time is 14,560 hours. The elapsed time for the facility is 24x365x23 = 201,480 hours.

2.3. Actual Maintenances and Inspections Performed on this System

Inspection is performed basically once a year during the period when the experiment is not conducted. There are so many components in the system, so not all the components are maintained every year.

There are 17 pumps, and they are disassembled and made adjustment every year. Water circulating pump for vacuum system is checked for rust, water leak and unusual noise. Drain pump is placed in water and no maintenance is made. Cooling towers are cleaned up every year. Rubber degradation and pipe rust are checked. Refrigerators are checked every year. Filters are also exchanged every year, and no special care is made. Valves are not touched and left as it is. Especially large valve in cooling water system for electric generator has large diameter pipe and hand-wound coil, and it is difficult for maintenance. Heat exchangers are not maintained for 10 years.

2.4. Failure Data

Failure rates of components are assigned based on the operational records of Heliotron J. Also, the data shown in nuclear industry are referred [3], [4]. Uncertainty ranges for failure rates are estimated based on the error factors given in the Reactor Safety Study [5].

The total operating time is 14,560 hours and no failure has occurred in the 17 pumps installed during that time, the failure rate during pump operation is 1÷ (17x 14,560) = 4.04×10^{-6}/h or less.
Since the total elapsed time is 201,480 hours, the standby failure rate during that time is obtained with the same consideration, 1÷ (17x 201,480) = 2.9×10^{-7}/h or less. There is an adjustment for water leakage from the pump bearings about once a year. The probability of failure will be about 1÷ (17x8,760) =6.7×10^{-6}/h.

Two cooling towers experienced water leaks. The total elapsed time is 201,480 hours, so the standby failure rate during that time will be about, 2÷ (5x201,480) = 2×10^{-6}/h. Once it did not start due to electricity. Demand failure could be estimated from this case.

Failure rates are set as shown in table 1, based on above experienced data and other industrial data, mainly in nuclear field [3], [4],[5].

Table 1. Failure rates set in the analysis.

Components	Failure mode	Failure rates	Remarks
Heliotron main part	Operating failure	2.0×10^{-6}/h	
	Standby failure	2.0×10^{-7}/h	
Pump, Refrigerator, Cooling tower, Liquid resistor, Electric Generator, Discharge tube heater/cooler	Demand failure	1.0×10^{-3}/D	not take into account
	Operating failure	1.0×10^{-6}/h	
	Standby failure	1.0×10^{-7}/h	
Valve	Operating failure	2.0×10^{-7}/h	
	Standby failure	2.0×10^{-8}/h	
Filter	Standby failure	2.0×10^{-8}/h	
Tank and other components	Deterioration over time (aging)	2.8×10^{-8}/h	

Figure 3 shows a comparison of failure rates between the values estimated in this analysis (orange color sticks) and the values used in other analyses (green and blue sticks) [6],[7],[8]. Filled color sticks correspond to operating failures and sticks with diagonal lines correspond to standby failures.

Values for other analyses are based on values from the nuclear industry. The components used in the Heliotron J system is smaller than the major components used in nuclear power plants. Then, smaller values are set for operational failures in this analysis.

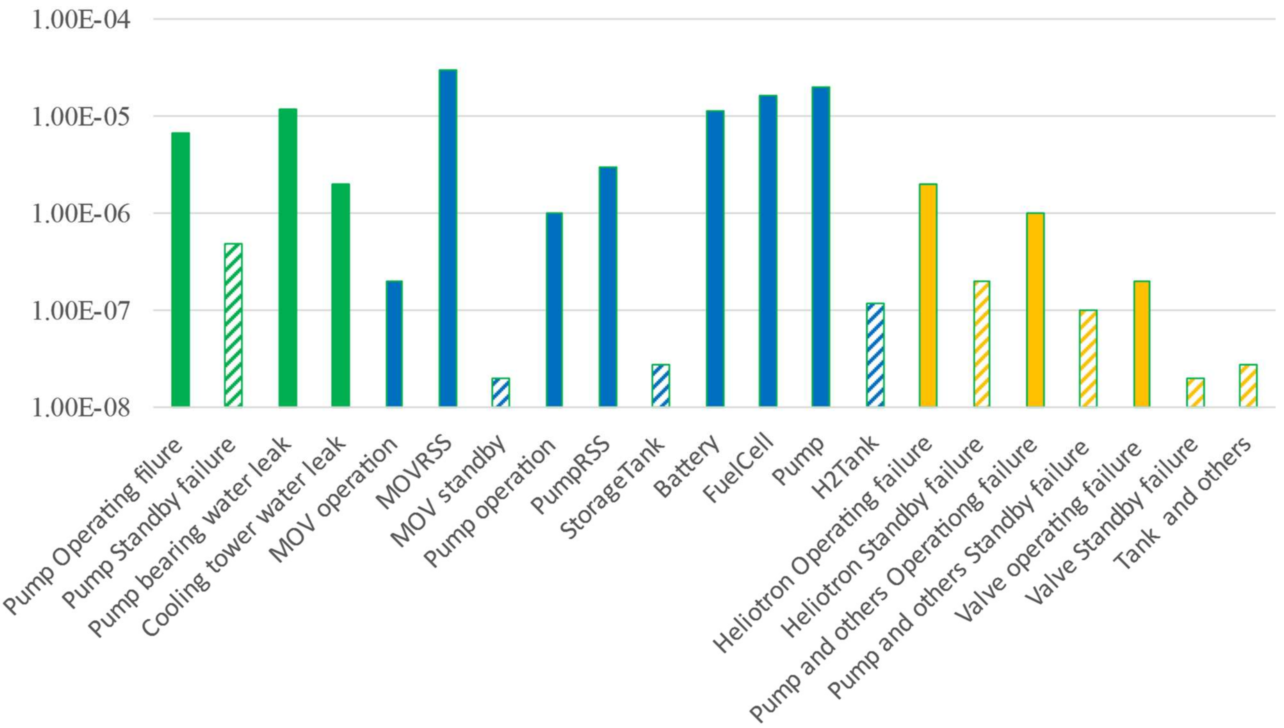

Figure 3. Failure rates comparison between this analysis and other analyses

3. MODELING BY THE GO-FLOW METHODOLOGY

3.1. OVERVIEW OF THE GO-FLOW METHODOLOGY

GO-FLOW [2] is a success-oriented system analysis technique that is capable to evaluate reliability and/or availability of the systems with complex time-sequence and phased-mission problems. The GO-FLOW method can also deal with common cause failure (CCF) analysis with uncertainty [9]. The modeling technique produces a chart which consists of signal lines and operators and represents the engineering function of the components/subsystems/system [2].

The GO-FLOW operators model function or failure of the physical equipment, logical gates, and signal transmissions. Generally, three types of signals are connected to an operator: main input signal(s) S, sub input signal(s) P, and an output signal R. Each operator has a logic for combining the inputs properly and producing the output. Specific probability (point estimates) of component operation or failure are given to operators as input data. Currently 14 operators are defined.

Signals represent some physical quantities or information. A signal line between two operators transmits a physical quantity or information in the direction of the arrow of the signal line. A quantity called “intensity” is associated with a signal. In general, the intensity indicates the probability that a signal is present. The existence of a signal is interpreted as the actual or potential existence of a signal. “Potential existence” means that a signal presents when all downstream resistances are eliminated. When a signal is used as a sub-input signal of the type-35, -37 and -38 operators, the intensity represents the time interval between successive time points.

A finite number of discrete time values (points) are required to express the system operational sequence. The value does not necessarily represent real time but corresponds to it and represents an ordering [2].

- **Common Cause Failure**

In GO-FLOW analysis, the Common Cause Failure (CCF) is treated by parametric model (α-factor model, β-factor model, MGL (Multiple Greek Letter) model and/or BFR (Binomial Failure Rate) model) [9]. Designate a component group for a specific common cause when creating the GO-FLOW chart. Assigning multiple CCF groups to a single GO-FLOW chart is possible. Then, provide the values for the parametric model of CCF.

The first step of the analysis is to construct a GO-FLOW chart, which is the model of the engineering system under consideration. An analyst interactively constructs a chart on a PC display with the support of the GO-FLOW chart editor as shown in Fig. 4.

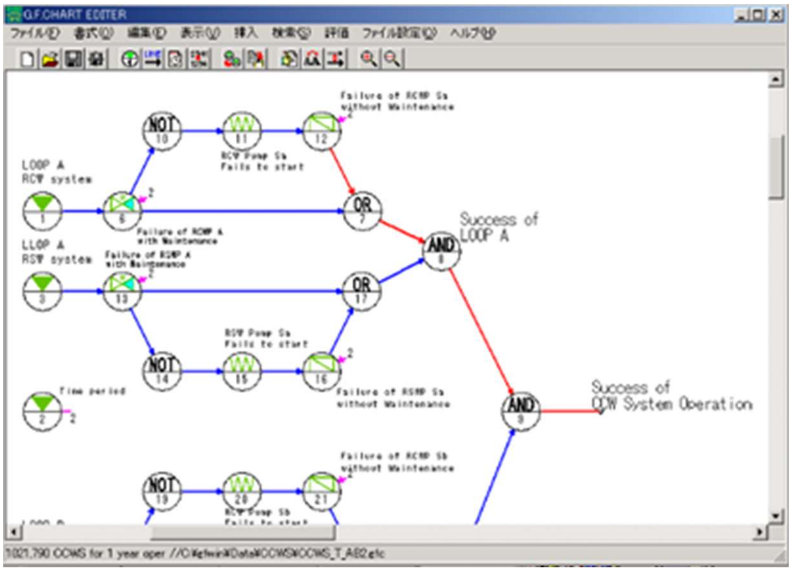

Figure 4. GO-FLOW chart editor.

The GO-FLOW chart is simple to construct and validate due to its consistency with the P&I diagram or process flow diagram of the engineering system under consideration. It's easy to make changes and updates to a GO-FLOW chart. The GO-FLOW has the ability to assess reliability/availability over time with just one calculation, while Fault Tree Analysis (FTA) only provides reliability/availability at one specific time. These are superior to FTA, and the present analysis is conducted only using the GO-FLOW methodology.

When building a chart, component failure data, including CCF data if required, and analysis conditions are provided. The GO-FLOW model analysis is performed from upstream to downstream along the signal lines. In most cases, only one or a few defined signals are of interest. These signal lines are called "final signals" and indicated by red color as seen in Fig. 4. An analysis is performed by one GO-FLOW chart with a single calculation on the GO-FLOW chart editor.

3.2. GO-FLOW Chart

The GO-FLOW chart has been made as shown in figure 5. Specific probabilities (point estimates) of component's operation or failure are given to operators as input data.

In this GO-FLOW chart, operator No.6 (signal generator) gives time intervals between successive time points and defines elapsed time of this Heliotron J system. Operators No.2 and 3 (signal generators) give elapsed time of system operation and standby state, respectively. Operators No.4 and 5 (signal generators) give information for maintenance activities. Operator No.10 (signal generators) gives start signal for the system operation and No.11 (signal generators) gives stop signal. Operators No.1,7, 8 and 9 are signal generators and give signal intensity of 1.0 at all the time points. They give possibility of perfect working condition for the components or sub system placed downstream. Other operators represent failure phenomena of components or logical combinations, AND or OR.

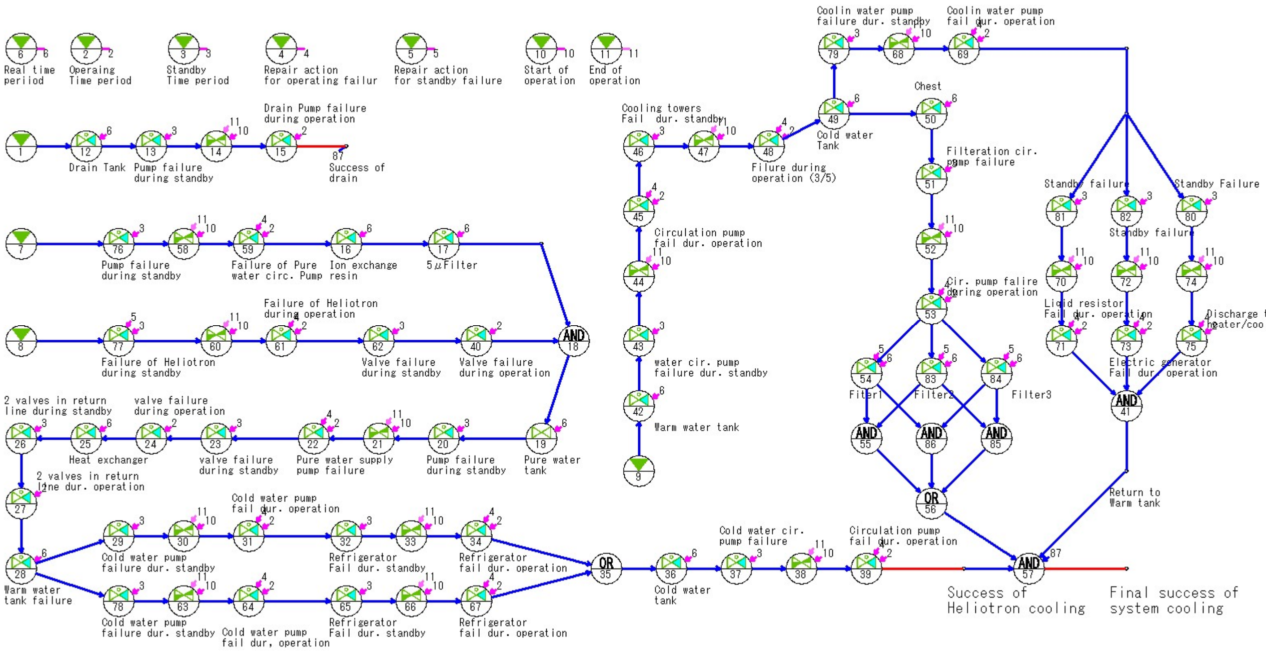

Figure 5. GO-FLOW chart of the Heliotron J Water-cooling system.

3.3. Maintenance Planning

Maintenance actions are set as sown in table 2. Base case is deduced from the actual maintenance activities performed in the Heliotron J.

Operating failure is a failure which occurs when the component is in operation, and it is usually easy to detect and to identify its cause. The maintenance activity for preventing the occurrence of operating failure is relatively clear and formalized. On the other hand, standby failure is a failure which occurs when the component is left motionless, and it is usually heard to identify its cause. Causes may include material denaturation, deterioration, oxidation, and corrosion. The maintenance activity for preventing the occurrence of standby failure is difficult. Most effective method is replacing a component by new one, but some components are non-replaceable.

Table 2. Repair actions for the components.

Components	Failure mode	Base case	Case A	Case B	Case C	Case D
Heliotron main part	Operating failure	O	O	O	O	O
	Standby failure	O	O	O	O	O
Pump	Operating failure	O	O	(O)	(O)	(O)
	Standby failure	-	O	(O)	(O)	-
Refrigerator	Operating failure	O	O	O	(O)	(O)
	Standby failure	-	O	O	(O)	-
Liquid resistor	Operating failure	O	O	(O)	(O)	(O)
	Standby failure	-	O	(O)	(O)	-
Electric Generator	Operating failure	O	O	O	(O)	(O)
	Standby failure	-	O	O	(O)	-
Discharge tube heater/cooler	Operating failure	O	O	(O)	(O)	(O)
	Standby failure	-	-	-	-	-
Valve	Operating failure	-	O	(O)	(O)	-
	Standby failure	-	-	-	-	-
Cooling Tower	Operating failure	O	O	O	O	O
	Standby failure	-	O	O	-	-
Filter	Standby failure	O	O	O	O	O
Tank and other components	Deterioration over time (aging)	-	-	-	-	-

Most important part in the system is “Heliotron main part”, and maintenance should be carefully made. It is set that maintenance actions are made for both “operating failure” and “standby failure”. In table 2, the mark “O” indicates maintenance action is made. It is assumed, after the maintenance, components become as good as new. In “base case”, other components are only maintained for operating failure, especially, valves and tanks are not subjected to maintenance.

In “Case A”, almost all the components are carefully maintained. This is a difficult task and not very realistic. In “Case B”, some components are maintained once every two years (indicated by “(O)” in table 2). In “Case C”, almost all the components are maintained once every two years. In “Case D”, it is shown a simplified maintenance schedule deduced from base case. Almost all the components are maintained once every two years as shown in table 2.

3.4. Time Points

In the GO-FLOW analysis, it is possible to analyze system operational sequence by defining a finite number of discrete time values (points). In this analysis, time points are defined as shown in table 3. In the table, it is also shown actual time durations, “start” and “end” signals and repair actions (negative values are used for cancelling elapsed time).

Table 3. Time Points defined in the Analysis.

Time point	meaning	month/day (weeks)	elapsed time	Operation time	Sandby time	Start of Operation	End of Operaion	Repair for operating Failure	Repair for standby Failure
1	**First year**	! (1/1)	0	0	0				
2		4/1(13weeks)	2160	0	2160				
3	start of operation	4/1(13weeks)	2160	0	2160	1			
4		9 /30(40weeks)	6552	728	5824				
5	end of operation	9 /30(40weeks)	6552	728	5824		1		
6	repair	10/1(41weeks)	6576	0	5848			-728	-5848
7	**Seconf year**	! (1/1)	8760	0	8032				
8		4/1(13weeks)	10920	0	10192				
9	start of operation	4/1(13weeks)	10920	0	10192	1			
10		9 /30(40weeks)	15312	728	13856				
11	end of operation	9 /30(40weeks)	15312	728	13856		1		
12	repair	10/1(41weeks)	15336	0	13880			-728	-8032
13	**Third year**	! (1/1)	17520	0	16064				
14		4/1(13weeks)	19680	0	18224				
15	start of operation	4/1(13weeks)	19680	0	18224	1			
16		9 /30(40weeks)	24072	728	21888				
17	end of operation	9 /30(40weeks)	24072	728	21888		1		
18	repair	10/1(41weeks)	24096	0	21912			-728	-8032
19	**4th year**	! (1/1)	26280	0	24096				
20		4/1(13weeks)	28440	0	26256				
21	start of operation	4/1(13weeks)	28440	0	26256	1			
22		9 /30(40weeks)	32832	728	29920				
23	end of operation	9 /30(40weeks)	32832	728	29920		1		
24	repair	10/1(41weeks)	32856	0	29944			-728	-8032
25	**5th year**	! (1/1)	35040	0	32128				
26		4/1(13weeks)	37200	0	34288				
27	start of operation	4/1(13weeks)	37200	0	34288	1			
28		9 /30(40weeks)	41592	728	37952				
29	end of operation	9 /30(40weeks)	41592	728	37952		1		
30	repair	10/1(41weeks)	41616	0	37976			-728	-8032
31	**6th year**	! (1/1)	43800	0	40160				
32		4/1(13weeks)	45960	0	42320				
33	start of operation	4/1(13weeks)	45960	0	42320	1			
34		9 /30(40weeks)	50352	728	45984				
35	end of operation	9 /30(40weeks)	50352	728	45984		1		
36	repair	10/1(41weeks)	50376	0	46008			-728	-8032
37	**End of 6th year**	12・31(52weeks)	52560	0	48192				

4. ANALYSIS RESULTS

Analysis results by the GO-FLOW methodology are shown in Figure 6. Availabilities of Heliotron J for base case and cases A to D are shown.

Experiments are performed in daytime, and the system is shut down during nighttime, So, in fact, over a six-month period, availability takes the form of a series of fine comb teeth. To simplify display and analysis, the fine comb teeth is omitted, and the envelope of the maximum value is shown.

“Base case” is close to the maintenance schedule that is actually implemented. Availability shows a clear decline over the six years analyzed. In Case A, careful maintenance is performed for almost all the components as shown in Table 3. Very good availabilities are obtained over the six years, but this maintenance method is extremely time-consuming, difficult to implement, and impractical.

In case B, some components are divided into two groups and maintenance is performed on an alternating schedule once every two years. In Case C, almost all the components are maintained once every two years.

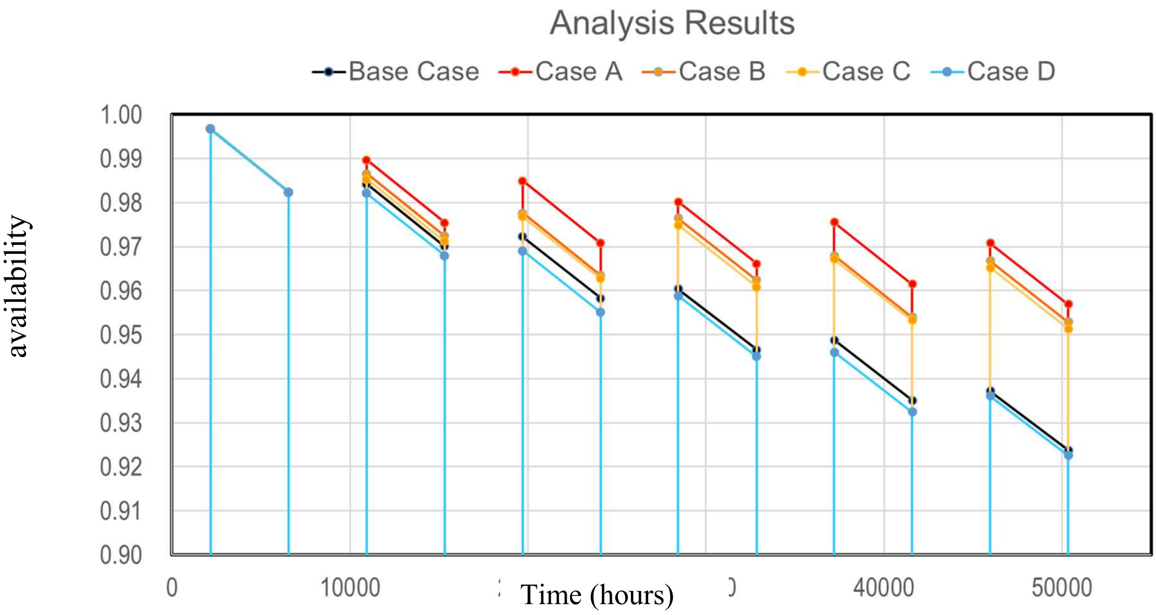

Figure 6. Availability of the Heliotron J Water-cooling system.

Cases B and C show almost the same availability over the six years, and they are close to Case A. It can be said that Case C is a relatively effective maintenance plan with little effort.

In Case D, “Base case” schedule is more simplified and almost all the components are maintained once every two years. The availability is very close to the one for “Base case”. Case D is the method that requires the least amount of effort, but it is reasonably effective. However, it would not be appropriate to adopt it as a maintenance plan.

5. CONCLUSION

Availability analysis of the Heliotron J water cooling system, which plays an important role in the operation of Heliotron J, was performed using the GO-FLOW methodology.

Analysis results shows that a relatively high level of availability can be achieved by dividing almost all the components into two groups, and they are carefully inspected and repaired on an alternating schedule once every two years (in Case C). The maintenance plan for Heliotron J can be determined based on the results of this analysis.

As the modelling and analysis framework by this GO-FLOW chart has been established, analysis of other cases with different maintenance conditions can be easily performed. The failure rate set at the present analysis can also be easily changed.

Additions of components and changes of system configuration can be easily handled by modifying the existing GO-FLOW chart.

The GO-FLOW analysis is expected to be applied for further detailed analysis conditions, for example, uncertainty analysis, graded recovery and so on.

Acknowledgements

This work was supported by the "Joint Usage/Research Program on Zero-Emission Energy Research, Institute of Advanced Energy, Kyoto University (ZE2023B-29).

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