

# Availability Analysis of Heliotron J by the GO-FLOW methodology with AI Technologies

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**Abstract**— Heliotron J is a device to obtain fundamental knowledge for the realization of nuclear fusion. It is located at the Institute of Advanced Energy, Kyoto University. For the successful operation of the Heliotron J, availability of the water-cooling systems is essential matter. Reliability/availability analysis of the cooling systems have been performed by the GO-FLOW methodology for possible maintenance schedules and methods. The analysis has been conducted by using AI technologies. Higher harmonic diagnostic technology has been also used for evaluating the present status of electrical components. It is possible to determine the degree of deterioration. Analysis results could be utilized for the decision of the strategy of maintenance schedule and method. Further sophistication and improvements of analysis framework is planned by using AI technologies.

**Keywords**— fusion research device, availability, GO-FLOW, maintenance, Chat GPT, Higher harmonic diagnostic technology

## I. INTRODUCTION

Heliotron J is a device to obtain fundamental knowledge for the realization of nuclear fusion. It 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 [1].

For the successful operation of the Heliotron J, availability of the water-cooling systems in the system is essential matter. Reliability/availability analysis of the cooling systems has been performed by the GO-FLOW methodology [2] for possible maintenance schedules and methods. The analysis has been conducted by using AI technologies.

Various modeling methods of the maintenance effects are suggested, which are surveyed by AI technology. One is the perfect maintenance; after the repair, components become as good as new. Less perfect maintenance model is also applied for some components.

Higher harmonic diagnostic technology [3] has been used for evaluating the present status of electrical components. The information is possible to utilize in the GO-FLOW analysis. The improvement of the diagnosis is expected by machine learning technology or image diagnosis technology for analog waveforms. These are future research subjects.

Failure rates of components are assigned based on the operational records of Heliotron J. Also, the data shown in nuclear industry [4], [5], [6] are referred.

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

## II. HELIOTRON J AND WATER COOLING SYSTEM

### A. Heliotron J

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.

### B. Water Cooling System

For the successful operation of the Heliotron J, availability of the water-cooling systems in the system is essential matter. The Figs. 1 and 2 are 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.

### C. System Operational Schedule

Since 1999, the system has been in operation for 26 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 5 hours per day.

The annual operating hours would be  $28\text{h/week} \times 6\text{ months} = 28 \times 26\text{ weeks} = 728\text{h/year}$ . Hence, the total operating time is 14,560 hours. The elapsed time for the facility is  $24 \times 365 \times 23 = 201,480\text{ hours}$ .

### D. Actual Maintenances and Inspections Performed on this System

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

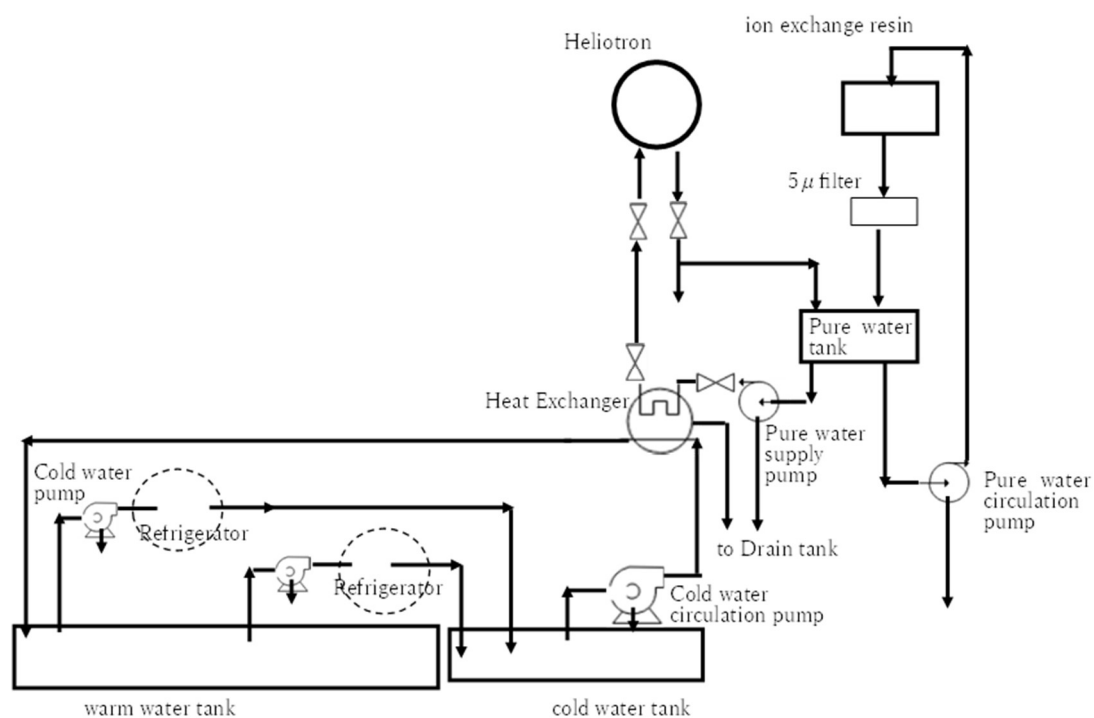


Fig. 1. Heliotron J Water-cooling system Part 1

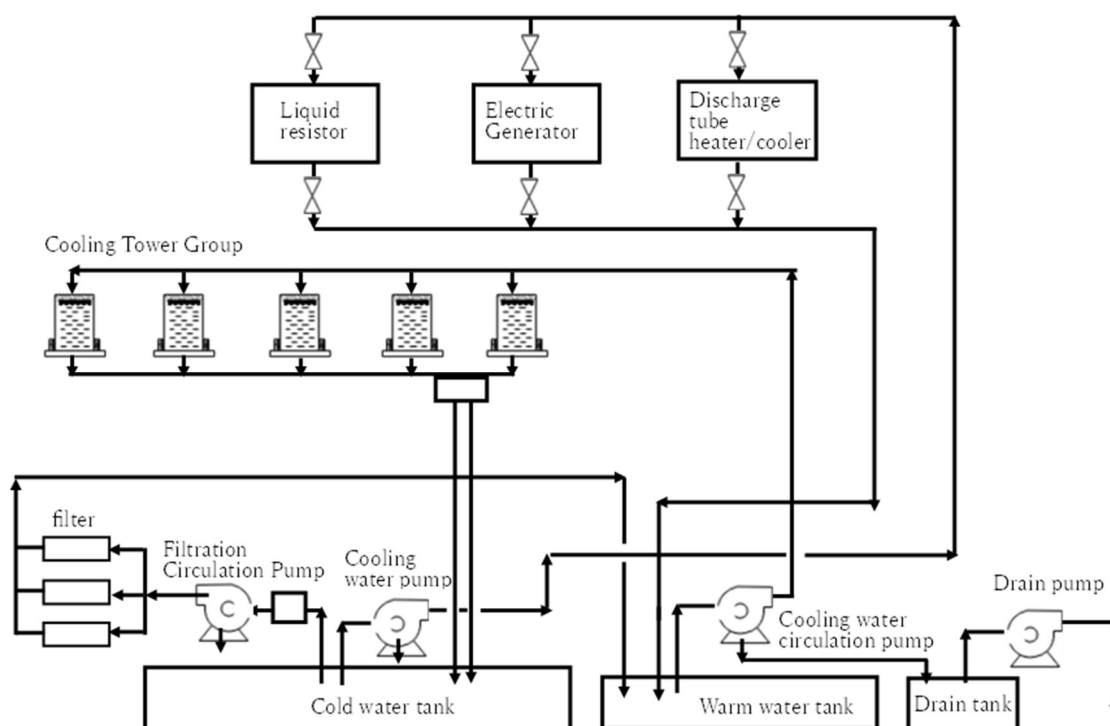


Fig. 2. Heliotron J Water-cooling system Part 2

components as Heliotron J 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.

Inspection is performed basically once a year during the period when the experiment is not conducted. 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.

### III. HIGHER HARMONIC DIAGNOSTIC TECHNOLOGY

The higher harmonic diagnosis system is a sort of condition monitoring system that uses higher harmonics element in the electric current running through the electric devise. It measures superimposed harmonics by measuring the leakage magnetic flux of the equipment's power cable using a search coil [3].

The data from more than 10,000 electrical devices was collected for over 10 years. As a result of disassembling the failed machines to verify the cause, location and the degree of deterioration of equipment failures from the tendency of the rise of higher harmonics. It is the condition diagnosis of equipment based on "statistical data analysis".

The technique is non-contact and uses live wires, so there is no need to stop the equipment. In addition, the measurement points are terminals on the control panel, making it safe and easy to diagnose submersible pumps, ceiling fans, etc.

It is possible to determine the degree of deterioration from measured data. For example, the bearing on the anti-load side had deteriorated 80% or higher, and it was necessary to inject grease into the bearing. The information is possible to utilize in the GO-FLOW analysis.

The improvement of the diagnosis accuracy is expected by machine learning technology or image diagnosis technology for detected analog waveforms. These are future research subjects.

### IV. 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 [4],[5]. Uncertainty ranges for failure rates are estimated based on the error factors given in the Reactor Safety Study [6].

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  $1 \div (17 \times 14,560) = 4.04 \times 10^{-6}/h$  or less.

Since the total elapsed time is 201,480 hours, the standby failure rate during that time is obtained with the same consideration,  $1 \div (17 \times 201,480) = 2.9 \times 10^{-7}/h$  or less. There is an adjustment for water leakage from the pump bearings about once a year. The probability of failure will be about  $1 \div (17 \times 8,760) = 6.7 \times 10^{-6}/h$ .

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,  $2 \div (5 \times 201,480) = 2 \times 10^{-6}/h$ . 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 [4],[5],[6]. 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.

TABLE I. FAILURE RATES SET IN THE ANALYSIS.

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

### V. MODELING BY THE GO-FLOW METHODOLOGY

#### A. 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 [7]. The GO-FLOW method can also deal with common cause failure (CCF) analysis with uncertainty [8]. A loop structured system can be modeled into GO-FLOW [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].

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.

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].

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 figure 3.

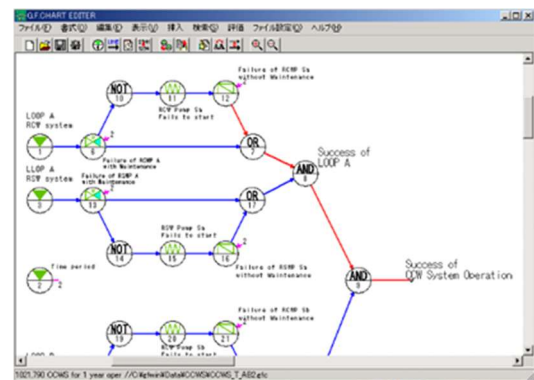


Fig. 3. GO-FLOW chart editor.

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. An analysis is performed by one GO-FLOW chart with a single calculation on the GO-FLOW chart editor.

### B. Support by Chat GPT

Chat GPT Plus has been utilized to assist in modeling the system to the chart. As the analysis target system is complex, the entire framework structure can be created as a starting point for modeling work.

It provides information on system structure, connectivity, operating conditions, and operating schedules. It also provides information on target equipment for maintenance and inspection, schedule information, as well as failure rate data for each piece of equipment and past failure history.

Under these conditions, Chat GPT returns a series of equations to calculate the availability of the system. After a careful examination of the contents and repeated exchanges to obtain a satisfactory formula, the actual calculations were requested, and the results could be graphed.

It is expected to point out errors and omissions during the modeling process. But, Reliability block diagram or GO-FLOW chart could not be still obtained by the Chat GPT.

Also the Chat GPT has suggested us various modeling methods of the maintenance effects. They are parametric imperfect repair model [10], renewal process model [11], Brown-Proshan model [12]. They are useful information for future analyses. In the present study, perfect maintenance is applied, that is, after the repair, components become as good as new. For some components, as valves or pipes, maintenance effects are only considered for operating failure mode. It is a kind of imperfect maintenance.

### C. Maintenance Planning

Maintenance actions are set as shown 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 hard 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..

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. 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.

TABLE II. REPAIR ACTIONS FOR THE COMPONENTS.

Components	Failure Mode	Base case	A	B	C	D
Heliotron main part	Operating failure	O	O	O	O	O
	Standby failure	O	O	O	O	O
Pump, Liquid resistor	Operating failure	O	O	(O)	(O)	(O)
	Standby failure		O	(O)	(O)	
Refrigerator, 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 Other components	Deterioration over time (aging)					

### D. GO-FLOW Chart

The GO-FLOW chart has been made as shown in figure 4. 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..

## VI. ANALYSIS RESULTS

Analysis results by the GO-FLOW methodology are shown in Figure 5. 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 2.

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..

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.

## VII. 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 with the support of AI technologies.

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 more sophisticated analysis conditions, for example, uncertainty analysis, graded recovery suggested by Chat GPT, and so on. Further improvement of the higher harmonic diagnosis system will be achieved by AI technologies.

## ACKNOWLEDGMENT

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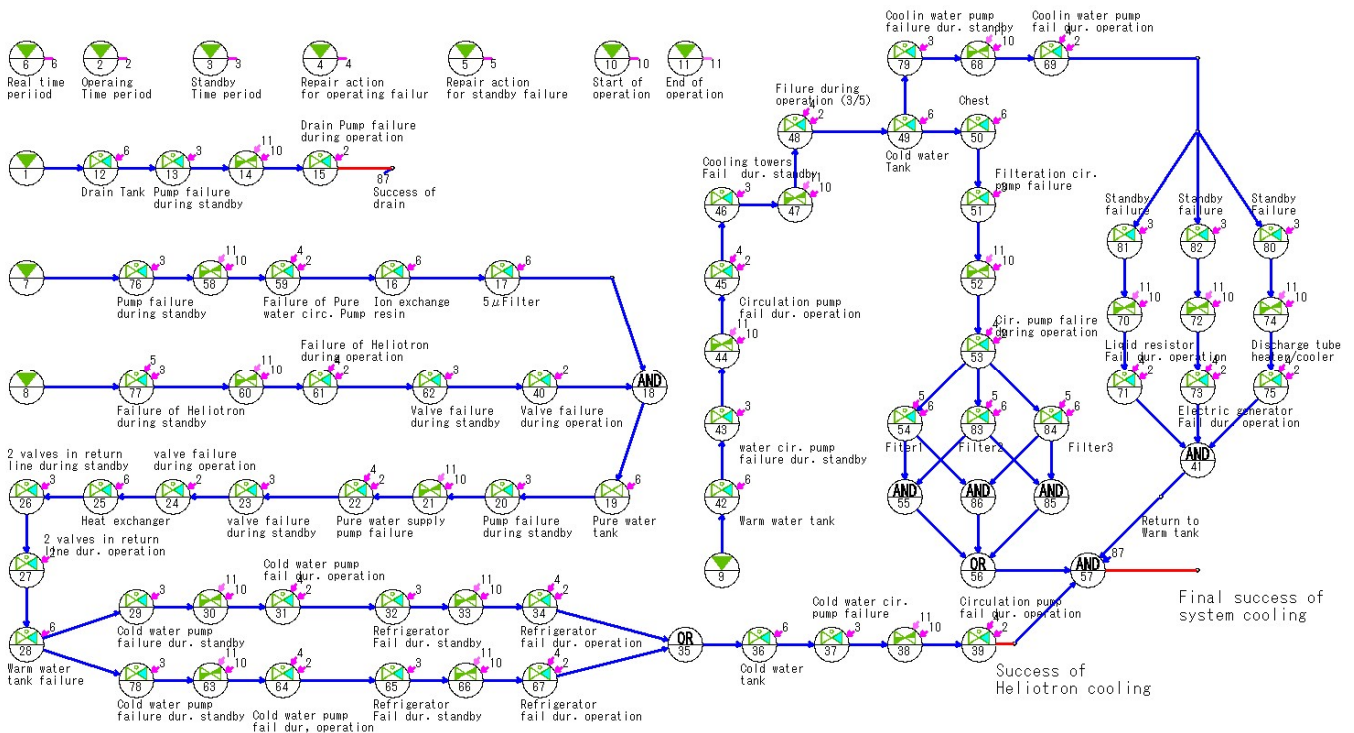


Fig. 4. GO-FLOW chart of the Heliotron J Water-cooling system.

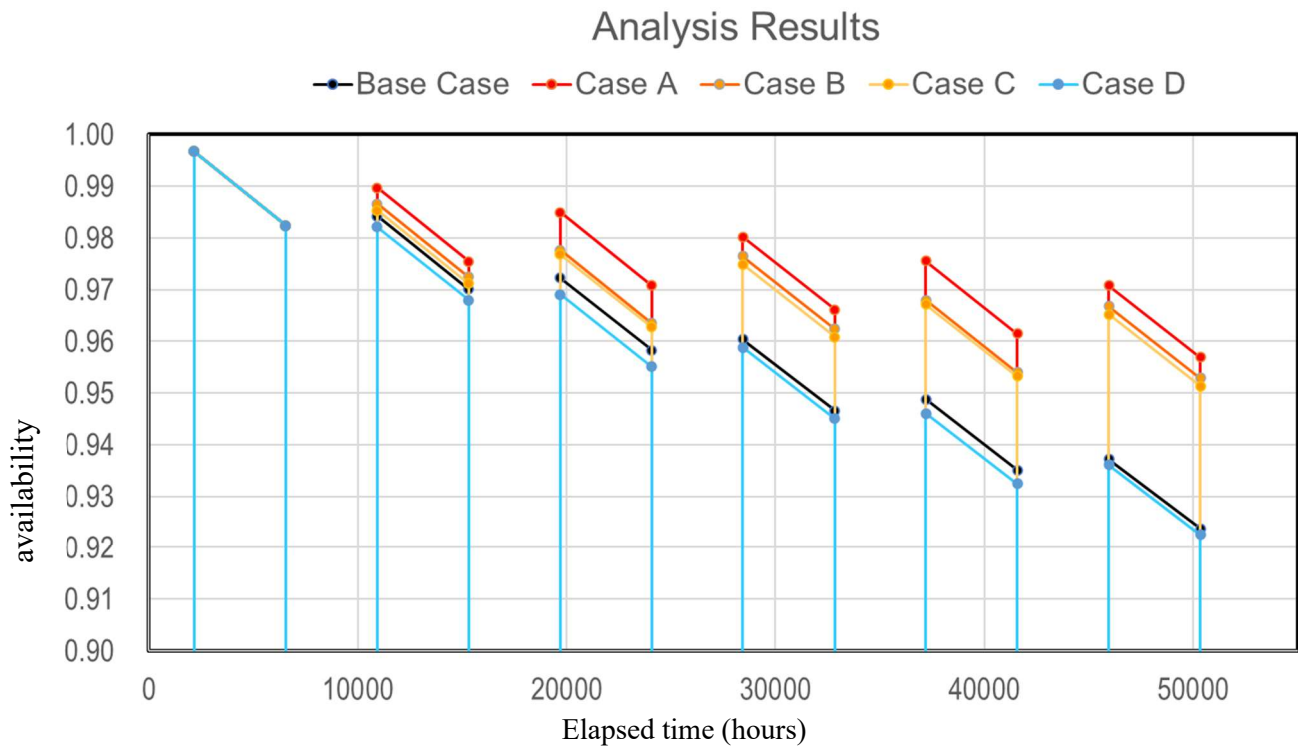


Fig. 5. Availability of the Heliotron J Water-cooling system.

#### REFERENCES

- [1] T. Obiki, et al. "First plasmas in Heliotron J", Nucl. Fusion, Vol.41, pp.833-844, 2001
- [2] T. Matsuoka, "Dynamic Behavior of Nuclear Power Plant State under Severe Accident Conditions: Analysis by the GO-FLOW Methodology and the Consideration of Loop Structures". In Aldemir, T (Eds.), Advanced Concepts in Nuclear Energy Risk Assessment and Management, pp.427-476, World Scientific Publishing Co Pte Ltd., 2018
- [3] H. Yoshikawa and J. Nitta, "Application of Higher Harmonics Diagnostic Method of Electric Power Source for Rapid Detection of Failed Electric Machine in a Real Nuclear Facility by Field Workers", Proceedings of Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC&HMIT 2019) (9-14 February 2019, Orlando, FL, USA)
- [4] Japan Atomic Energy Society, A standard for Procedures of Probabilistic Safety Assessment of Nuclear Power Plants during Power Operation (Level 1 PSA). AESJ-SC-P008, 2008
- [5] IAEA, Survey of ranges of Component reliability data for use in probabilistic safety assessment. IAEA-TECDOC-508, 1989
- [6] U.S.NRC, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400, NUREG-75/014, 1975
- [7] T. Matsuoka, "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 and System Safety. Vol. 233; <https://doi.org/10.1016/j.res.2023.109086>, May 2023
- [8] T. Matsuoka and M. Kobayashi, "The GO-FLOW reliability analysis methodology—analysis of common cause failures with uncertainty", Nuclear Engineering and Design, Vol. 175, pp.205-214, 1997.
- [9] T. Matsuoka, "Availability Analysis of a Loop Structured System - Application of the GO-FLOW methodology to a distributed energy system consisting of a solar panel, a rechargeable battery and a fuel cell -", Proceedings of International Conference on Probabilistic Safety Assessment and Management & Asian Symposium on Risk Assessment and Management, PSAM17 \$ ASRAM2024(7-11 October 2024, Sendai, Japan)
- [10] M. Yanez, F. Joglar and M. Modarres, "Generalized renewal process for analysis of repairable systems with limited failure experience", Reliability Engineering and System Safety. Vol. 77, pp.167-180, 2002.
- [11] T. Nakagawa, Maintenance Theory of Reliability, Springer 2005
- [12] M. Brown and F. Proschan, "Imperfect repair", Journal of Applied Probability, Vol. 20, pp. 851 – 859, 1983