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Availability and redundancy design considerations for Electron-Ion Collider cooling water systems and components

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DISCLAIMER

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Abstract

The Electron-Ion Collider (EIC) is composed of several large-scale systems, which all require highly available cooling systems based on the Conceptual Design Report. Since the overall EIC availability goal is 85%, all the subsystems will contribute. Availability is defined by the time that a component or system is functional given a required or scheduled run time. The focus of the project was to determine if redundant or extra cooling water and deionized water pumps were needed in a subsystem to increase the overall EIC availability. The largest subsystem in the ring is the 10 o'clock cooling system, so this was used for redundancy analysis. Relationships between the components were defined as parallel, series, or m-out-of-n for the cooling towers, valves, pumps and heat exchangers to perform calculations. A comparison between an original system versus a redundant one was then done using component availability from industry standards. Cost analysis was also performed to see how much the availability and cost would decrease if the redundancy application was not chosen. The Collider-Accelerator Department (CAD) also has a calculation in place for the Relativistic-Heavy Ion Collider (RHIC), so cooling water failure data was collected from their operational log and analyzed for real-life component availability. A comparison of component availability from the CAD data to the industry standards was made through the 10 o'clock cooling system layout. The results showed that the subsystems need to have over a 98% availability for an 85% goal, and that the CAD data is very close to the industry component standards. The cost differential is miniscule compared to the potential availability increase. Therefore, redundant systems can increase the overall EIC availability by a sizable amount and are worth implementing.

I. Introduction

Reliability analysis is the study of how reliable and available a system is based on individual components within the system. The focus of the analysis is on the Radio Frequency (RF) 1010 system in the Electron-Ion Collider (EIC) ring. This is the biggest system in the ring and will thereby have the largest cooling system. The purpose is to determine how much of an impact a redundant system will have on reaching the overall EIC goal of 85% availability. This will enable an analysis of the other systems that need cooling water around the ring. In addition, cost analysis of making one system more redundant versus another for a higher availability can be used later from this study. This will factor into value engineering and determining which systems would have the lowest costs in redundancy to increase the overall availability. Figure 1 provides a clearer relationship between the cost and value that is needed for the project[1].

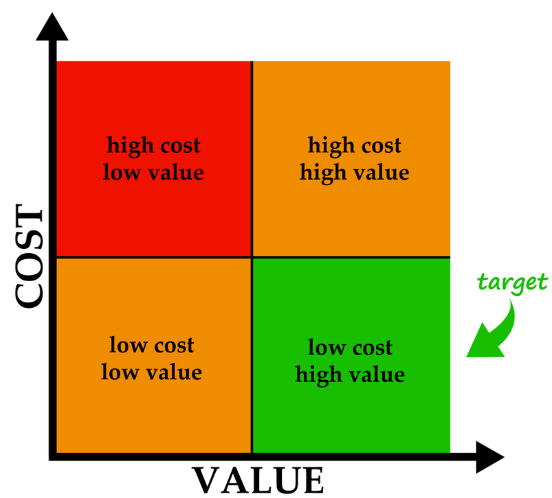


Figure 1: The relationship between cost and value for a project decision[1]

The relationships between each component in a subsystem are very important and contribute heavily to the final availability calculated. The systems within the ring themselves are then included in another availability calculation to determine the overall availability of a large-scale system. The breakdown of the EIC is shown below with a sample of few systems in

Figure 2. The relationships between all the systems are series, so the availability of each is just multiplied to find the final value.

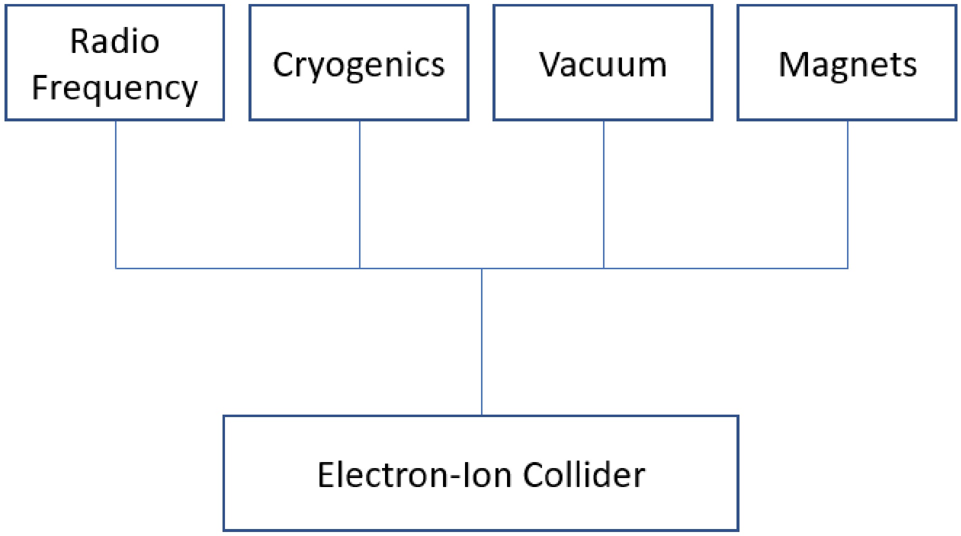


Figure 2: Systems within the Electron-Ion Collider that will have series relationships in determining the overall availability

II. Updates to the RF 1010 Cooling System

The RF 1010 system was first created in Summer 2021 with three pumps and one standby per train (2 total)[2]. Since the overall system is identical for each half and has 6 pumps and 2 standbys total, half of the system will be modeled. This system is analyzed for redundancy to determine whether there needs to be a standby at all. The analysis requires reliability comparisons between a regular system and a redundant system. The cost of an additional pump is a factor to consider when determining how much it costs to have the system offline without a backup in place already.

The electrical system requires a maximum power usage of 100 hp per unit in the cooling system. However, based on the designs from the prior year, the three pumps have an approximate power usage of 130 hp each. The logical action is to increase the functional pumps by one on each train. Therefore, the total number of active pumps is 8 while there are still 2 redundant pumps. Figure 3 below shows one train of the 1010 RF system, which has four 25% cooling water pumps and one standby. This means that one train will have a total of five 25% pumps.

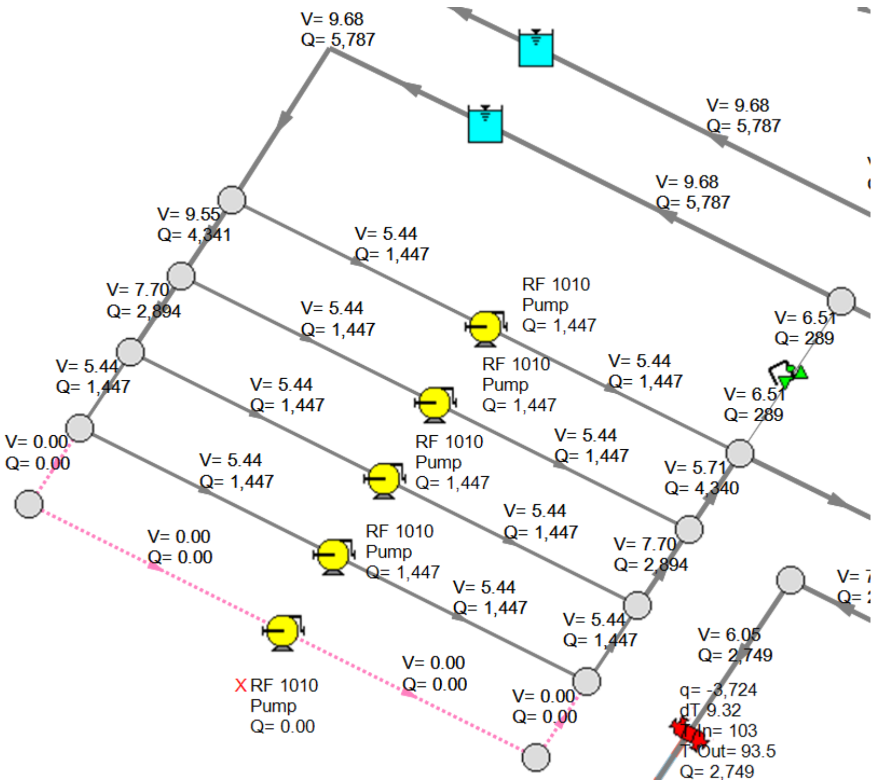


Figure 3: Fathom model of the changed 1010 RF system to incorporate an additional pump

Adjustments to the Fathom model were required to simulate the output results. Each train was adjusted by dividing the total flow rate of 5497.94 gpm by 4. This meant that each of the pumps had a volumetric flow of 1446.83 gpm at 70% efficiency, while the previous model required 1929.10 gpm. This decreased the power and resulted in the range of 96.81 hp and 98.34 hp. Figure 4 below outlines the new data provided through the simulation.

Jct	Results Diagram	Name	Vol. Flow (gal/min)	Mass Flow (lbm/sec)	dP (psid)	dH (feet)	Overall Efficiency (Percent)	Speed (Percent)	Overall Power (hp)	BEP (gal/min)	% of BEP (Percent)	NPSHA (feet)
7	Show ...	RF 1010 Pump	1,447	199.7	80.31	186.6	70.00	N/A	96.81	N/A	N/A	77.05
52	Show ...	RF 1010 Pump	1,447	199.7	80.79	187.8	70.00	N/A	97.39	N/A	N/A	76.20
55	Show ...	RF 1010 Pump	1,447	199.7	81.29	188.9	70.00	N/A	98.00	N/A	N/A	75.62
59	Show ...	RF 1010 Pump	1,447	199.7	80.29	186.6	70.00	N/A	96.79	N/A	N/A	77.05
64	Show ...	RF 1010 Pump	1,447	199.7	80.78	187.7	70.00	N/A	97.37	N/A	N/A	76.20
65	Show ...	RF 1010 Pump	1,447	199.7	81.28	188.9	70.00	N/A	97.98	N/A	N/A	75.62
67	Show ...	RF 1010 Pump	1,447	199.7	81.58	189.6	70.00	N/A	98.34	N/A	N/A	75.29
70	Show ...	RF 1010 Pump	1,447	199.7	81.56	189.6	70.00	N/A	98.32	N/A	N/A	75.28

Figure 4: Pump data for 1010 RF system

The changes were made to the full subsystem of the RF 1010 building and are included in Figure 5 as an indication of how many components are required for the successful operation of the EIC.

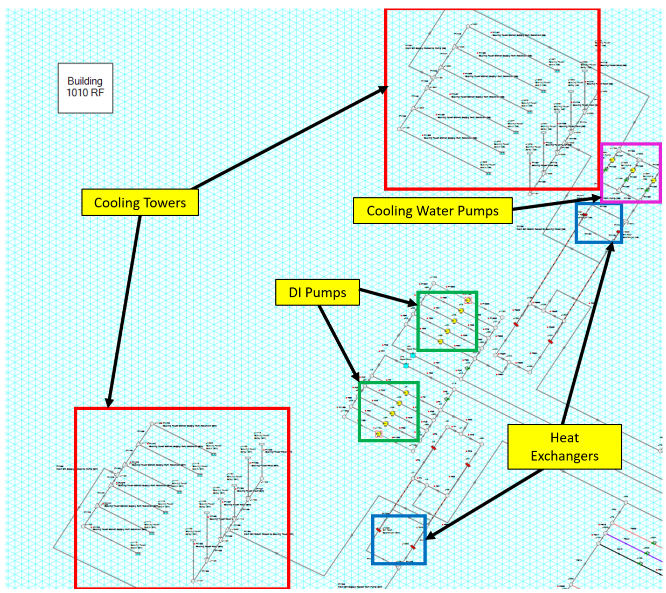


Figure 5: Labeled RF 1010 system

III. Research on Reliability Approaches

Research was first done to understand the difference between reliability and availability. Reliability is how dependable a component or system will be, given a period of time. Availability is a percentage that describes how many hours a system was functional and running through a specific time period. For example, a component that was running for 9 hours in an expected run time of 10 hours would have an availability of 90%.

The next step was to determine the correlation between the two for analysis of the system. The reliability of the system depends on the failure rate (time^-1) and the operation time. The equation that demonstrates this relationship is shown below[3]:

$$Reliability = e^{-\lambda t} \tag{1}$$

The failure rate needs to be very low in order for the reliability to be high. The operation time also factors in, so the smaller the value, the higher the reliability.

The availability depends on the mean time between failure (MTBF) and mean time to repair (MTTR). The equation representing availability is shown below[4]:

$$A = \frac{MTBF}{MTBF+MTTR} \tag{2}$$

Based on this, it is apparent that the MTBF needs to be larger and the MTTR needs to be much smaller to get a high availability. The MTBF and failure rates are inverses of each other. The MTBF and MTTR are retrieved from empirical data or industry standards. Both are in units of time.

Availability is first designed through block diagrams highlighting the relationships between all the components in the system. The series model multiplies the availability of each component but the parallel model multiplies 1-the availability of each component and subtracts from 1. The equations are below. Figure 6 shows how the series and parallel relationships are shown in block diagrams.

$$A_{sys,\,series} = A_1 \cdot A_2 \quad \text{and} \quad A_{sys,\,parallel} = 1 - (1 - A_1) \cdot (1 - A_2) \tag{3}$$

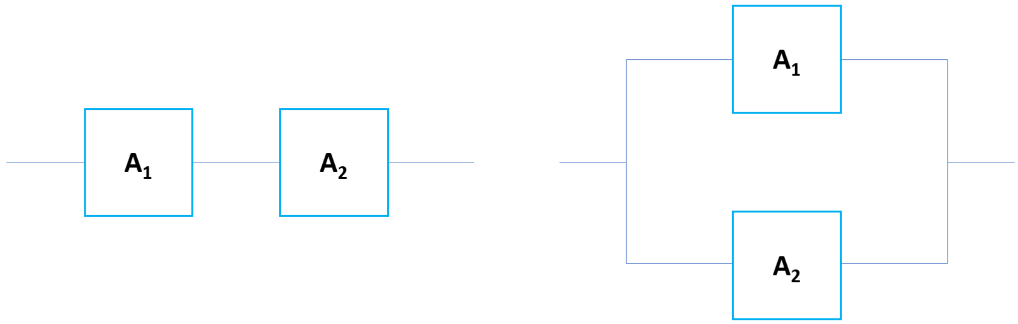


Figure 6: Series model (Left) and Parallel model (Right)

The reliability and availability relationships are exactly the same, so the equations for series and parallel in regards to reliability will be:

$$R_{sys,\,series} = R_1 \cdot R_2 \quad \text{and} \quad R_{sys,\,parallel} = 1 - (1 - R_1) \cdot (1 - R_2) \tag{4}$$

In a series model, if one component goes out, the line of operation gets shut down. The parallel model is a more reliable system addition because if one component goes out, another one can still be functioning. Thus, redundant components are shown through the parallel model.

The system at hand is a bit more complicated than a simple series and parallel block diagram, because all components need to be functioning for the system to work in the non-redundant case. Therefore, applying the m-out-of-n approach is useful here. This means that out of n components in parallel, m need to work. An example block diagram of this is shown below:

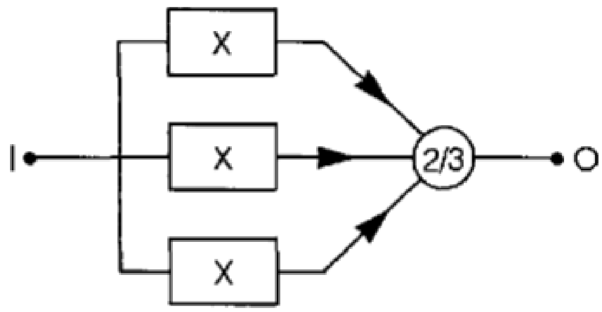


Figure 7: m-out-of-n block diagram analysis[3]

The figure describes 3 components in parallel with a requirement of 2 to work for the system to continue functioning. The equation used to describe this is the binomial distribution[3]:

$$A_s = \sum_{r=0}^{n-m} \frac{n!}{r!(n-r)!} A^{n-r} (1 - A)^r \tag{5}$$

This equation assumes that the components are identical and have identical failure rates. R is the reliability of the component. However, since n=m for the non-redundant system, the equation simplifies to a basic series model, in which all the reliabilities are multiplied with each other.

Additionally, a standby pump needs to be used in the analysis for the redundant system. The cooling water system has 3 active pumps while the DI water system has 4 active pumps. Each system will have 1 standby pump. The symbol used to represent this in a block diagram is:

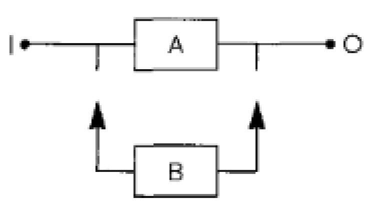


Figure 8: Standby redundancy pump[3]

The m-out-of-n system and the standby redundancy model will be combined to represent the pump systems. The standby redundancy will follow the m-out-of-n system equations. This is because the standby redundancy equations are for series relationships instead of the required parallel model m-out-of-n models. Therefore, the block diagram includes series, m/n analysis, and standby calculations. The summary of symbols and formulas used in the analysis is shown below in the two figures.

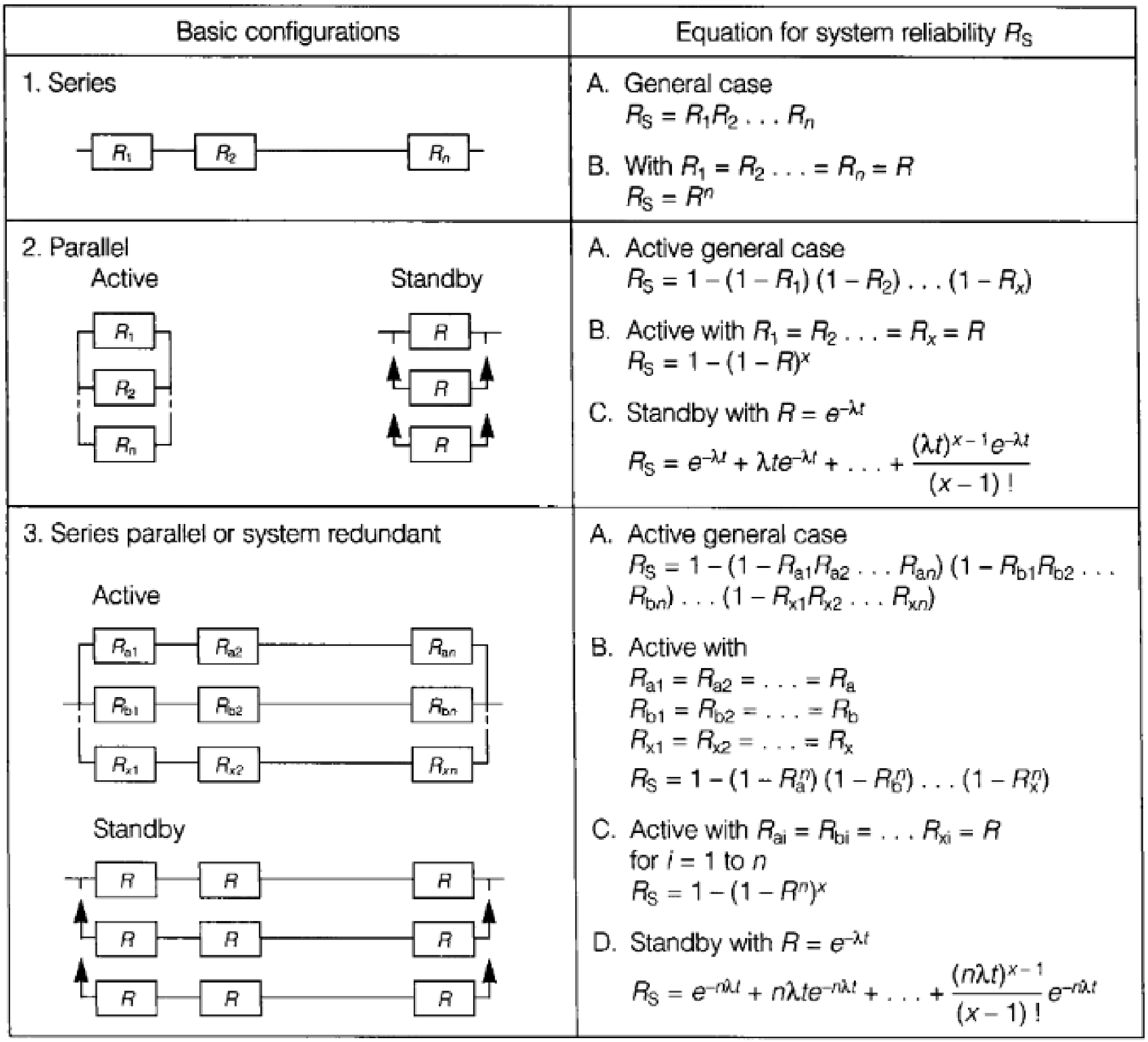


Figure 9: Summary of series, parallel and standby equations and diagrams[3]

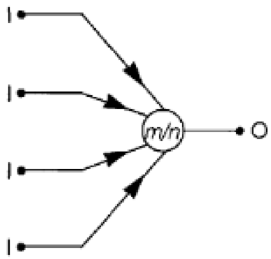
Symbol/Abbreviation	Meaning
	*m/n* is symbol used to show *m*-out-of-*n* items needed for system success in an active redundant configuration

Figure 10: The symbol representing m/n analysis[3]

IV. Block Diagram of RF 1010 Building

The block diagram of the RF 1010 building includes the cooling towers, valves, filter, pumps, and heat exchangers. Standards and data sheets from the Institute of Electrical and Electronics Engineers (IEEE), the International Atomic Energy Agency (IAEA), and the Nuclear Regulatory Commission (NRC) Historic Component Reliability were used to gather information on failure rates of the components. Pumps are centrifugal motor-powered and the valves associated with specific components are shown in Figure 10 below.

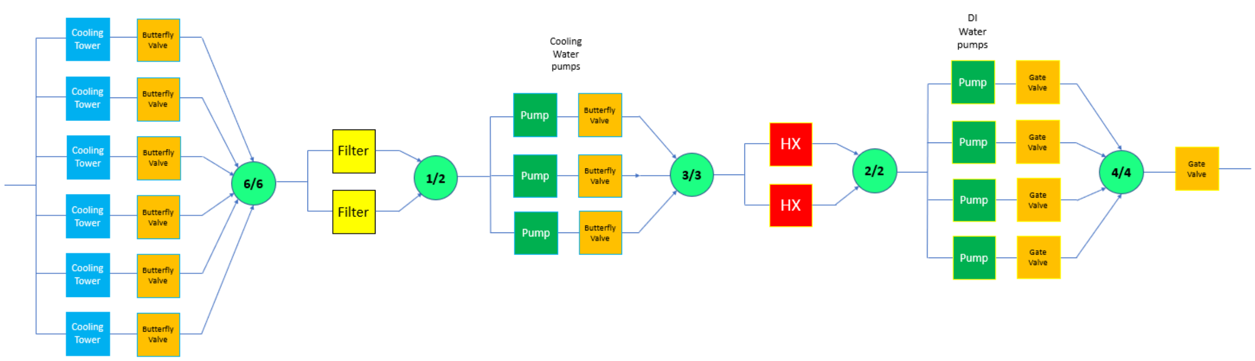


Figure 10: RF 1010 non-redundant block diagram for one half of the RF system

To make the process of solving simpler, the block diagram was divided into series and parallel blocks. The assumptions for the calculations are that identical component types within a subsystem have identical reliability values to simplify the procedure. Figure 11 shows the non-redundant system while Figure 12 shows the redundant system.

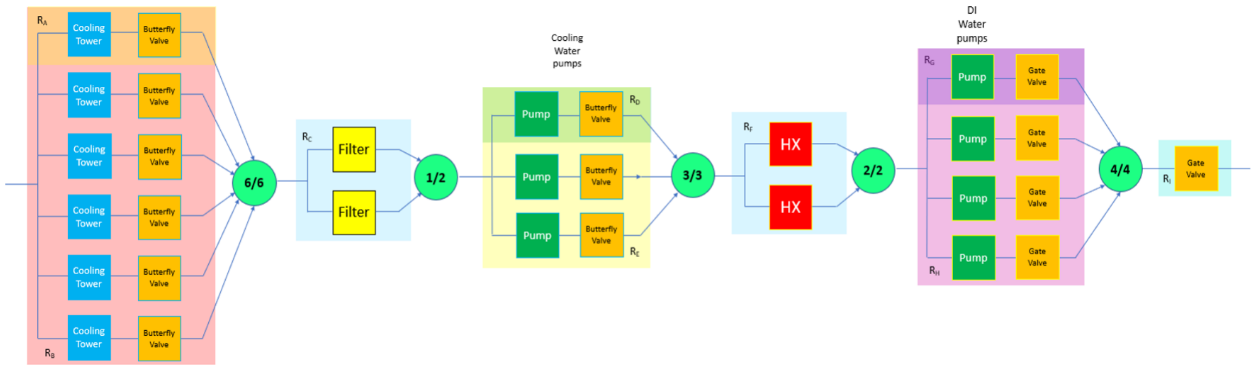


Figure 11: Block diagram grouping components into series and parallel relationships for RF 1010

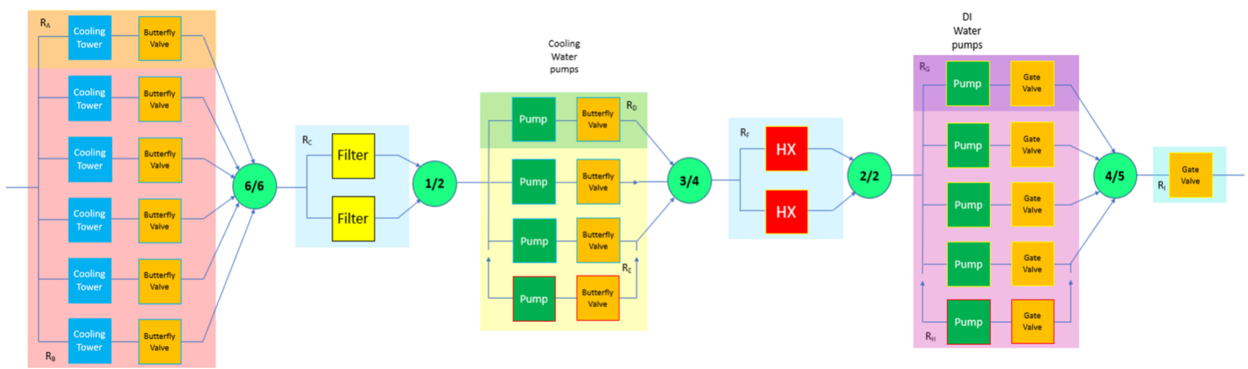


Figure 12: Block diagram representing a redundant 1010 RF system with standby pumps

When performing analysis on the system, the cooling system can be analyzed first. The 6/6 means the entire system has to work in order for the system to run. This is effectively a series relationship between six cooling towers and butterfly valves. For other sections of the block diagram with the green circle and the fraction, the same series analysis can be done. This includes the cooling water pumps, heat exchangers, and DI water pumps. A close-up of the cooling tower subsection is shown below.

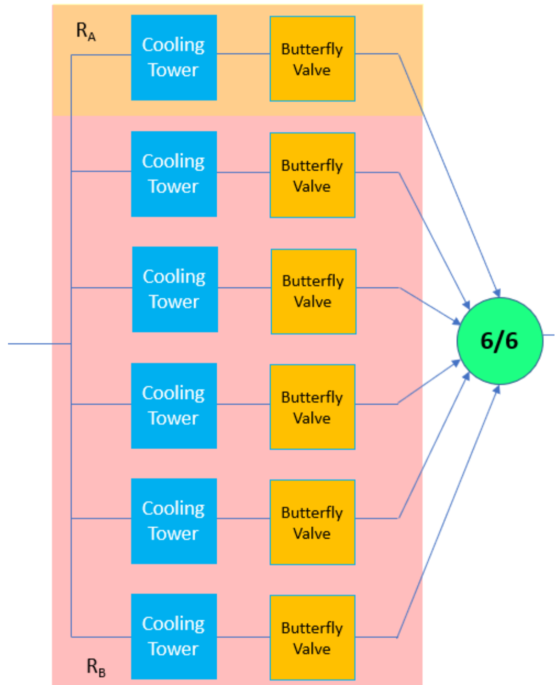


Figure 13: Cooling tower and butterfly valves in a series relationship through m/n analysis

The standby components are added to the redundant system for the pump systems. The m/n analysis and the standby redundancy pump is combined in Figure 14 shown below.

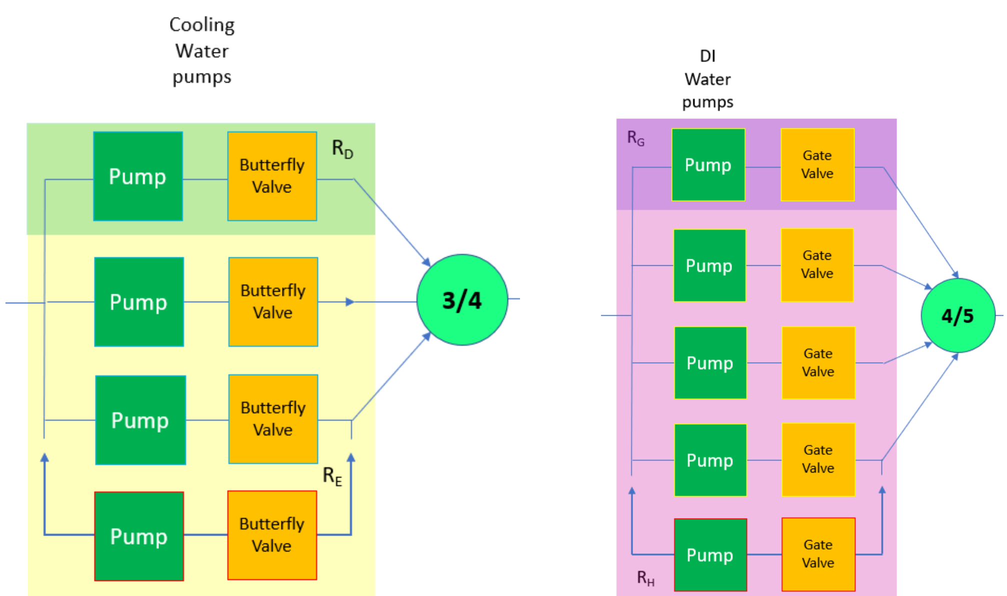


Figure 14: Pump system with standby redundancy and m/n analysis

Sample calculations for the RF 1010 model can be done for the non-redundant and redundant cooling water systems. By using the IEEE and IAEA standards, each availability and reliability for the components can be found. A summary table of the information is depicted below in Table 1. The reliability is calculated using equation (3) while the availability is calculated using equation (2). Table 2 provides the m/n calculations for the components that have a redundancy by using equation (5).

Table 1: Reliability and Availability calculated for each component based on a 28 week operation time

Component	Failure Rate (/hr)	MTTR (hr)	MTBF (hr)	Reliability	Availability
Centrifugal Pump (500-2499 gpm)[5]	2.51E-05	114	3.98E04	88.86%	99.71%
Centrifugal Pump (500-2499 gpm): Composite[5]	1.83E-05	180.4	5.46E04	91.75%	99.67%
Gate Valve[5]	1.90E-06	3.3	5.26E05	99.11%	100%
Butterfly Valve[5]	1.20E-06	1.9	8.33E05	99.44%	100%
Filter[6]	3.00E-05	unknown	3.33E04	86.84%	100%

Table 2: Reliability analysis for m/n configurations where m is not equal to n

Equation Terms	Filter	Cooling Water Pumps	DI Water Pumps
n	**2**	4	5
m	**1**	3	4
n-m	**1**	1	1
Reliability	$R_{s,1} = 0.9827$	$R_{s,2} = 0.9591$	$R_{s,3} = 0.9317$

Therefore, using Table 1 and 2, the reliability can be calculated for both systems. Table 3 summarizes the availability calculation.

Table 3: Steps for calculating the overall system availability for both the non-redundant and redundant cooling systems

Non-Redundant System	Redundant System
$A_A = A_{CT} \cdot A_{BV,\,CT}$	$A_A = A_{CT} \cdot A_{BV,\,CT}$
$A_B = A_A^{\ 6}$	$A_B = A_A^{\ 6}$
$A_C = A_{s,1}$	$A_C = A_{s,1}$
$A_D = A_{pump,\,CW} \cdot A_{BV,\,CW}$	$A_D = A_{pump,\,CW} \cdot A_{BV,\,CW}$
$A_E = A_D^{\ 3}$	$A_E = A_{s,2}$
$A_F = A_{HX}^{\ 2}$	$A_F = A_{HX}^{\ 2}$
$A_G = A_{pump,\,DI} \cdot A_{GV,\,DI}$	$A_G = A_{pump,\,DI} \cdot A_{GV,\,DI}$
$A_H = A_G^{\ 4}$	$A_H = A_{s,3}$
$A_I = A_{GV}$	$A_I = A_{GV}$
$A_{sys} = A_B \cdot A_C \cdot A_E \cdot A_F \cdot A_H \cdot A_I$	$A_{sys} = A_B \cdot A_C \cdot A_E \cdot A_F \cdot A_H \cdot A_I$

The reliability and availability broken down for each component that appears in the 1010 RF system is shown in Table 4 below. These are directly calculated from the standards aforementioned. The cooling tower is the only component that does not appear in the standards, so it is assumed to have a reliability and availability of 99.5%. The original system will be “N” while the redundant system will be called “N+1”. Table 5 shows a comparison of the calculations for the N and N+1 systems with a final availability and reliability calculated for one train.

Table 4: RF 1010 Cooling Water component reliability and availability summary[7]

Component	Reliability	Availability
Cooling Tower	0.995	0.995
Cooling tower Isolation valve (butterfly)	0.994	1.000
DI Filter	0.868	1.000
Cooling water pumps	0.918	0.997
Cooling water pump Butterfly valve	0.994	1.000
Heat Exchanger	0.986	1.000
DI Water pumps	0.918	0.997
DI Water pump Gate Valve	0.991	1.000
Gate Valve	0.991	1.000

Table 5: N and N+1 system calculated values for reliability and availability (one train)[7]

		N System Calculation		N+1 System Calculation	
Block		**Reliability**	**Availability**	**Reliability**	**Availability**
RA		0.9894	0.9950	0.9894	0.9950
RB	CT System	0.9381	0.9704	0.9381	0.9704
RC	Filter	0.9827	1.0000	0.9827	1.0000
RD		0.9124	0.9967	0.9124	0.9967
RE	CW System	0.7594	0.9902	0.9591	0.9999
RF	HX	0.9722	1.0000	0.9722	1.0000
RG		0.9094	0.9967	0.9094	0.9967
RH	DI Water	0.6838	0.9869	0.9317	0.9999
RI	Gate Valve	0.9911	1.0000	0.9911	1.0000
		R_{sys}	A_{sys}	R_{sys}	A_{sys}
		46.12%	94.82%	79.37%	97.02%

Since the previous calculation was only for one train, the availability needs to be squared to determine the overall availability for the 1010 RF. The summary for the N and N+1 systems is shown below. Therefore, the availability for the system in the N case is 89.91%, while the N+1 case has a higher availability of 94.13%. The difference is 4.22%.

Table 6: Availability calculation and difference for each type of system

	Availability		
	N	N+1	Difference
One Train	94.82%	97.02%	2.20%
Full 1010	89.91%	94.13%	4.22%

V. Cooling System Scenarios

Several cooling system scenarios were made to see how the systems' availabilities compare. The scenarios chosen were one 100%, two 100%, two 50%, and three 50% pumps for cooling water and DI water systems. The cooling towers were reduced to 4 for a simple calculation.

The first system mentioned doesn't have any redundancies so it is called a "N" system. The entire system is effectively in series when also accounting for the m-out-of-n system reduction. Figure 15 belows shows this layout. Figure 15 through 18 shows the three other models aforementioned. The 2 100% has double the amount of original pumps so it is a 2N system. The 2 50% model is a N system, while the 3 50% model is a N+1 system.

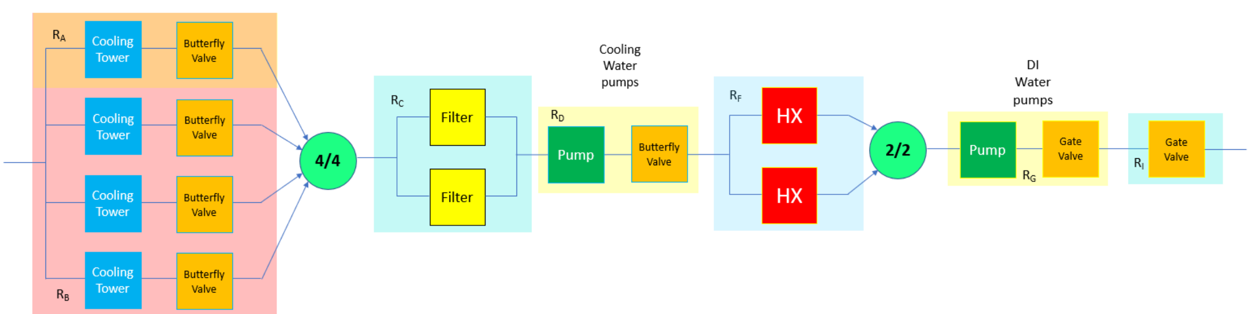


Figure 15: 1 100% (N) system representing a modification of the RF 1010 cooling system components

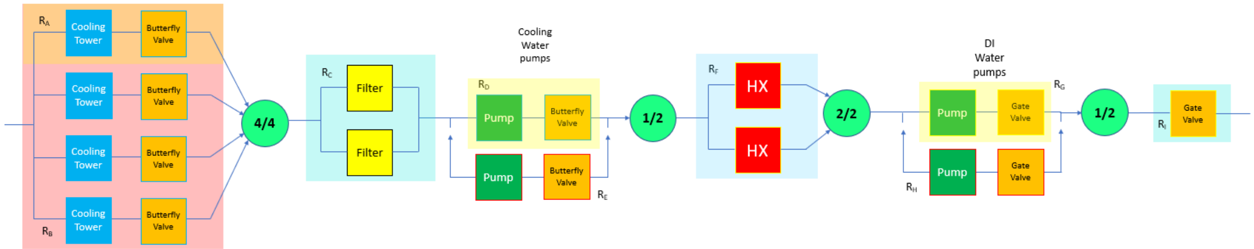


Figure 16: 2 100% (2N) system representing a modification of the RF 1010 cooling system components

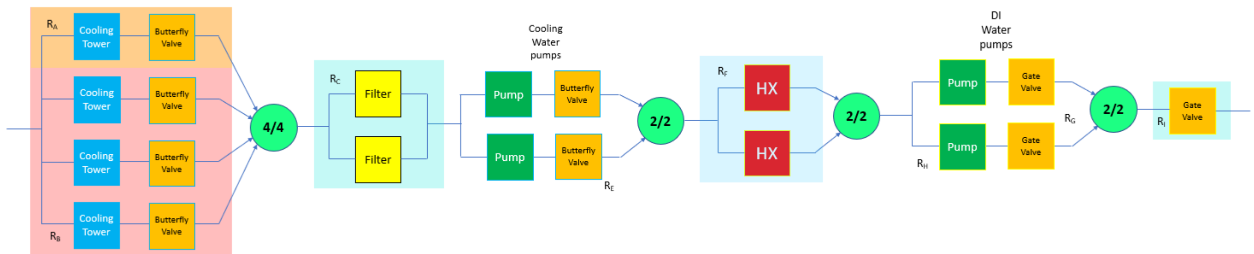


Figure 17: 2 50% (N) system representing a modification of the RF 1010 cooling system components

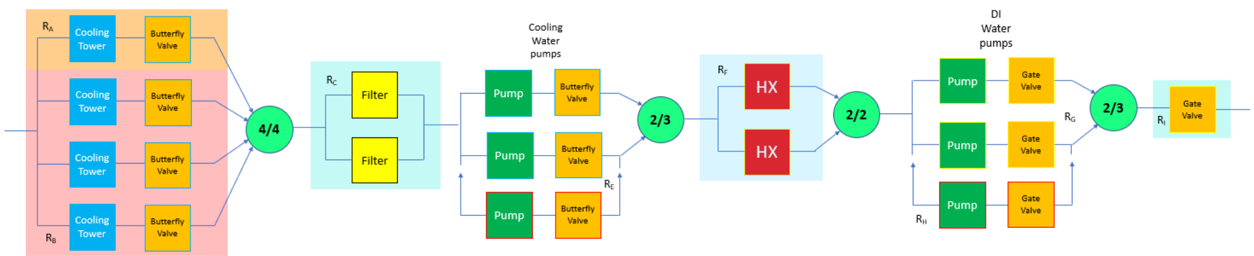


Figure 18: 3 50% (N+1) system representing a modification of the RF 1010 cooling system components

The two main scenarios to compare were the 2X50% and 3X50% since the others were lower in availability. The difference in cost was calculated to determine how much of an impact a redundant system would have. The components are still the same as before, so Table 4 was used for calculation. The availability results are shown below in Table 7.

Table 7: Availability for 2 general and smaller-scale scenarios

	2x50% (N)	**3x50% (N+1)**
ΔAvailability$_{\text{2 trains}}$	Base	2.5%
ΔCost$_{\text{2 trains}}$	Base	$258,996

VI. Availability Calculation Sample from RHIC

Part of the research was to determine how the availability of a system is currently calculated. The Collider-Accelerator Department has their own operational report that documents failures in their systems and conducts weekly availability calculations for the overall Relativistic Heavy Ion Collider (RHIC). Figure 19 was provided by Christopher Naylor, which showed the calculations used for the availability.

$$\text{Availability} = \frac{actual\ beam\ time}{scheduled\ beam\ time} \equiv \frac{Beam\ use\ time}{Calendar\ time - scheduled\ interruptions}$$

$$\textbf{RHIC Availability} = \frac{Physics + Machine\ Development + Machine\ Setup + Experiment\ Setup + Accelerator\ Experiments}{(Physics + Machine\ Development + Machine\ Setup + Experiment\ Setup + Accelerator\ Experiments) + Failures}$$

$$\text{DOE expected beam hours} = (\#\ of\ weeks\ - 1\ week\ overhead) \times \left(\frac{160\ available\ hours}{1\ week}\right) \times \mathbf{0.85}$$

Figure 19: Availability equations used by CAD to determine weekly availability for the RHIC

The Collider Accelerator Department provided documented instances for failures in the cooling system. The operator log failure analysis is shown below, which includes the duration, impact, severity, and component that caused failure. Data was collected from 2007 to the present for cooling water failures.

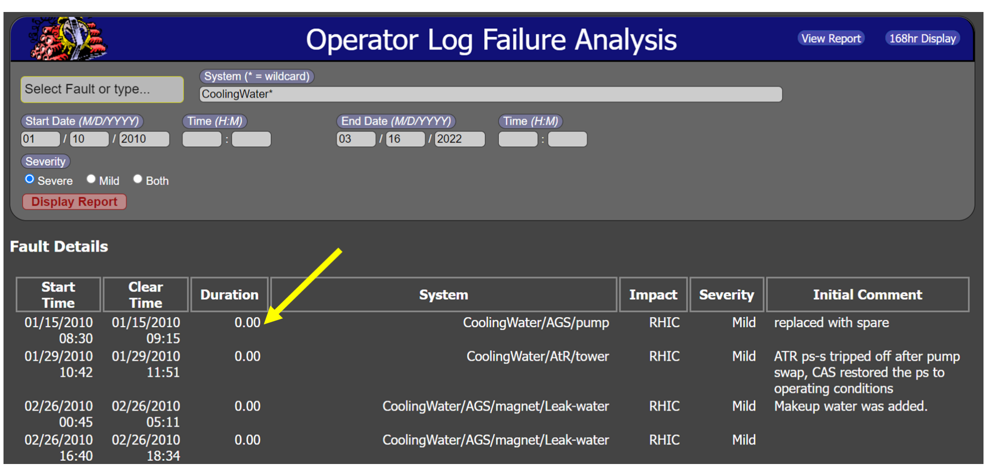


Figure 20: Operator Log Failure Analysis page describing the information documented in failure entries

The data was exported to a spreadsheet, which was organized as shown below in Figure 21. The data was organized by year and the dates in which the failures occurred were converted into week numbers for easier analysis. Some component information was missing so I had to manually assign information based on the comments left on the failures. The scheduled operation time per year was also needed for availability calculations for the individual components themselves. This data was received from the CAD operation website and is detailed in Table 8.

Sch Op Time (wk	Instan	Year	Week	Duration	MTBF	Location	Group 1	Component	Misc.	Issue	Impact	Severit	Availability_
19	1	2022	10	61.92	106.1	AGS	rf	tower	Flow	Overtemp	RHIC	Severe	63.1%
19	2	2022	8	1.27	166.7	AGS	magnet	valve	Flow	Overtemp	RHIC	Severe	99.2%
19	3	2022	6	14.03	154.0	Booster|BtA	rf	piping and HX	Leak		RHIC	Severe	91.6%
19	4	2022	5	0.13	167.9	Linac|LtB		pump			BLIP	Mild	99.9%
19	5	2022	4	13.37	154.6	NSRL	PowerSupply	deionizer	Flow	Overtemp	FT	Severe	92.0%

Figure 21: Failure data entries organized to show year, week number, duration, component, severity, and calculated availabilities

Table 8: RHIC scheduled operating time per year converted to weeks

Year	RHIC Scheduled Ops	Weeks	Rounded weeks
2007	assumed 19 weeks	19	19
2008	3081.9	18.3	19
2009	3926.07	23.4	24
2010	4316.07	25.7	26
2011	4082.24	24.3	25
2012	3599.06	21.4	22
2013	2827.74	16.8	17
2014	3523.7	21.0	21
2015	3873.76	23.1	24
2016	3249.68	19.3	20
2017	3139.44	18.7	19
2018	4053.92	24.1	25
2019	4278.12	25.5	26
2020	4645.23	27.7	28
2021	3764.69	22.4	23
2022	3042.07	18.1	19

The components were first organized by failures per year. The years were analyzed to see how many failures were reported per component in Table 9. For example, the chiller had 3 counts of failure in 2013 with a sum of availability as 269.7% for those weeks. Since the scheduled operation time was 17 weeks, the weeks without failure are 14. These weeks have a

100% availability for the chiller. Therefore, an average availability was determined by the example calculation:

$$Availability = \frac{(14*100\%)+269.7\%}{17} = 99.81\%$$

Table 9: Excerpt from organized component availability data spreadsheet

Component	Year	Weeks without failure	Average Availability	Sch Op Time (wks)	Counts of Failure	Sum of Availability for weeks with Failure
chiller	2013	14	99.81%	17	3	296.7%
chiller	2015	23	99.85%	24	1	96.4%
chiller	2017	18	99.86%	19	1	97.3%
chiller	2018	22	99.28%	25	3	282.0%
chiller	2021	22	99.95%	23	1	98.8%
chiller	2022	18	99.08%	19	1	82.6%
controls	2009	23	99.97%	24	1	99.4%
controls	2010	25	99.58%	26	1	89.2%
controls	2013	15	99.81%	17	2	196.7%
deionizer	2009	22	99.86%	24	2	196.6%
deionizer	2014	20	99.94%	21	1	98.7%
deionizer	2022	16	99.56%	19	3	291.6%

Finally, the averages taken per year were also averaged to find the final availability per component. Thus, based on Table 9, the chiller availabilities were taken from 2013 to 2022 and averaged to result in the value below:

$$Chiller\ Availability = \frac{99.81\%+99.85\%+99.86\%+99.28\%+99.95\%+99.08\%}{6} = 99.64\%$$

The same is done for the rest of the components and summarized in Table 10. The data is then incorporated in a graph visually showing the difference in availabilities in Figure 22. As observed, the components all have a 99% availability or higher. This is a remarkable result since this shows the RHIC is operating very well and almost close to industry standards.

Table 10: Final averaged component availabilities using the Collider Accelerator failure data

Component	Availability
Chiller	99.64%
Controls	99.79%
Filter	99.88%
Flow Switch	99.85%
Piping and HX	99.30%
Pump	99.71%
Tower	99.09%
Valve	99.91%
Deionizer	99.78%
Other	99.89%
Instrumentation	99.98%
Air Compressor	99.71%

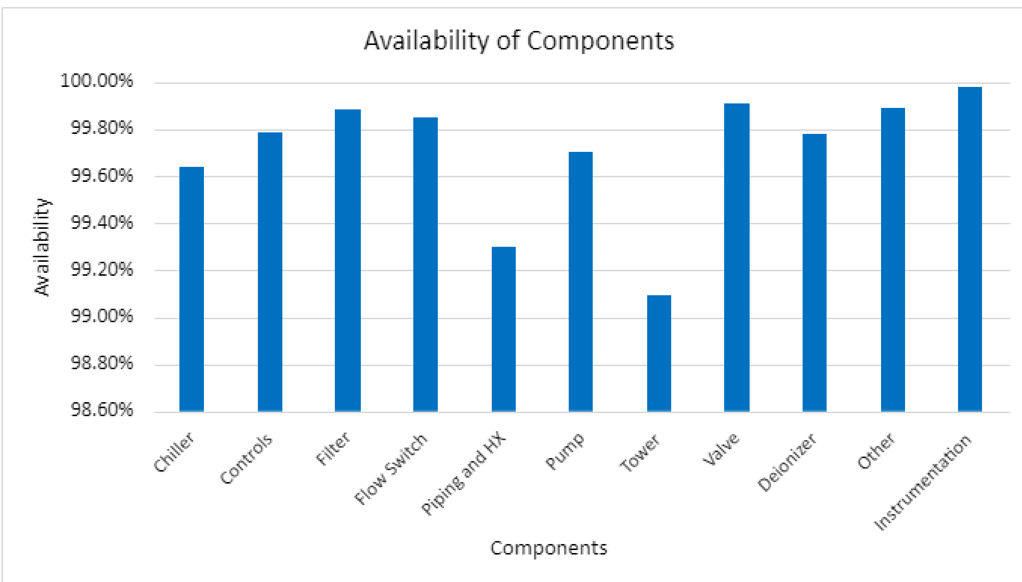


Figure 22: Availability of components calculated based on CAD failure data

VII. Overall Electron-Ion Collider Availability

The previous calculations for the Radio Frequency and general scenarios were used in an overall calculation of availability. The systems within the EIC don't have an availability calculation established, so a sample reference system was used. This was done to see what typical numbers would be target availabilities for systems within a larger one. The Stanford

Linear Accelerator Collider (SLAC) National Accelerator Laboratory has 8 systems that contribute to the overall availability, shown under NLC systems and Availability in Figure 23. As observed, there isn't an even distribution of availability, so some systems may perform better for a lower cost.

NLC Systems	Availability
Power Supplies	0.975
Magnets	0.975
RF Systems	0.950
Motors	0.975
BPMs	0.990
Controls	0.985
Utilities	0.995
Miscellaneous	0.995
Totals:	**0.85**

Figure 23: Sample reference systems for overall system analysis[4]

The RF 1010 availabilities are included in the sample just to see how the overall system will be affected by changes in availabilities of systems within. The cooling system is included under utilities, but is not representative of the overall utilities in the ring. The difference in utilities was 4.22%, but the overall difference was 3.6%. This is useful information for when we retrieve actual data from all the systems in the EIC.

N System		
System		Av (%)
Power Supplies		97.6%
Magnets		97.6%
RF		95.2%
Motors		97.6%
BPMs		99.0%
Controls		98.5%
Utilities		89.9%
Misc		99.5%
TOTAL AVAILABILITY		77.2%

N+1 System		
System		Av (%)
P.S.		97.6%
Magnets		97.6%
RF		95.2%
Motors		97.6%
BPMs		99.0%
Controls		98.5%
Utilities		94.1%
Misc		99.5%
TOTAL AVAILABILITY		80.8%

Figure 24: Sample overall EIC calculation with reference data to demonstrate changes in availabilities

Using this information with the cost differences, the sample calculations can be summarized in the table below. Therefore, the redundancy should be the default choice and if not included, the availability would be lacking by 3.62%.

Table11: Overall EIC Impact in difference of availability and cost

	Overall EIC Impact	
	N+1	N
Δ Availability	Base	-3.62%
ΔCost	Base	-$336K

VIII. Conclusion

Based on the calculations done, it is apparent that having redundancy in the pumping subsystems will increase the RF 1010 cooling system availability, which will then increase the overall availability. Omitting the redundancy will cost the department a 3.62% availability, with a cost difference of $336,000. The cost differential is much less than the potential for availability. Therefore, having a redundant system can increase the overall EIC system availability to meet the assumed goal of 0.85.

Some suggestions for the future would be to look into which systems in the EIC can be modified to increase the availability for a lower cost compared to other systems. Evenly distributing the availability per system is not realistic when the systems are all vastly different in size. Therefore, a larger and more complex system will be able to have a lower availability since another much simpler system will carry the higher availability to reach the overall goal. This was analyzed on a much smaller scale when filters could have redundancy for a lower cost to drive the availability up compared to the other components within the system.

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