Specialists Workshop on Advanced Human-Machine Systems Studies for Complex Energy Systems

Reliability/Availability evaluation of Heliotron by GO-FLOW

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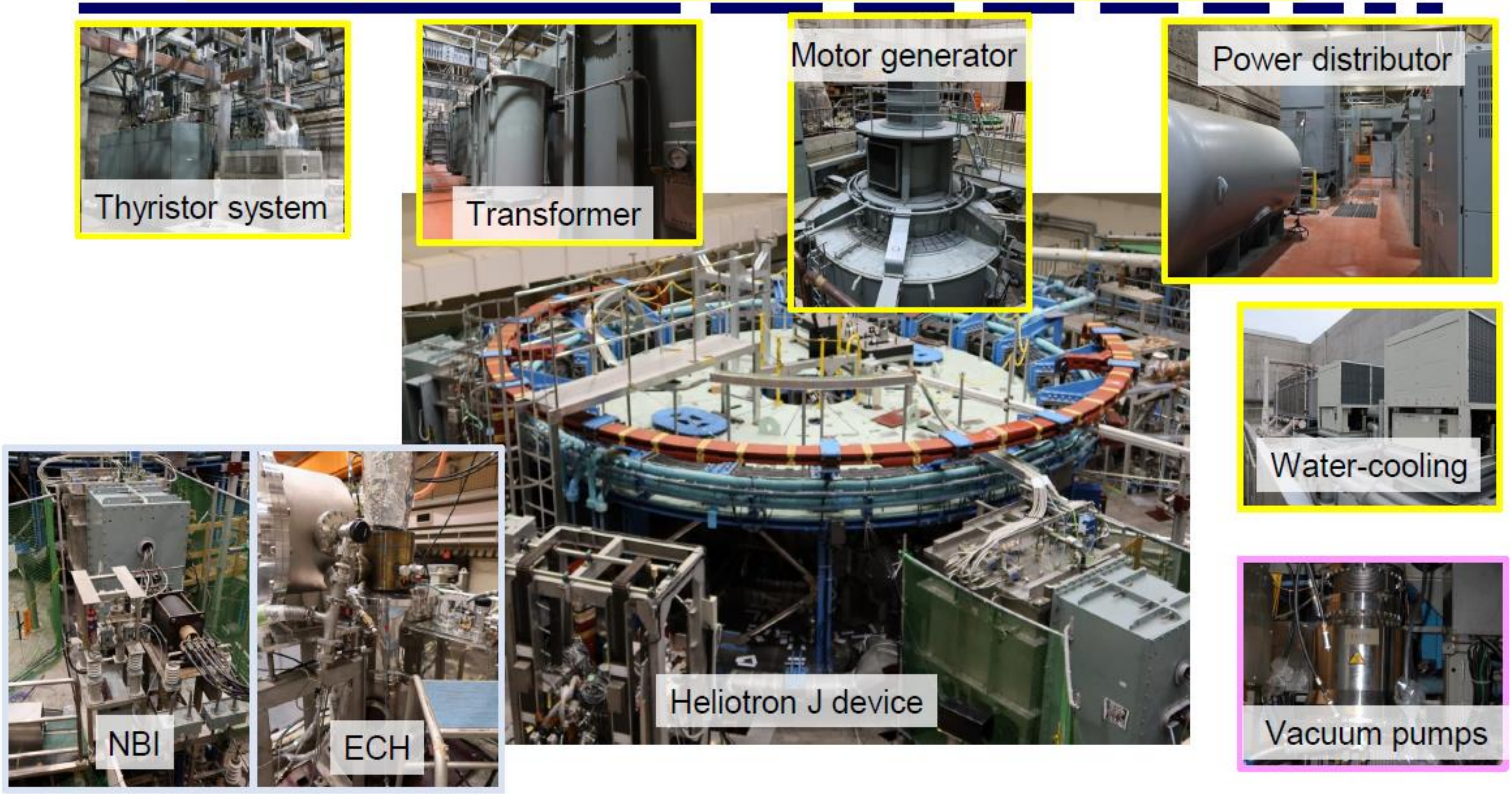
Contents of the presentation

- Heliotron J is a fusion research device located at the Institute of Advanced Energy, Kyoto University.
- 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 of the cooling systems have been performed by the GO-FLOW methodology for possible maintenance schedules and methods.

Heliotron J

- *Heliotron J is a fusion research device, specifically a helical-axis heliotron designed to study plasma confinement.*
- *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 .*
- *For the successful operation of the system, availability of the water-cooling systems in the Heliotron J is essential matter.*

Major Components of composing Heliotron J system



Main part of Heliotron J

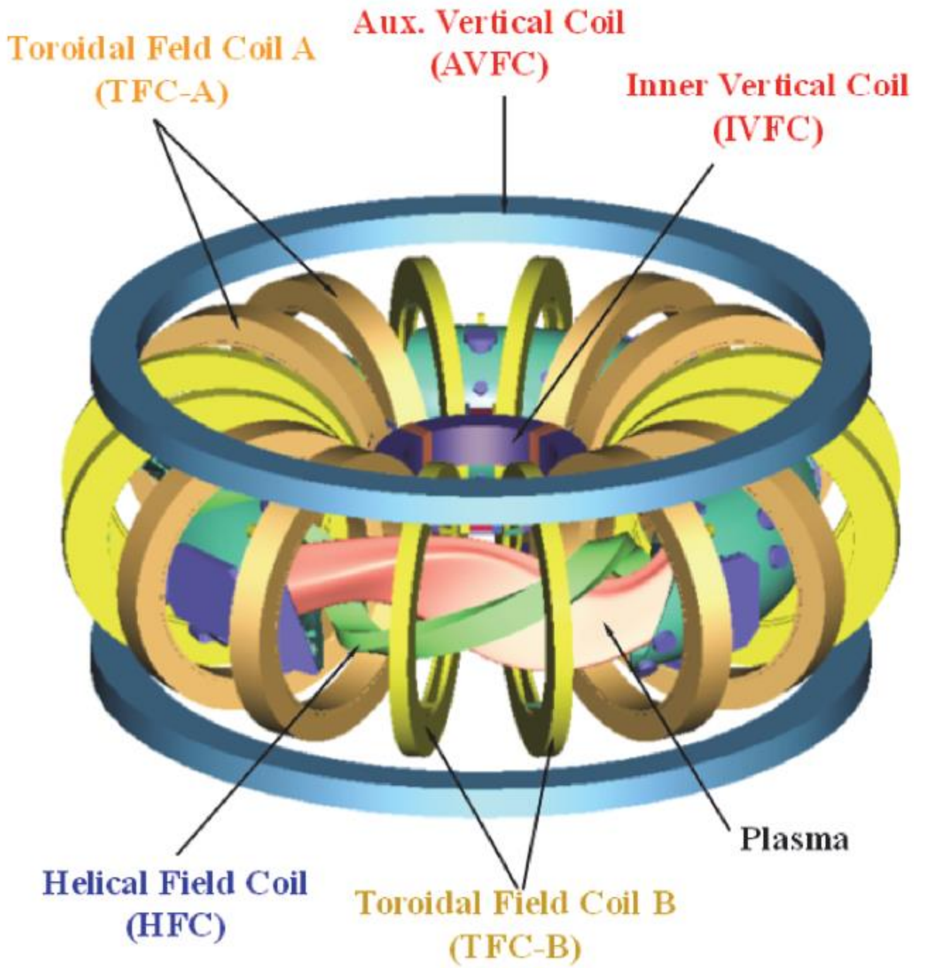


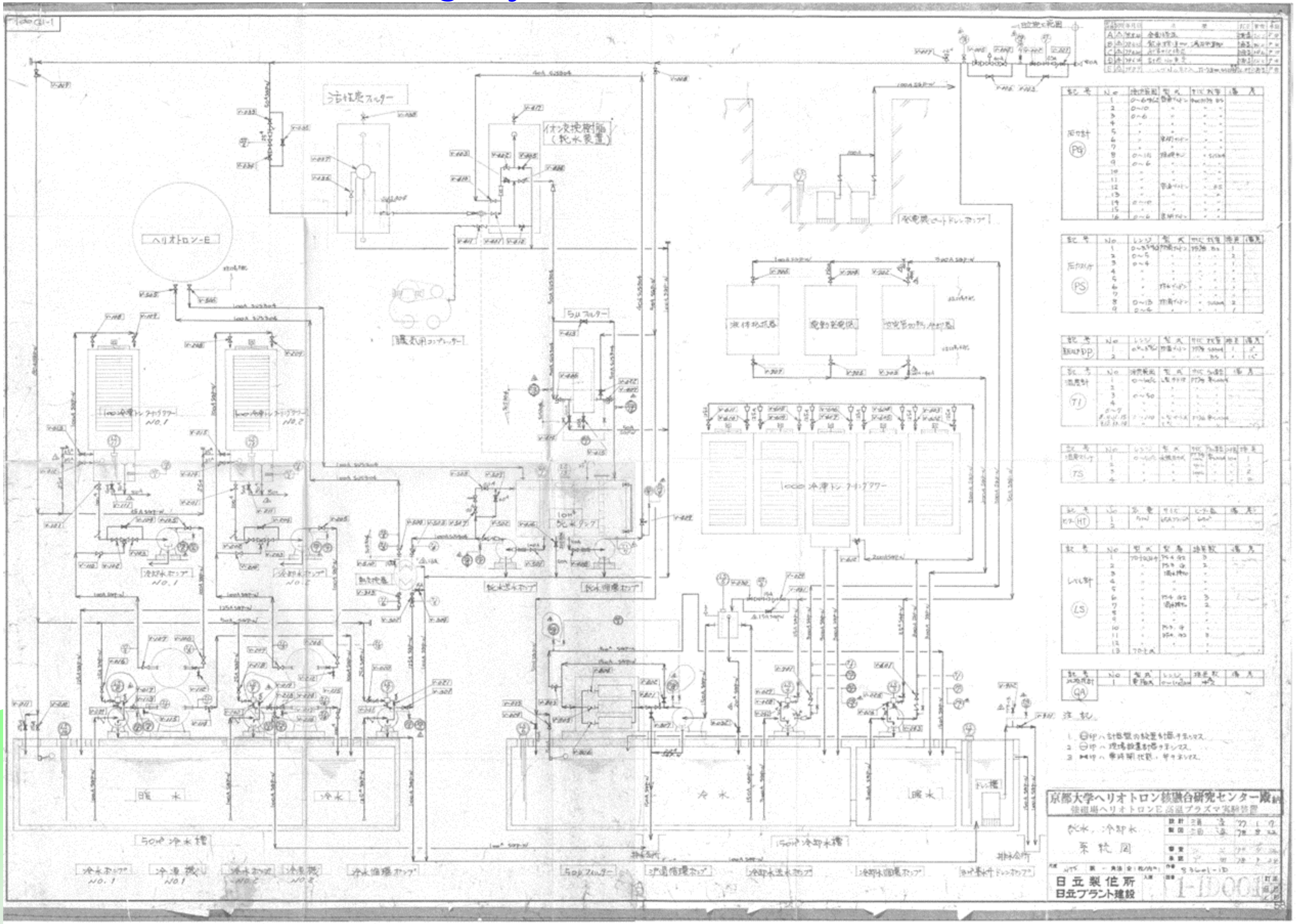
図 1：Heliotron J 概要図

Facility Operation Performance

- *Since 1980, it has been in operation for 23 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.*
- *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.

Water-cooling systems in the Heliotron J



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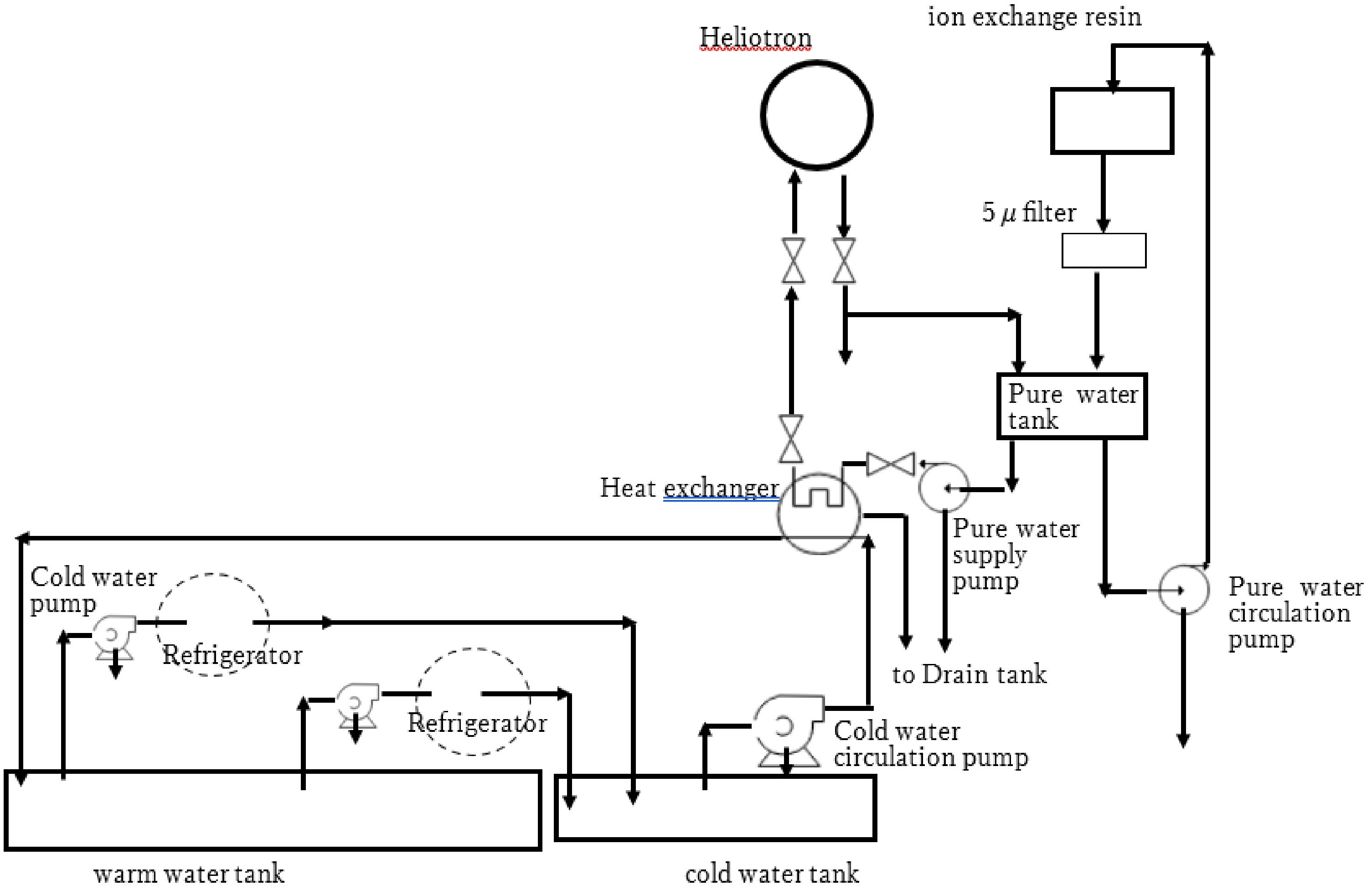
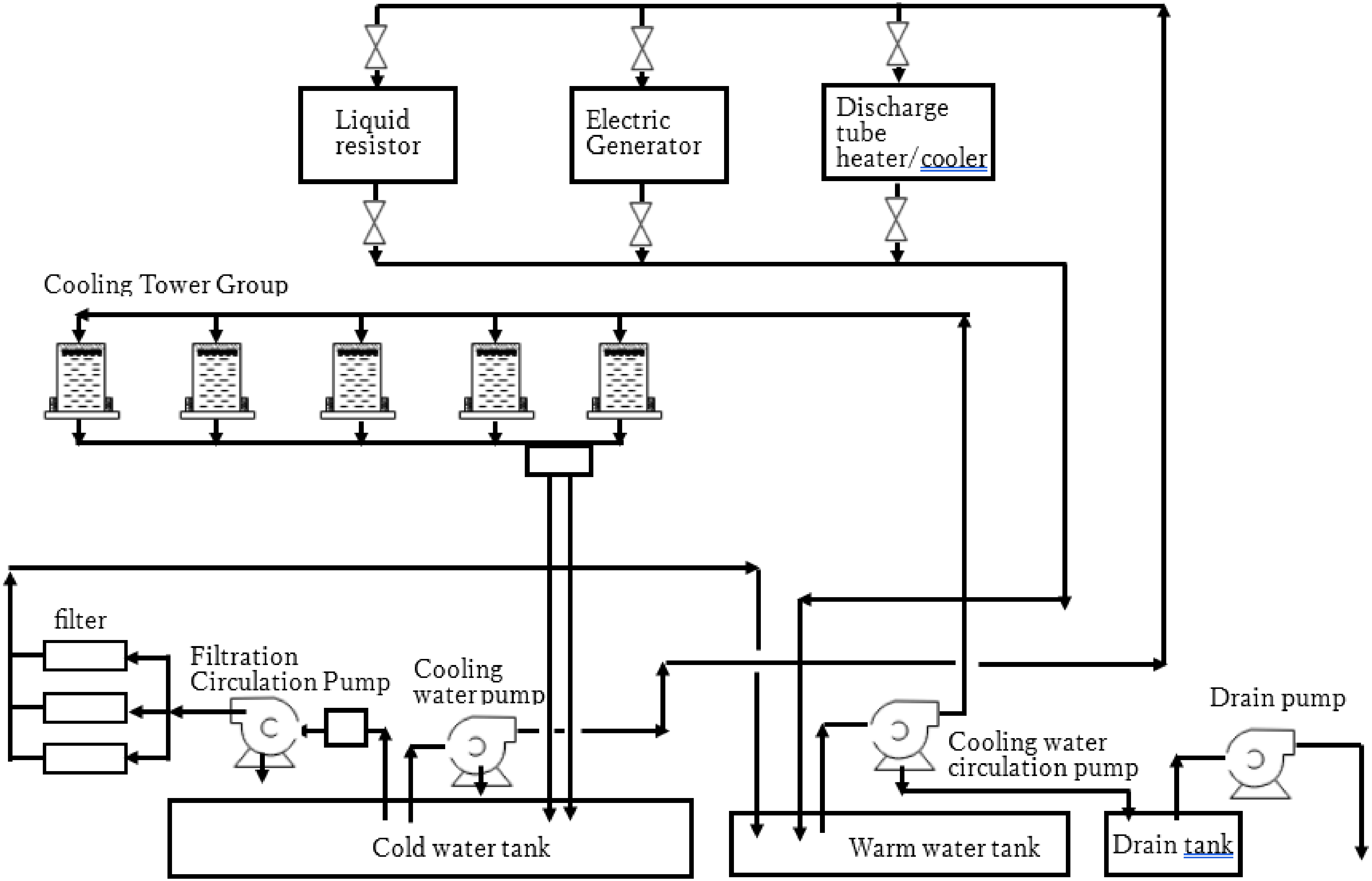
The following two diagrams can be created as a configuration diagram with the main equipment taken from the diagram on the previous page.




Liquid resistor
Electric Generator
Discharge tube heater/cooler
Cooling Tower Group
filter
Filtration Circulation Pump
Cooling water pump
Cold water tank
Warm water tank
Cooling water circulation pump
Drain pump
Drain tank

Operating conditions of the water cooling system

- *Inspection is performed once a year*
- *Water cooling system can be operated with one refrigeration unit.*
- *The cooling function can be maintained with three of the five cooling towers.*

Estimation of Equipment Failure Rates

- The total operating time is 14,560 hours and no failure has occurred in the 10 pumps installed during that time, the failure rate during pump operation is
  1÷(10x14,560)=6.9×10^{-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 considertion,
  1 ÷ (10x201,480)=5×10^{-7}/h or less.

Estimation of Equipment Failure Rates(2)

- ✓ There is an adjustment for water leakage from the pump bearings about once a year. The probability of failure will be about

  $$1 \div (10 \times 14{,}560) = 1.2 \times 10^{-5}/h.$$

- ✓ 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,

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

Estimation of Equipment Failure Rates(3)

✓ Values adopted in other analysis cases

	RSS
(1) Motor/Air operated valve	
failure of open/close action $3.6x10^{-3}$/D	$1x10^{-3}$
failure during usage $2.0x10^{-7}$/hour	$3x10^{-5}$
failure during standby $2.0x10^{-8}$/hour	
(2) Pump	
fails to start $2.7x10^{-2}$/D	$1x10^{-3}$
failure during operation $1.0x10^{-6}$/hour	$3x10^{-6}$
(3) Turbine	
fails to start $2.7x10^{-2}$/D	

failure during operation $1.0x10^{-6}$/hour

(4) Turbine generator

fails to start $1x10^{-4}$/D

failure during operation $1.0x10^{-6}$/hour

(5) Condensate water storage tank

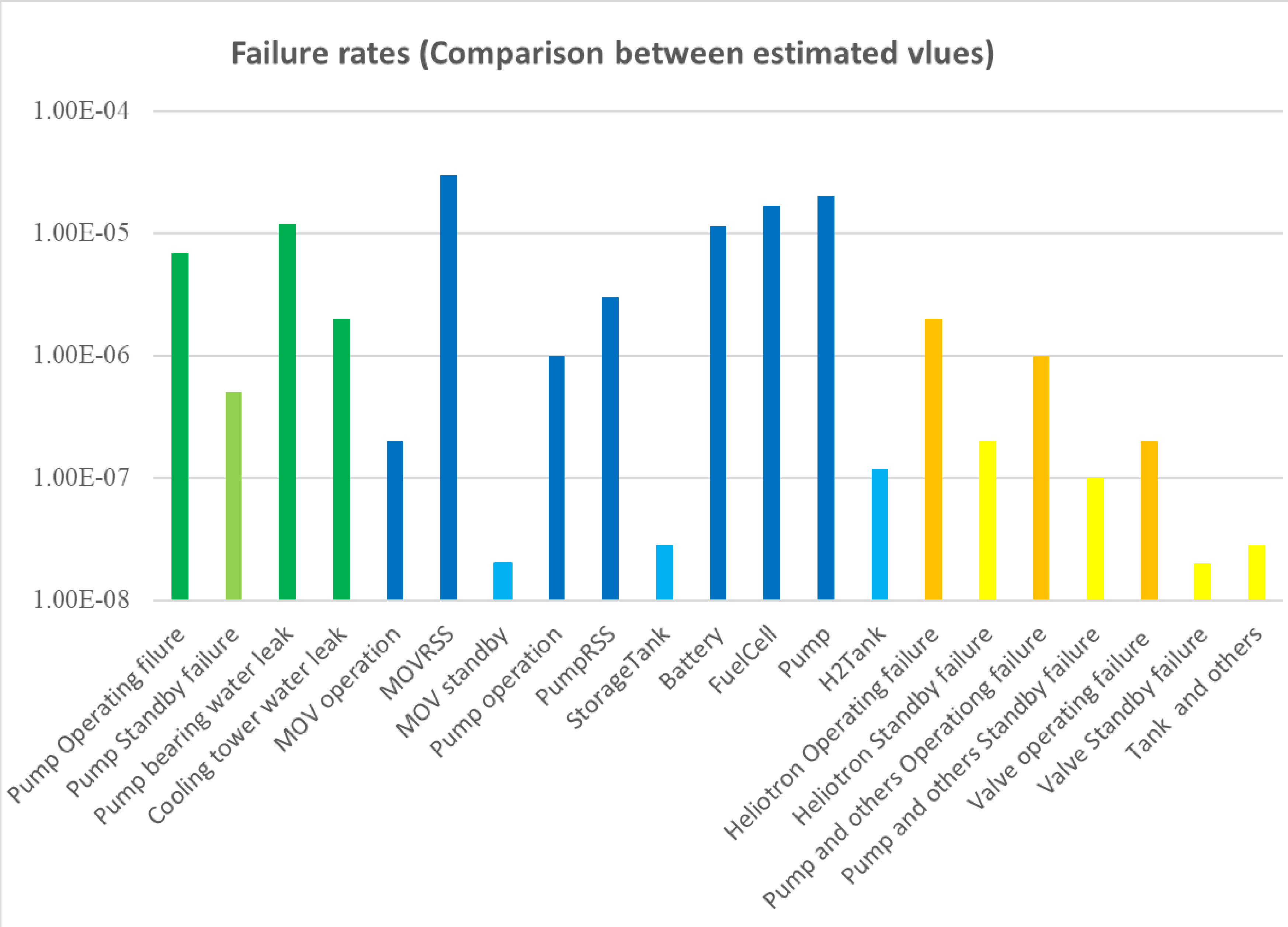
failure during operation $2.8x10^{-8}$/hour

✓ Values adopted in other analysis cases (2)

Components	Capacity	Lifetime	Failure rate	
Solar panel	maximum 20kWh/day	30years	3.8E-6/h	Failure
Rechargeable battery	20kWh	10years	1.14E-5/h	Failure
Fuel cell	10kWh/day	60,000h	1.67E-5/h	Failure
Motor		50,000h	2E-5/h 1.1E-4/D	Failure to run Failure to start
Pump		50,000h	2E-5/h	Failure to run
H_2 tank			1.2E-7/h	Leak & Plug
O_2 flow			1E-8/h	Plug
DC-AC inverter			2.8E-7/h	Failure

Failure rates set in this analysis

componentsPump,	Failure mode	Failure rates	remarks
Heliotron Main Part	Operating failure	2.0E-6/h	
same as above	Standby failure	2.0E-7/h	
Pump, Refrigerator, Cooling tower, Liquid resistor, Electric Generator, Discharge tube heater/cooler	Demand failure	1.0E-3/D	not take into account
same as above	Operating failure	1.0E-6/h	
same as above	Standby failure	1.0E-7/h	
valve	Operating failure	2.0E-7/h	
same as above	Standby failure	2.0E-8/h	
Tank and other components	Deterioration over time (aging)	2.8E-8/h	


Failure rates (Comparison between estimated vlues)
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
Pump Operating filure
Pump Standby failure
Pump bearing water leak
Cooling tower water leak
MOV operation
MOVRSS
MOV standby
Pump operation
PumpRSS
StorageTank
Battery
FuelCell
Pump
H2Tank
Heliotron Operating failure
Heliotron Standby failure
Pump and others Operationg failure
Pump and others Standby failure
Valve operating failure
Valve Standby failure
Tank and others

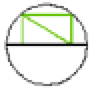
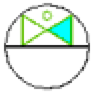
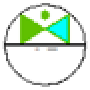
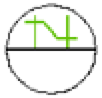
The GO-FLOW Methodology

- GO-FLOW methodology 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. The modeling technique produces a chart which consists of signal lines and operators and represents the engineering function of the components/subsystems/system.

The GO-FLOW Methodology(2)

- The GOFLOW operators' type, number, shape and functions are summarized in the following slides.
- The operators model function or failure of the physical equipment, logical gates, and signal transmissions.
- Specific probabilities (point estimates) of component operation or failure are given to operators as input data.

Type	Shape	Description	Main inputs	Sub inputs	Output
21		Two state operator	$S(t)$	–	$R(t)=S(t)\cdot P_g$
22	OR	OR gate	$S_1(t), S_2(t) \cdots S_n(t)$	–	$R(t)=1.0-\prod_{i=1}^{n}[1.0-S_i(t)]$
23	NOT	NOT gate	$S(t)$	–	$R(t)=1.0-S(t)$
24	DIF	Difference operator	$S(t)$	–	$R(t)=1.0-S(t')$ $R(t_1)=0.0$
25		Signal generator	–	–	$S(t)$ or $P(t)$
26		Closed state operator	$S(t)$	$P(t)$	$R(t)=S(t)\cdot O(t),\quad O(t_1)=P_p$ $O(t)=O(t')+[1.0-O(t')]\cdot P(t)\cdot P_g$
27		Open state operator	$S(t)$	$P(t)$	$R(t)=S(t)\cdot O(t),\quad O(t_1)=1.0-P_p$ $O(t)=O(t')\cdot[1.0-P(t)\cdot P_g]$
28	DLY	Delay operator	$S(t)$	–	$R(t)=S(t-k);\ (t-k)>0$ $R(t)=S(t_1);\ (t-k)\leq 0$
30	AND	AND gate	$S_1(t), S_2(t) \cdots S_n(t)$		$R(t)=\prod_{i=1}^{n}S_i(t)$

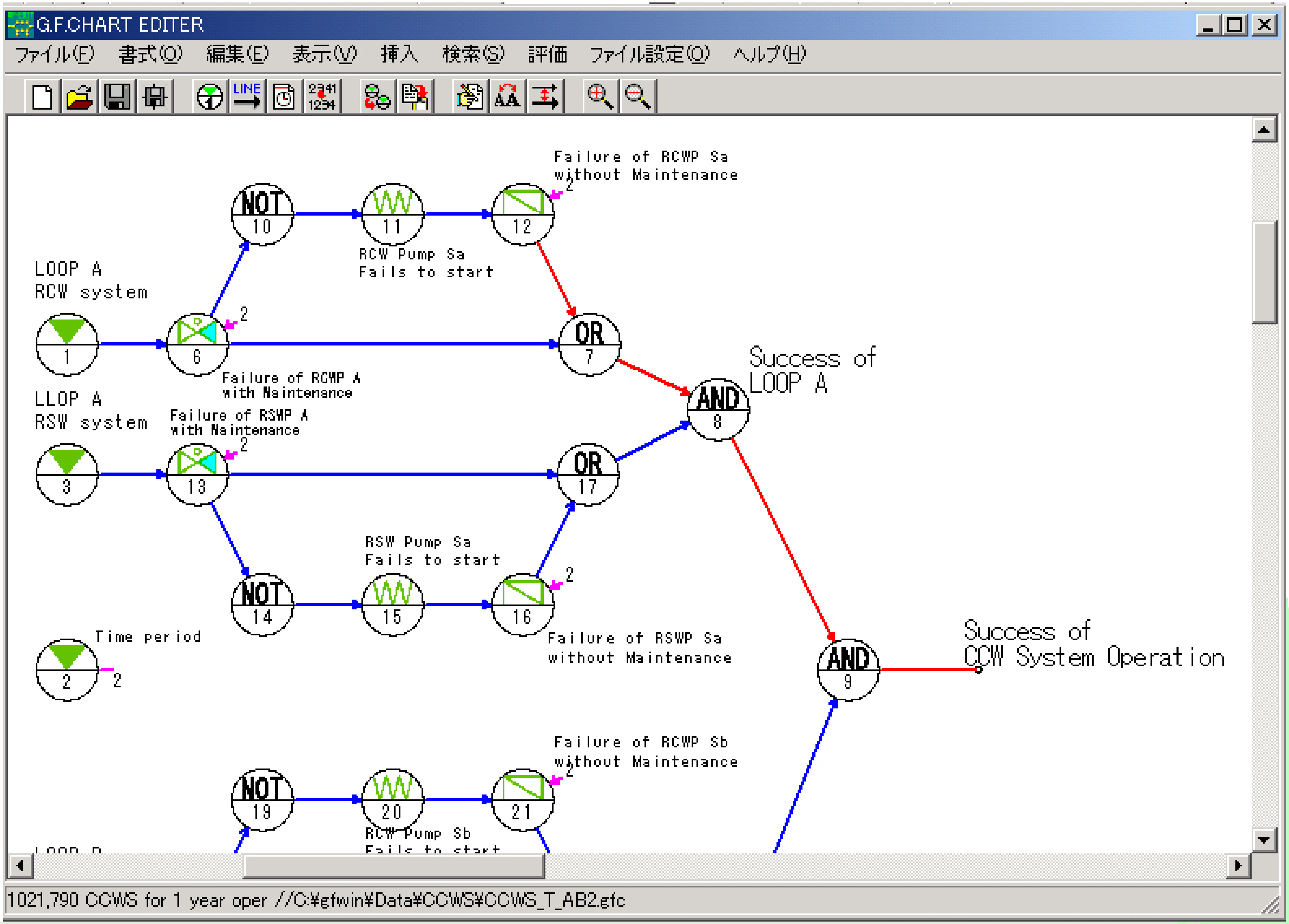
Type	Shape	Description	Main inputs	Sub inputs	Output
35		Aging work operator	$S(t_1), S(t_2) \cdots S(t_n)$	$P_1(t_1), P_1(t_2) \cdots P_1(t_n);\quad P_2(t_1), P_2(t_2) \cdots P_2(t_n);\quad \cdots\cdot$	$R(t) = S(t)\left[\frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}\exp\left\{-(\lambda+\mu)\sum_i \sum_{t_k \le t} P_i(t_k)\min\left[1.0, \frac{S(t_k)}{S(t)}\right]\right\}\right]$
37		Aging open state operator	$S(t)$	$P_1(t_1), P_1(t_2) \cdots P_1(t_n)$ $P_2(t_1), P_2(t_2) \cdots P_2(t_n)$ $\cdots\cdot$	$R(t) = S(t)\left[\frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}\exp\left\{-(\lambda+\mu)\sum_i \sum_{t_k \le t} P_i(t_k)\right\}\right]$
38		Aging closed state operator	$S(t)$	$P_1(t_1), P_1(t_2) \cdots P_1(t_n)$ $P_2(t_1), P_2(t_2) \cdots P_2(t_n)$ $\cdots\cdot$	$R(t) = S(t)\left[1.0 - \frac{\mu}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu}\exp\left\{-(\lambda+\mu)\sum_i \sum_{t_k \le t} P_i(t_k)\right\}\right]$
39		Open/Close action operator	$S(t)$	$P_1(t)$ $P_2(t)$	$R(t) = S(t) \cdot O(t),\quad O(t_1) = P_p$ $O(t) = O(t') + [1.0 - O(t')] \cdot P_1(t) \cdot P_O$ $O(t) = O(t') \cdot [1.0 - P_2(t) \cdot P_C]$
40		Phased mission operator	$S(t)$	–	$R(t) = 1.0\ ;\quad (t < t_i)$ $R(t) = S(t)\ ;\quad (t_i \le t \le t_j)$ $R(t) = S(t_j)\ ;\quad (t_j < t)$

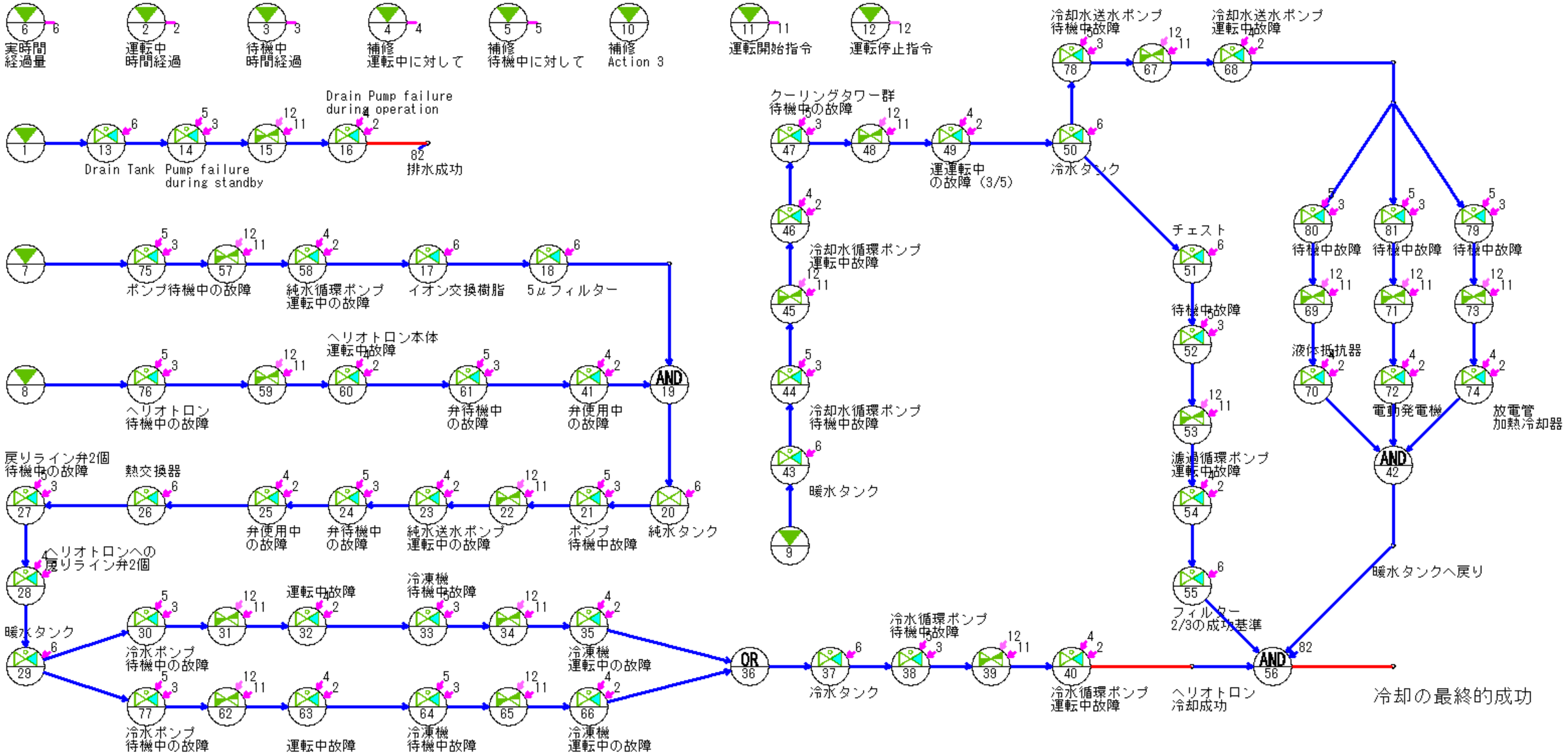
In this Figure,
$S(t)$ = main input signal S at time point t,
$P(t)$ = sub input signal at time point t,
$R(t)$ = output signal at time point t,
$O(t)$ = probability for valve in open state at time point t,
t' = time point immediately before the time point t,
t_i, t_j = start time point and end time point of a specific phase,
k = number of time points delayed,
P_g = probability for successful operation,
P_p = probability for premature operation,
P_o = probability for valve successful open,
P_c = probability for valve successfully close,
λ = failure rate of a component,
μ = recovery rate of a component.

Modeling to the GO-FLOW chart

- The first step of the analysis is to construct a GO-FLOW chart which consists of signal lines and operators to represent the engineering function of the components/subsystems/system composes the engineering system under consideration.
- GO-FLOW chart is constructed by using the Chart Editor as shown in the next slide.
- The GO-FLOW chart taking into account the system diagram, equipment operation, and maintenance and inspection.

GO-FLOW chart editor




実時間
経過量
運転中
時間経過
待機中
時間経過
補修
運転中に対して
補修
待機中に対して
補修
Action 3
運転開始指令
運転停止指令
冷却水送水ポンプ
待機中故障
冷却水送水ポンプ
運転中故障
Drain Pump failure
during operation
Drain Tank
Pump failure
during standby
排水成功
クーリングタワー群
待機中の故障
運運転中
の故障 (3/5)
冷水タンク
チェスト
待機中故障
待機中故障
待機中故障
ポンプ待機中の故障
純水循環ポンプ
運転中の故障
イオン交換樹脂
5μフィルター
冷却水循環ポンプ
運転中故障
待機中故障
液体抵抗器
電動発電機
放電管
加熱冷却器
ヘリオトロン本体
運転中故障
ヘリオトロン
待機中の故障
弁待機中
の故障
弁使用中
の故障
AND
冷却水循環ポンプ
待機中故障
濾過循環ポンプ
運転中故障
AND
戻りライン弁2個
待機中の故障
熱交換器
弁使用中
の故障
弁待機中
の故障
純水送水ポンプ
運転中の故障
ポンプ
待機中故障
純水タンク
暖水タンク
ヘリオトロンへの
戻りライン弁2個
暖水タンクへ戻り
運転中故障
冷凍機
待機中故障
暖水タンク
冷水ポンプ
待機中の故障
冷凍機
運転中の故障
OR
冷水循環ポンプ
待機中故障
フィルター
2/3の成功基準
冷水タンク
冷水循環ポンプ
運転中故障
ヘリオトロン
冷却成功
AND
冷却の最終的成功
冷水ポンプ
待機中の故障
運転中故障
冷凍機
待機中故障
冷凍機
運転中の故障

Conditions for inspection and repair

- There are so many components in the cooling systems, and it is very difficult to maintain all the components at every year.
- Important active components like pump, valve, motor are checked and repaired every year.
- Less important components as passive components like filter, pipes are checked once every two years or three years.
- Inspection and maintenance will not be conducted for other static equipment in some analysis case.
- The perfect maintenance; after the repair, components become as good as new.
- Less perfect maintenance is a graded recovery with considering different degree of restoration.

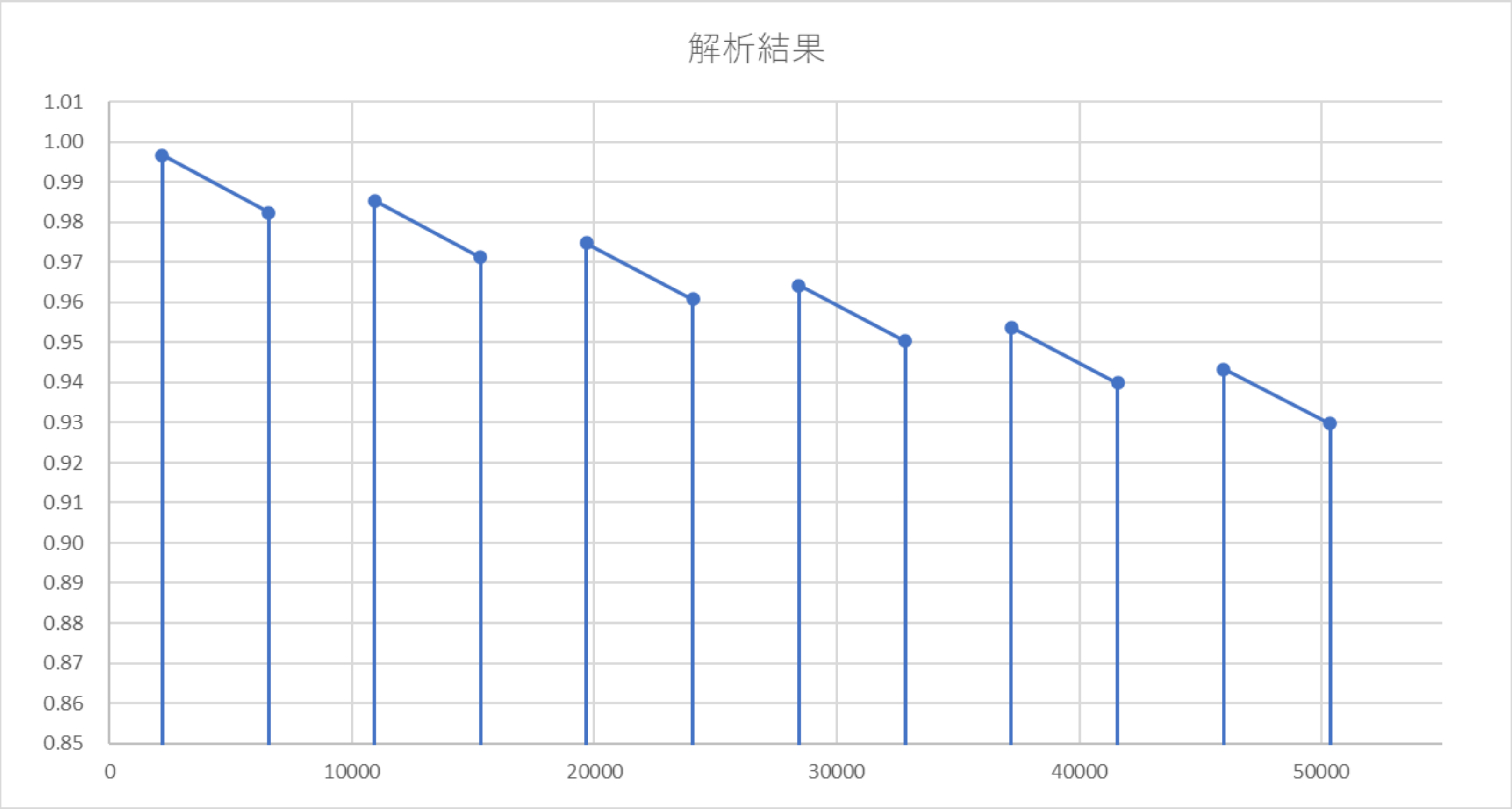
Time points defined in the analysis

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(13週)	2160	0	2160				
3	start of operation	4/1(13週)	2160	0	2160	1			
4		9 /30(40週)	6552	728	5824				
5	end of operation	9 /30(40週)	6552	728	5824		1		
6	repair	10/1(41週)	6576	0	5848			-728	-5848
7	**Seconf year**	! (1/1)	8760	0	8032				
8		4/1(13週)	10920	0	10192				
9	start of operation	4/1(13週)	10920	0	10192	1			
10		9 /30(40週)	15312	728	13856				
11	end of operation	9 /30(40週)	15312	728	13856		1		
12	repair	10/1(41週)	15336	0	13880			-728	-8032
13	**Third year**	! (1/1)	17520	0	16064				
14		4/1(13週)	19680	0	18224				
15	start of operation	4/1(13週)	19680	0	18224	1			
16		9 /30(40週)	24072	728	21888				
17	end of operation	9 /30(40週)	24072	728	21888		1		
18	repair	10/1(41週)	24096	0	21912			-728	-8032
19	**4th year**	! (1/1)	26280	0	24096				
20		4/1(13週)	28440	0	26256				

Time points defined in the analysis (Cont.)

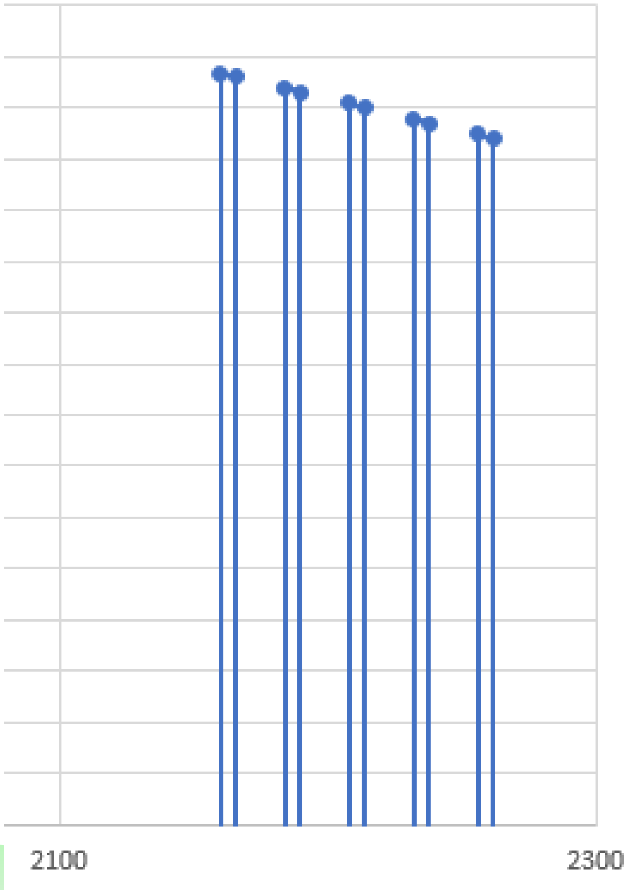
Time point	meaning	month/day (weeks)	elapsed time	Operation time	Sandby time	Start of Operation	End of Operaion	Repair for operating Failure	Repair for standby Failure
21	start of operation	4/1(13週)	28440	0	26256	1			
22		9 /30(40週)	32832	728	29920				
23	end of operation	9 /30(40週)	32832	728	29920		1		
24	repair	10/1(41週)	32856	0	29944			-728	-8032
25	**5th year**	! (1/1)	35040	0	32128				
26		4/1(13週)	37200	0	34288				
27	start of operation	4/1(13週)	37200	0	34288	1			
28		9 /30(40週)	41592	728	37952				
29	end of operation	9 /30(40週)	41592	728	37952		1		
30	repair	10/1(41週)	41616	0	37976			-728	-8032
31	**6th year**	! (1/1)	43800	0	40160				
32		4/1(13週)	45960	0	42320				
33	start of operation	4/1(13週)	45960	0	42320	1			
34		9 /30(40週)	50352	728	45984				
35	end of operation	9 /30(40週)	50352	728	45984		1		
36	repair	10/1(41週)	50376	0	46008			-728	-8032
37	**End of 6th year**	12・31(52週)	52560	0	48192				

Analysis results (Base case)



- Complete annual inspection and maintenance of the main body of the heliotron.
- Pumps and valves were repaired for major failure modes foe once a year.
- No inspection and maintenance was performed on other static equipment.

(attention) Actual graph style



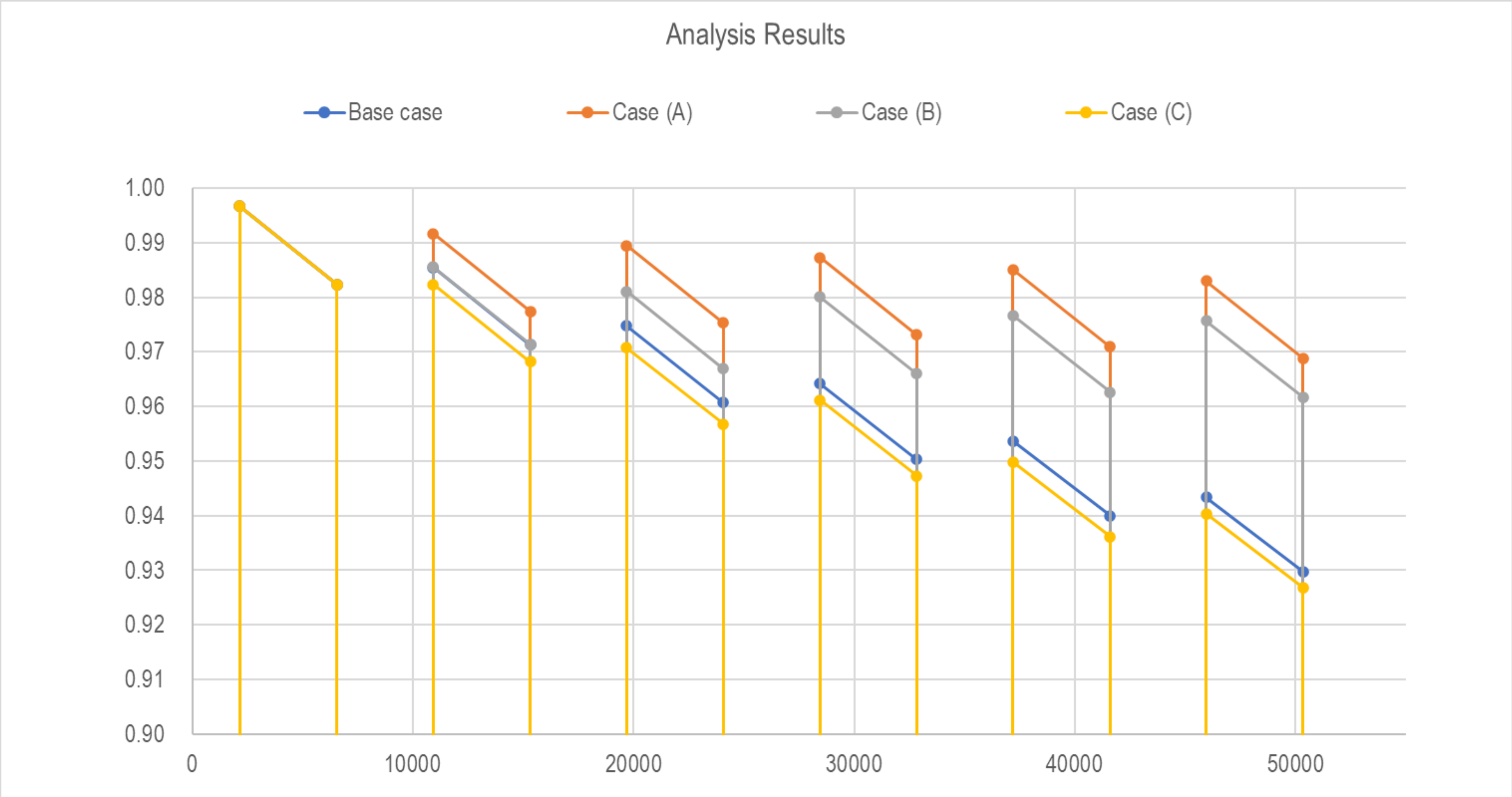
Analysis conditions for other cases

A) Careful inspection and repair will be performed for pumps, refrigerators, cooling towers, liquid resistors, electric generators, discharge tube heat coolers, and valves, covering also failure modes in standby mode. Inspection and maintenance will not be conducted for other static components.

B) Major components will be divided into two groups, each of which will be carefully inspected and repaired every other two years.

C) Major components will be divided into two groups, each of which will be inspected and repaired every other two years in response to operational failure modes.

Analysis results (2)



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Disscusions on the analysis results

- A relatively high level of reliability can be achieved by dividing major equipment into two groups, each of which is carefully inspected and repaired every other two years.
- Since the modeling and analysis system to this GO-FLOW chart has been established, analysis of other cases with different maintenance and inspection conditions can be easily performed.
- The failure rate set at this time can also be easily changed.
- Additions of components and system configuration changes that require consideration can be easily handled by modifying the existing GO-FLOW chart.

Conclusions

- *Reliability/availability analysis of the water cooling system, which plays an important role in the operation of Heliotron J, was performed using the GO-FLOW method.*
- *The results of the analysis provided useful knowledge.*
- *The GO-FLOW analysis is expected to be applied for further detailed analysis conditions.*
  - *Uncertainty analysis*
  - *Graded recovery*
  - *Analysis cnditions for more realistic cases*