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Fluid dynamic simulation and analysis of water-cooling systems for the Electron-Ion Collider

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Abstract

The Electron-Ion Collider is the newest large-scale project at Brookhaven National Laboratory. The collider's purpose is to provide further advancements in the knowledge of the universe's origin by accelerating particles near the speed of light. Our project for this 3.8 km ring was to create a thermal hydraulic steady-state simulation design of the water-cooling system to be cost-effective and energy efficient, as envisioned by Charlie Foltz, the EIC Infrastructure Division Director. The system would include a supply and return header, which cools several thousand components of the ring. The water would then be returned and cooled down using a system of cooling towers and plate and frame heat exchangers. Due to the size of the system and the complexity of the network analysis, a fluid dynamic simulation software, AFT Fathom, was used. Since previous methods of maintaining systems relied on building upon smaller real-life models and implementing empirical data, this flow model was unique and first of a kind in the domain of accelerator design, construction and operation. Therefore, our hydraulic team piloted a new method to perform network analysis on a large scale cooling system. We successfully created several test scenarios for system behavior in a shorter time compared to the method of performing hand calculations. Cooling specifications for heat rejection, pressure drop, flow rate, and pipe sizing were changed based on the individual systems of the vacuum, radio frequency (RF), magnet and power supply, and cryogenics sections. Finally, we used DOE guidelines to perform life-cycle cost analysis with net present value and carbon saving analysis on the systems where pipe size could be optimized.

I. Introduction

The Electron-Ion Collider is a large model, which requires cooling systems for every component to ensure the temperatures are in safe ranges. A hydraulic model is extremely beneficial to assess the behavior of the system at different components, especially for something as complex as this. Charlie Foltz, the Infrastructure Division Director for the EIC, decided that the hydraulic model was the best approach. AFT Fathom, a cooling simulation software, was used to get a comprehensive understanding of network analysis with such a large system. The ring is broken down into various systems, which was worked on throughout the summer. The first section includes the vacuum ring, which follows the path of the outer ring in Figure 1.

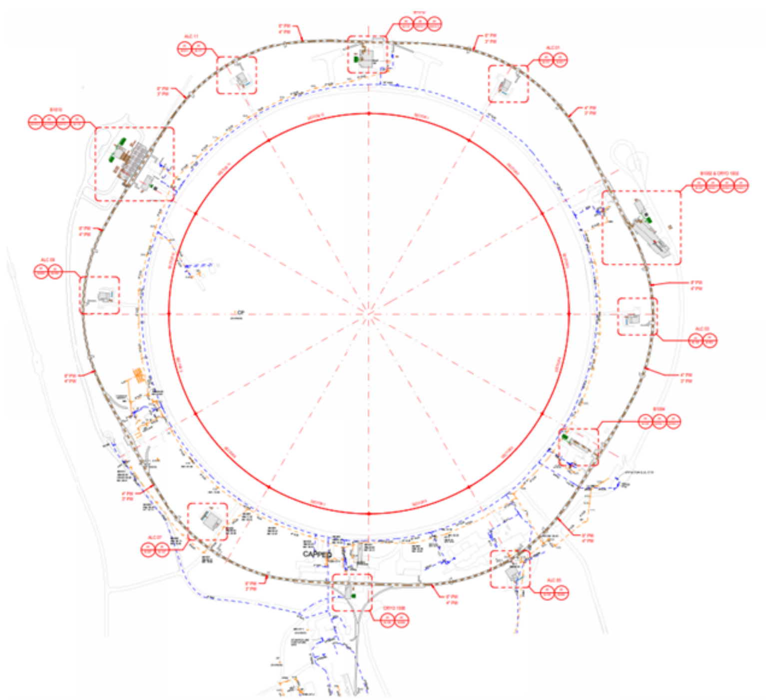

Figure 1: EIC Layout with buildings for cooling

The next sections included the radio frequency (RF) systems. The cooling department worked closely with other interns who designed the layout of power amplifier units in Creo. We added the magnets and power supplies in one system, and the final systems included the Cryogenics buildings from the 1002, 1006, and 1010 buildings.

We designed the layout of all buildings and systems and then used inputs to match cooling requirements of each individual component within the systems from a Master Spreadsheet. The team ultimately utilized a brand new method of cooling system design in a fraction of the time it would take for hand calculations.

II. Vacuum Ring

The vacuum ring follows the perimeter of the EIC. Since the ring is large and complex, it was divided in half between two interns. First, quadrants were easier to create to determine the proper layout and parameters. Each quadrant was composed of arcs, straight sections, and interaction regions (IRs). The arc sections have 16 heat rejection components, while the straights have 5 and the IRs have 6. Additionally, each of these sections had their own set of parameters that needed to be met. The data for each section is compiled in Table 1 below.

Table 1: Summary of the Vacuum System cooling specifications

Section	Heat Load (kW)	Pressure Drop, dP (psi)	Temperature Rise, dT (℉)	Velocity (ft/s)	Flow Rate (gpm)	Nominal Size (in)
Arc	65	28	27.7	5.4	16	0.75
Straight	42	32.3	18	5.4	16	1.00
IR	27	8	23	7.2	8	0.50

The model data is also displayed in the software to keep track of all required parameters, as seen in Figure 2. We first created each loop for the sections and then added all of the data values.

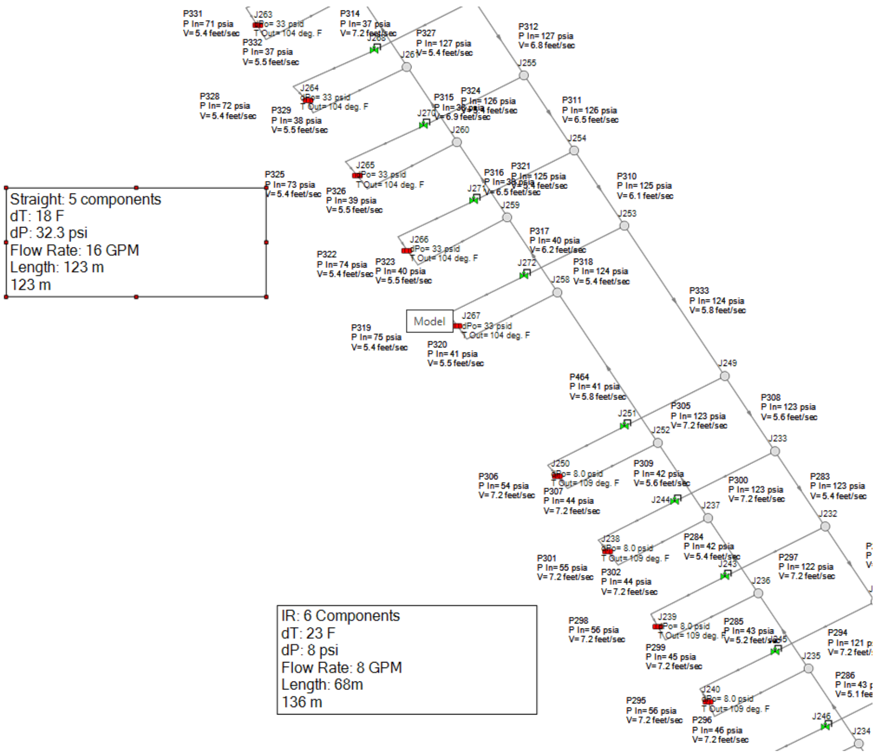

Figure 2: Straight and IR Sections of the Vacuum Ring

Along with the data provided in a master spreadsheet, loss values specifically associated with the heat rejection components were determined through the Darcy-Weisbach Equation. This equation is as follows:

$$h_f = K\frac{v^2}{2g}.$$

The velocity is in feet per second and head is in feet, while gravity is in feet per second squared. The loss factor, K, is unitless. The velocity is found through the simulation and varies depending on the section. Each section has its own loss factor value, which is detailed in information boxes on the model, shown in Figure 3. These values set the required pressure drop across the heat rejection components.

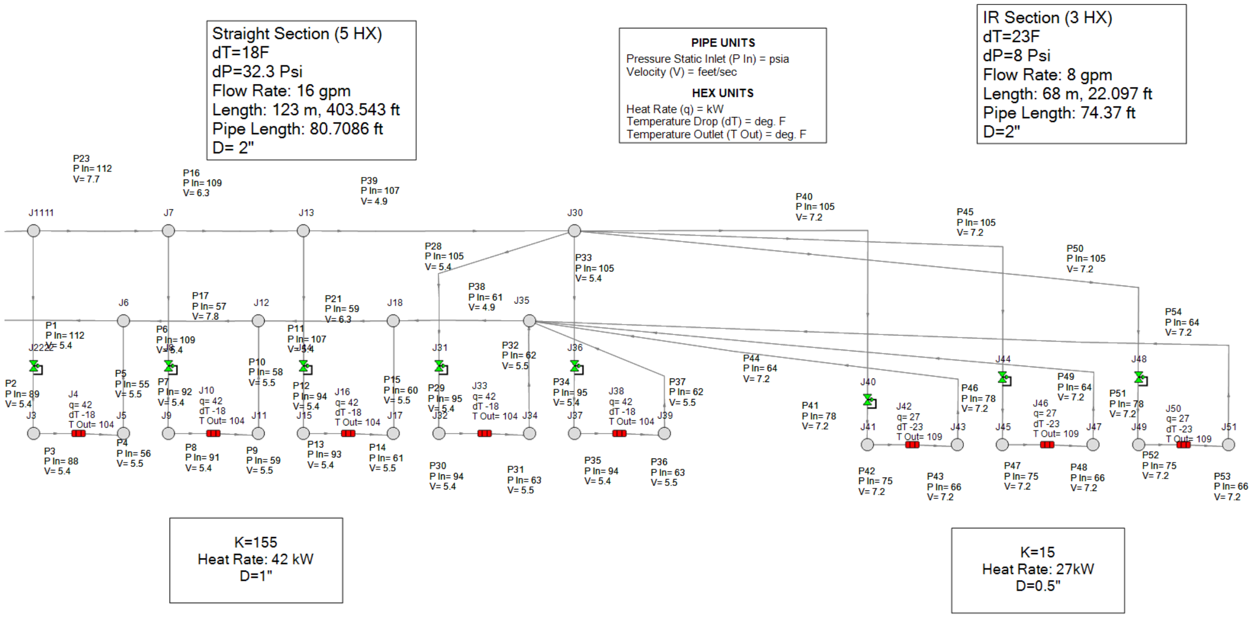

Figure 3: Loss factors and cooling specifications detailed on straight and half IR sections

The pump systems for the vacuum system, as well as the rest of the systems are made up of two running pumps and one stand-by pump. The stand-by pump is meant to illustrate a situation in which one pump would be shut down or in maintenance. All pumps are set to run at half the required gpm of the system, and any pumps that do not have a real pump curve are assumed to operate at 70% efficiency. All systems also include two plate and frame heat exchangers that cool down the water to the required 86℉. A figure of the standard layout is displayed in Figure 4.

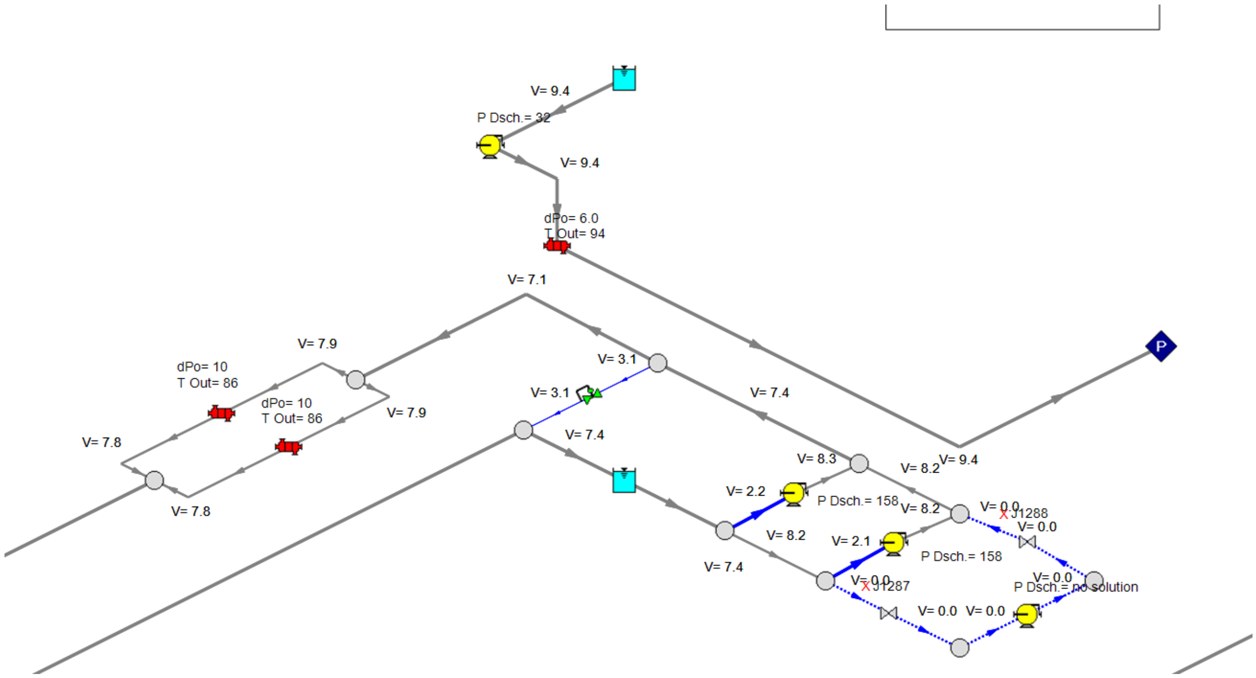

Figure 4: Pumps and Heat Exchanger Layout

Since only half of the ring needed to be designed, the northern halves were mirrored across a horizontal axis to create the bottom two quadrants of the ring. Also, since each quadrant is controlled by its own building, connections between the quadrants are made in the form of closed valves. This is to prevent mixed flow between the two sides, but in the event that one quadrant is down, it can get water from another quadrant.

Both halves of the EIC vacuum ring consist of 96 heat rejection components, with 3 arcs, 6 straight sections, 2 full IR sections, and 2 half IR sections. Both models included half IR sections, located at the 6 and 12 o'clock positions, which connect the left and right side. The two models side by side are shown below in Figure 5.

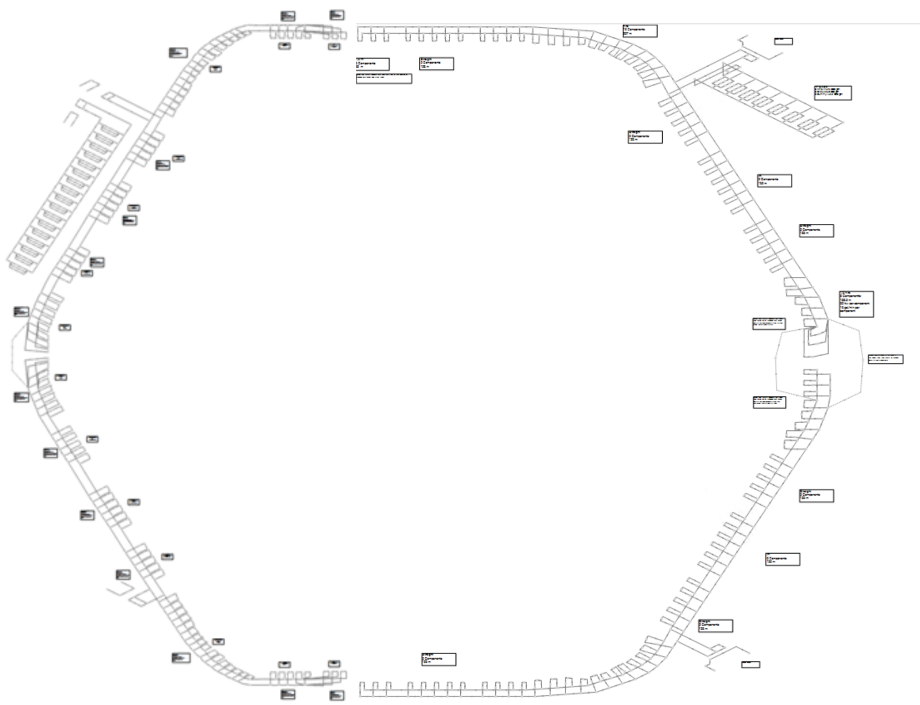

Figure 5: Two halves of the Vacuum system ring

III. Radio Frequency System

1002 RF System

There are 26 sections of heat rejection components in the 1002 building RF system. These heat rejection components are in place for the 13 cavities in the 1002 building. Each section consists of a power amplifier (PA), circulator, and dummy load (absorber). All RF systems consist of these three components per unit. The sections are also broken up into twenty 591 MHZ cavities, and six 1773 MHZ cavities. The heat load for these cavities was calculated by summing up the heat load values provided by the RF system group, and dividing the total heat load amongst the total number of sections in the RF system. This was done because the original number of cavities was modified, so the heat load and flow rate per cavity had to be adjusted. The data tables below summarize the cooling requirements and Figure 6 shows the 1002 RF layout.

Table 2: 591 MHZ unit cooling specifications

Section	**Heat Load (kW)**	**Pressure Drop (psi)**	**Temperature Rise (℉)**	**Flow Rate (gpm)**	**Loss Factor, K**
Power Amplifier	30	45	11.9	16.95	200.09
Circulator	0.76	30	4.9	1.05	213.18
Dummy Load	30	30	25.9	7.898	87.42

Table 3: 1773 MHZ unit cooling specifications

Section	**Heat Load (kW)**	**Pressure Drop (psi)**	**Temperature Rise (℉)**	**Flow Rate (gpm)**	**Loss Factor, K**
Power Amplifier	10	45	11.9	5.66	257.01
Circulator	0.25	30	4.9	0.351	1980.65
Dummy Load	10	30	25.9	2.63	108.8

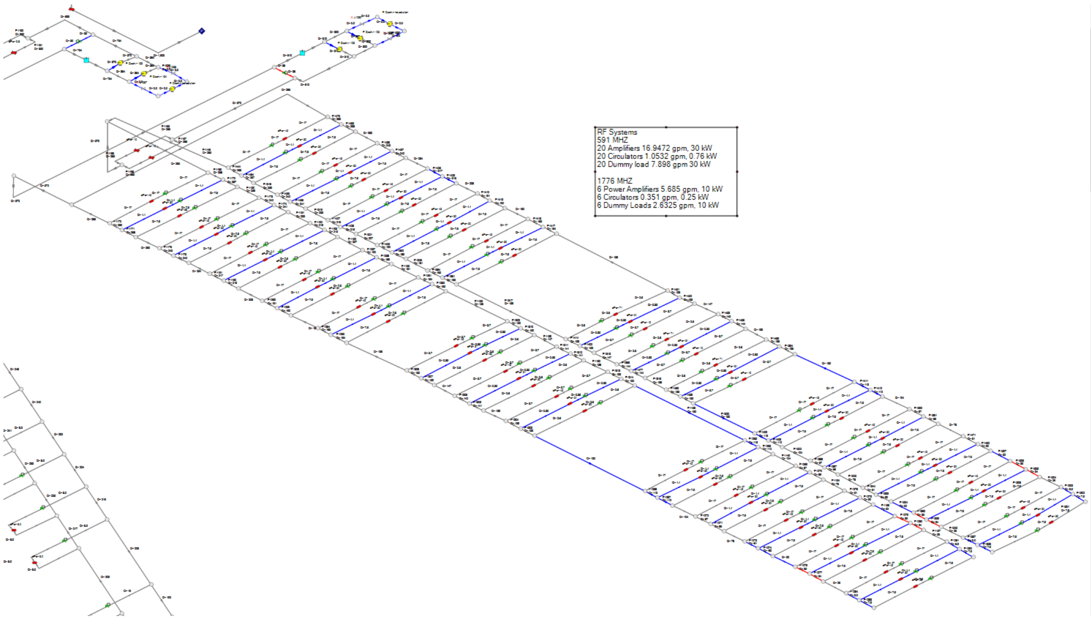

Figure 6: 1002 RF Building Overall Layout

1010 RF System

There are 36 sections of heat rejection components in the 1010 RF system. Originally, there were supposed to be 34 units, but the heat load and flow rates were totaled and divided among 36. The resulting calculations are summarized in Table 4 below.

Table 4: RF 1010 unit cooling specifications

Section	Heat Load (kW)	Pressure Drop (psi)	Temperature Rise (℉)	Flow Rate (gpm)	Loss Factor, K
Power Amplifier	377.78	45	12	226.34	98.93
Circulator	9.44	30	4.9	14.04	84.00
Dummy Load	53.36	30	5.0	77.09	96.40

Two rows of 18 were created and each unit was grouped in pairs to replicate the Creo layout of the 1010 building. The layout used is shown in Figure 7.

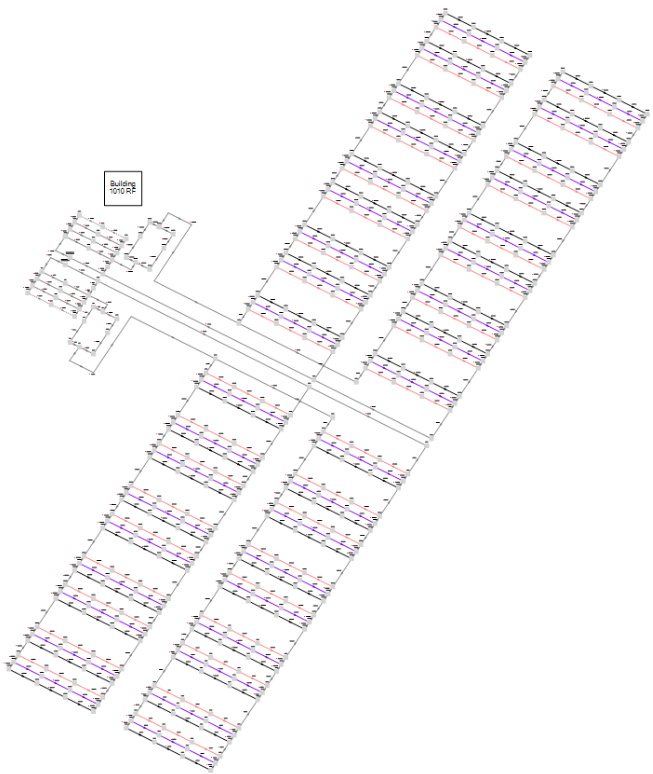

Figure 7: 1010 RF Building Overall Layout

A close-up of the pumping system is displayed in Figure 8. There are three pumps functioning in each circuit, with a total of 6 pumps. There is one standby pump each as a backup. Both circuits have two plate and frame heat exchangers to cool down the water.

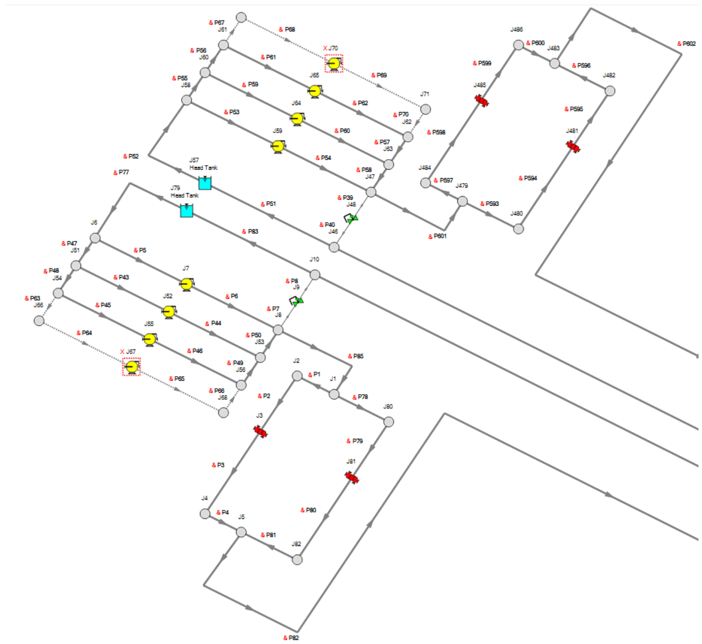

Figure 8: RF 1010 Pumping System

Optimization

When designing a system, optimizing the model is a large part of analysis. This stems from the realization that two pipe sizes can result in the velocity parameter being between 5 ft/s and 10 ft/s. Part of the optimization requires analyzing the benefits of using a pipe size that provides a cheaper installation cost versus one that provides a cheaper pump power cost. One example was for the power amplifier section of the RF system. Three pipes for each of the 36 sections could either be 3 inches in diameter, or 4. When analyzing the power cost, it was seen that the 3 inch pipe had a higher cost total. However, the total cost for piping installation was higher for the 4 inch pipe. By comparing the two costs, it can be seen that the power cost is much higher than the installation, so the 4 inch pipe should be chosen for the system, as it results in a lower overall cost. Table 5A summarizes the information.

Table 5A: Optimization of pipe sizes for power cost and pipe cost

Pipe Size (in)	Velocity in pipe (ft/s)	Power (kW)	Cost for Power	Cost per unit	Total Cost for piping
3	8.7	470.10	$2,783,462.10	$145.50	$147,711.60
4	5.1	391.86	$2,320,203.06	$163.00	$165,477.60
		Difference	$463,259.04		$(17,766.00)

Furthermore, saving on power costs results in savings for carbon emissions as well. Based on information from the U.S. Energy Information Administration, there are 0.92 pounds of CO2 emissions per kWh [1]. Using this information, a calculation can be done to determine exactly how much CO2 is being used per year. Referring to Table 5B, multiplying columns A through D together by 7 days a week results in column E. This provides the emissions of CO2 per year. As we can see, the 3 inch pipe has a much higher emission of CO2 and assuming the EIC will run for 20 years, the emissions already make 40.6 million pounds. This is compared to 33.9 million pounds of CO2 from the 4 inch pipe. The difference is a factor of 1.9, so these calculations should be used for determining the best pipe size, not only for cost, but in terms of lower carbon emissions as well.

Table 5B: Carbon Emissions comparison for operating 3 inch pipe vs. 4 inch pipe

	A	B	C	D	E
Pipe Size (in)	**Power (kW)**	**Operating Weeks per year**	**Operatin g Hours per Day**	**Pounds of CO2 per kWh**	**Pounds of CO2 emission per year**
3	470.10	28	24	0.92	2,034,442
4	391.86	28	24	0.92	1,695,845
				Savings per year	338,598

1004 RF System

The 1004 RF System is angled like the 1010 building, except it is in the 4 O'Clock location of the EIC ring. This system is much smaller than the previous system and includes only one pumping circuit with 15 units. The full configuration is shown below in Figure 9.

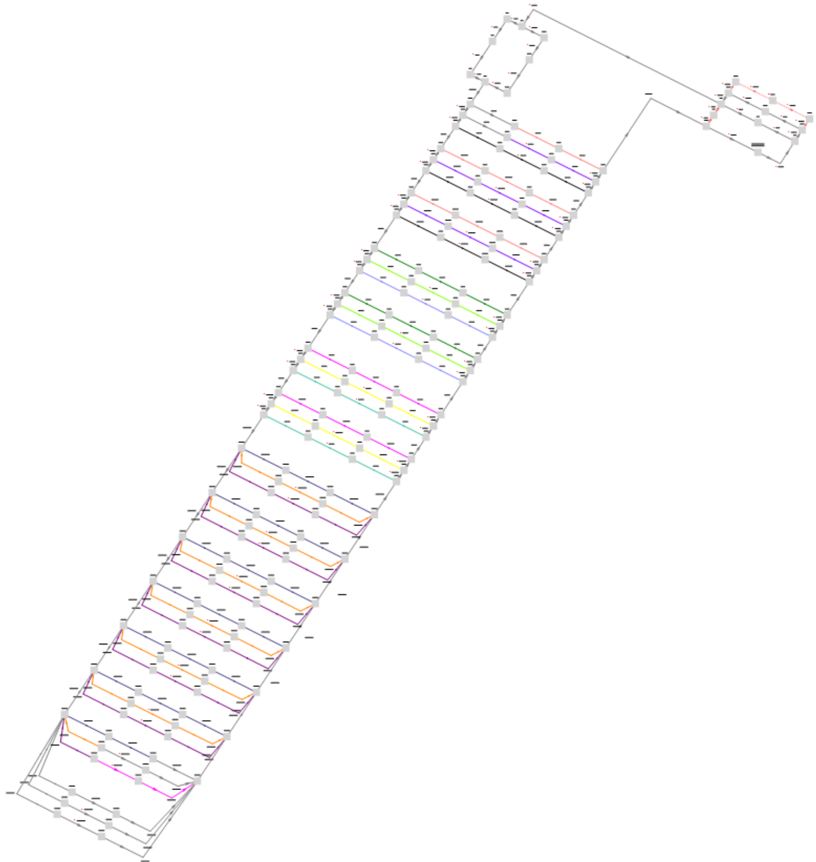

Figure 9: RF 1004 Full Configuration

Although the system is smaller, the units are not all uniform. This is much harder to design since all components need to be carefully matched to the respective cooling specification. There are a total of 5 groups and the data is summarized in Table 6 below, which includes the number of units each.

Table 6: RF 1004 Cooling Specifications for each group

Number of Units	Heat Rejection Component	Heat Rate (kW)	Flow Rate (gpm)	Pressure Drop (psig)	Temperature Rise (℉)
3	Power Amplifier	40	22.63	45	12.1
	Circulator	1	1.40	30	4.9
	Dummy Load	40	10.53	30	25.9
2	Power Amplifier	70	26.54	44	18
	Circulator	1	0.76	30	9
	Dummy Load	70	17.69	30	27
2	Power Amplifier	80	30.33	44	18
	Circulator	1	0.76	30	9
	Dummy Load	80	20.22	30	25.9
7	Power Amplifier	120	67.9	45	12.1
	Circulator	3	4.21	30	4.9
	Dummy Load	120	31.59	30	25.9
1	Power Amplifier	50	28.30	45	12.1
	Circulator	1.3	1.76	30	4.9
	Dummy Load	50	13.16	30	25.9

The first group with three units is shown in the image below in Figure 10.

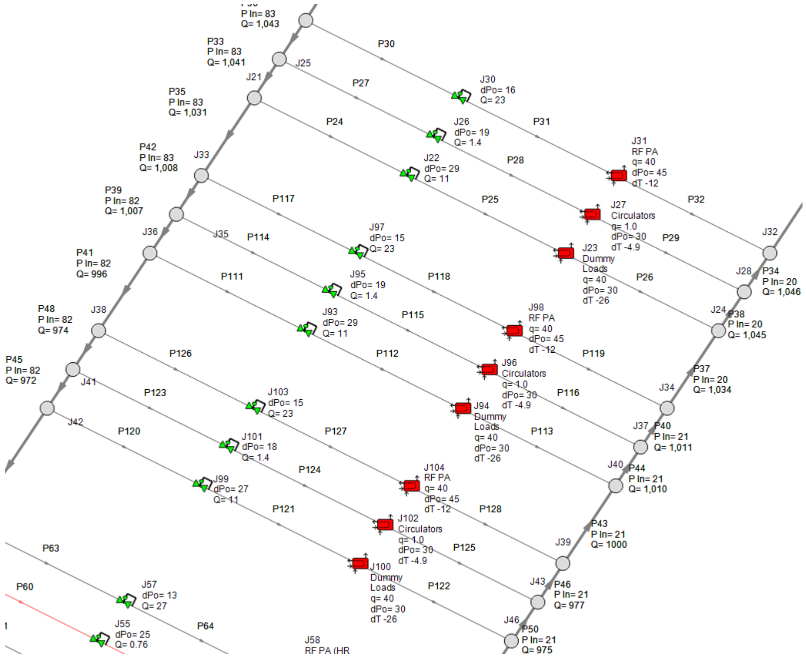

Figure 10: RF 1004 close-up of first group of units

1006 RF System

The 1006 RF System is laid out vertically in a horizontal building. All 14 units are identical, which makes it easier to model. The units have been laid out in two rows of 7. The full model is in Figure 11, while a close-up of one RF unit is in Figure 12.

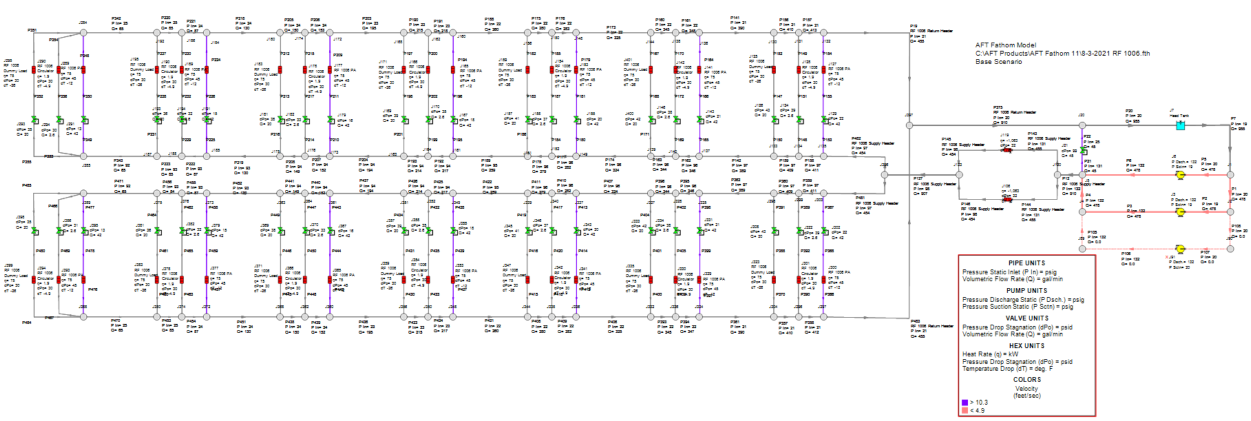

Figure 11: RF 1006 Building with 14 RF Units and Data

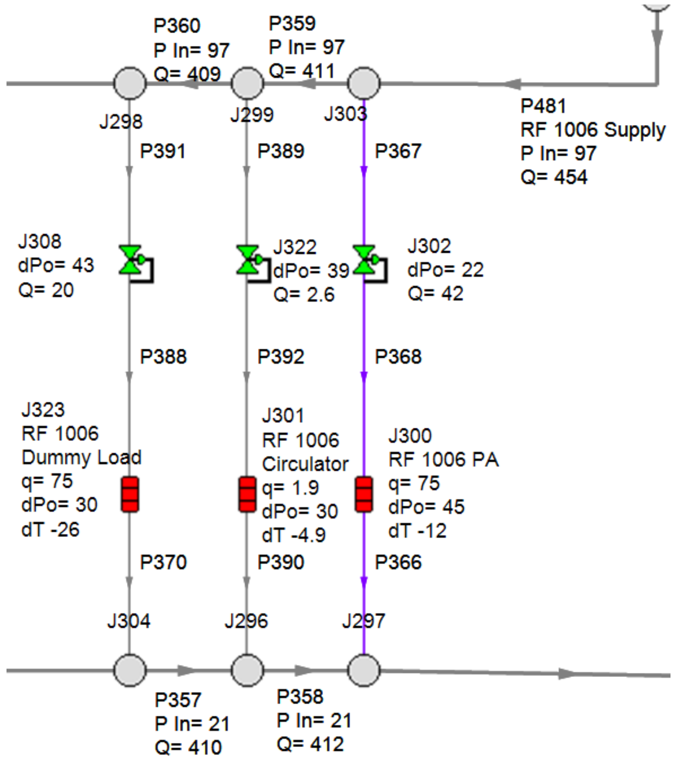

Figure 12: One unit from RF 1006 Layout zoomed in

IV. Magnets and Power Supplies

The magnet and power supply system was made to follow the circumference of the ring, like the vacuum system. Since the information for the exact number of magnets is currently in flux, the best method of approach was to create 4 magnet and power supply cooling components per quadrant. A master spreadsheet provides the information for each magnet for the ring, so the total flow rate and total heat load was calculated. Then, the values were divided by 16 to provide a single value for each of the control valves and heat rejection components. The total flow rate was found to be 999.1 gpm and the total heat load was 4381.90 kW. Therefore, each heat rejection component would need to have a flow rate of 62.44 gpm and a heat load of 273.86 kW. Values for the power supply system have not been implemented into the simulation, so place holders have been set for them. Closed control valves were used to keep any flow from going through these areas. The finished magnet layout is shown below.

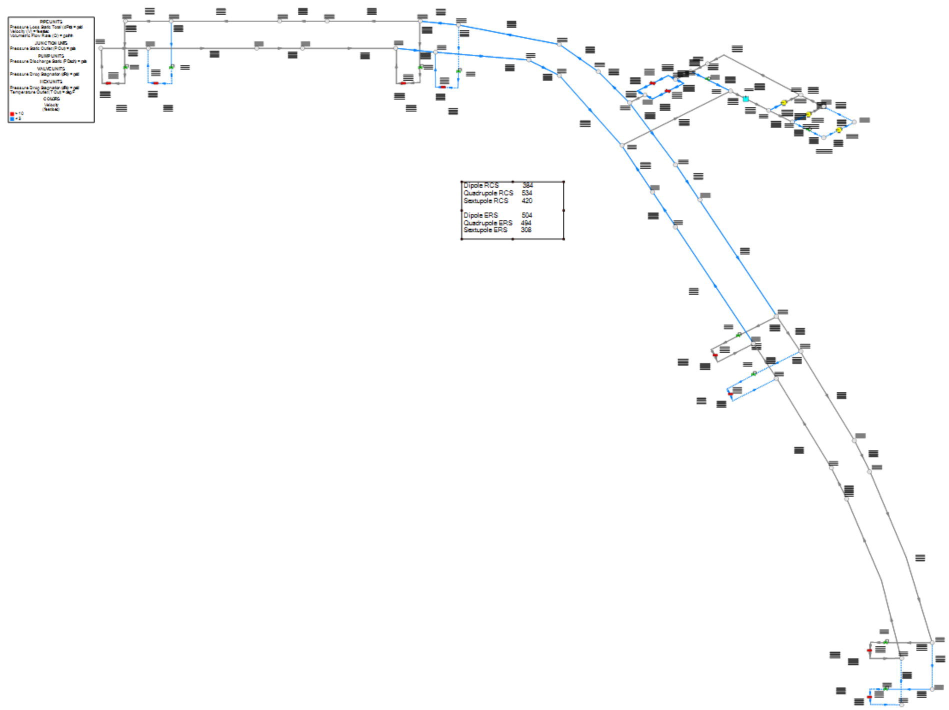

Figure 13: Magnet System

V. Cryogenics

1002 Cryo

The 1002 Cryo building was dimensioned to be approximately 140 feet in length and 50 feet in width. The building layout has not been finalized, so the position of the systems are arbitrary. Each component in the system is grouped with components of the same type. The system is made up of 10 heat rejection components: 3 vacuum compressors, 2 helium compressors, 1 R&R cold compressor, 1 air compressor, 1 insulating vacuum pump, and 2 guard vacuum pumps. A manifold or "home run" layout was made at the end because the supply and return headers need to be 2 inches in diameter or more. Once the size goes below, the pressure in the system starts to get very high. To keep it under control, the manifolds are used. The layout is in Figure 14.

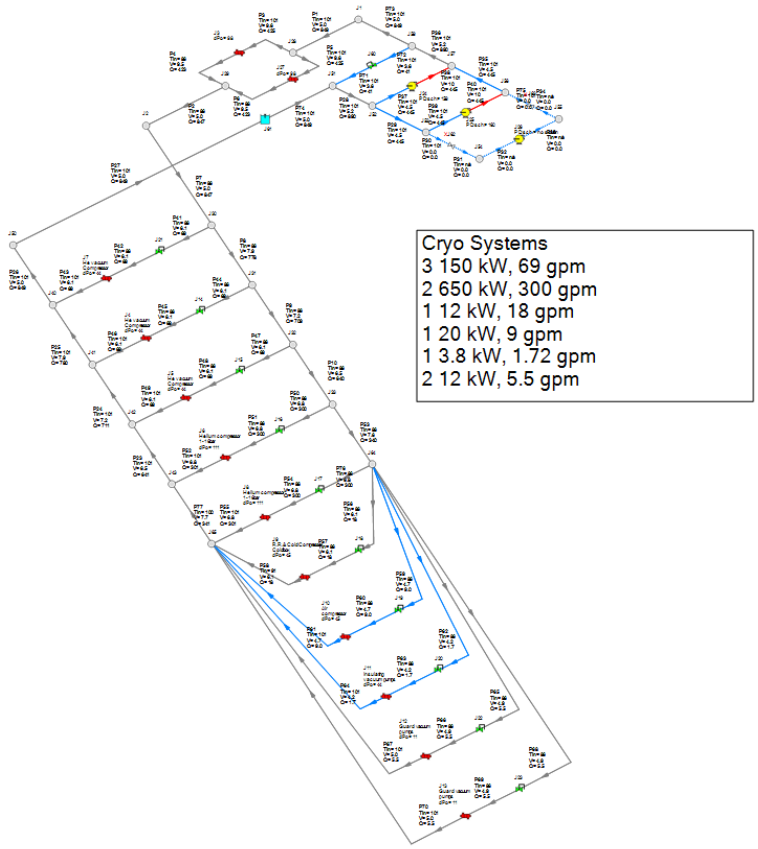

Figure 14: 1002 Cryogenics System Overall Layout

1006 Cryo

The 1006 Cryo building was dimensioned as 30.32 feet in length and 58.95 feet in width. This layout is very similar to the 1002 Cryo building with a manifold portion at the end to prevent higher pressure. The 1006 building has only 8 units, so it is much smaller. Figure 15 provides a representation of the units.

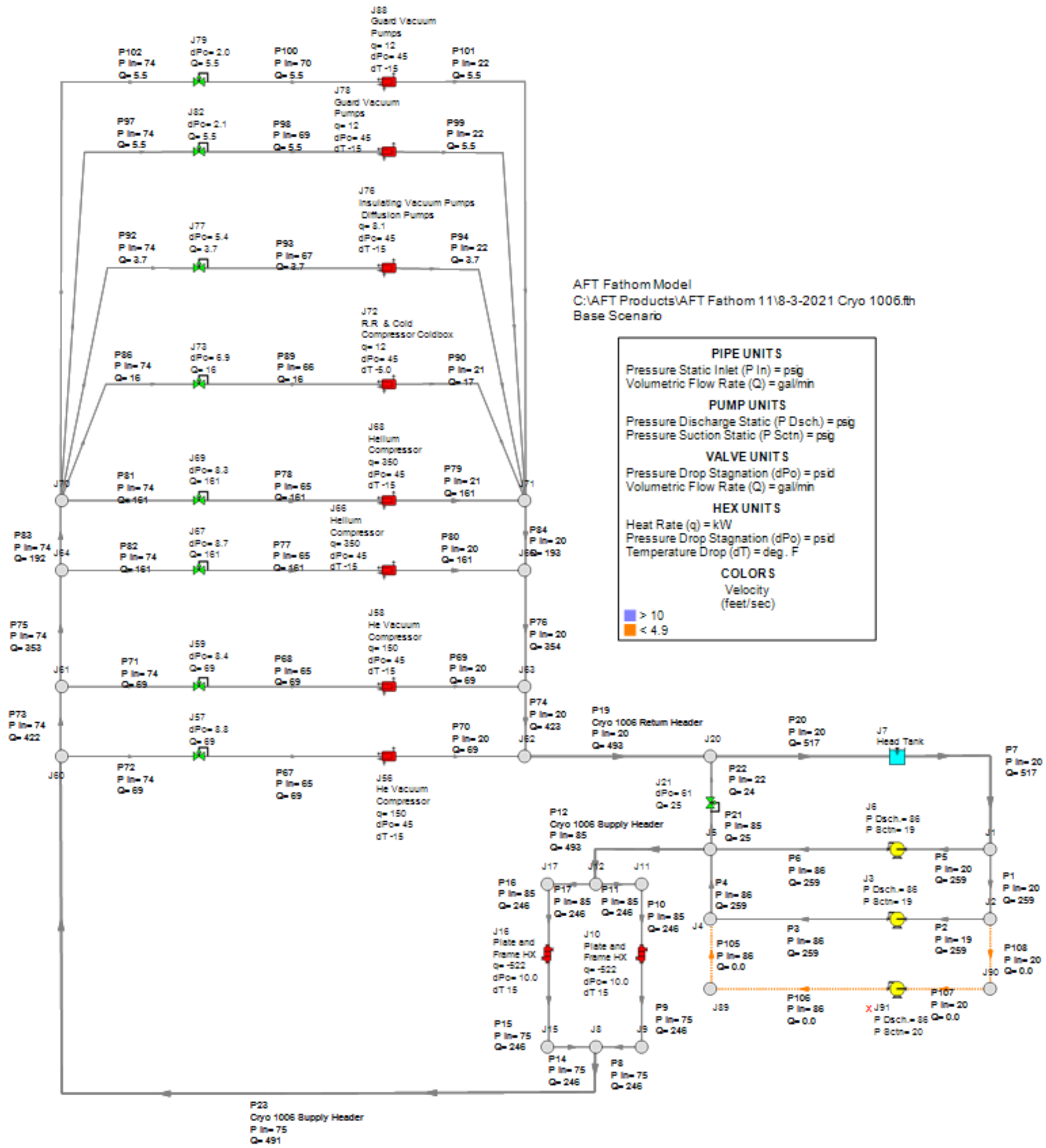

Figure 15: Layout of 1006 building with 8 heat rejection components

1010 Cryo

The 1010 Cryo building was dimensioned from the HDR Drawings to be 101.33 feet in length and 48 feet in width. The full layout of the components within the building were not finalized, so the cooling layout was made to follow the building dimensions. This system had 9 units in total and had the same units as the 1006 Cryo system, except it also includes an insulating vacuum pump. This is displayed in Figure 16.

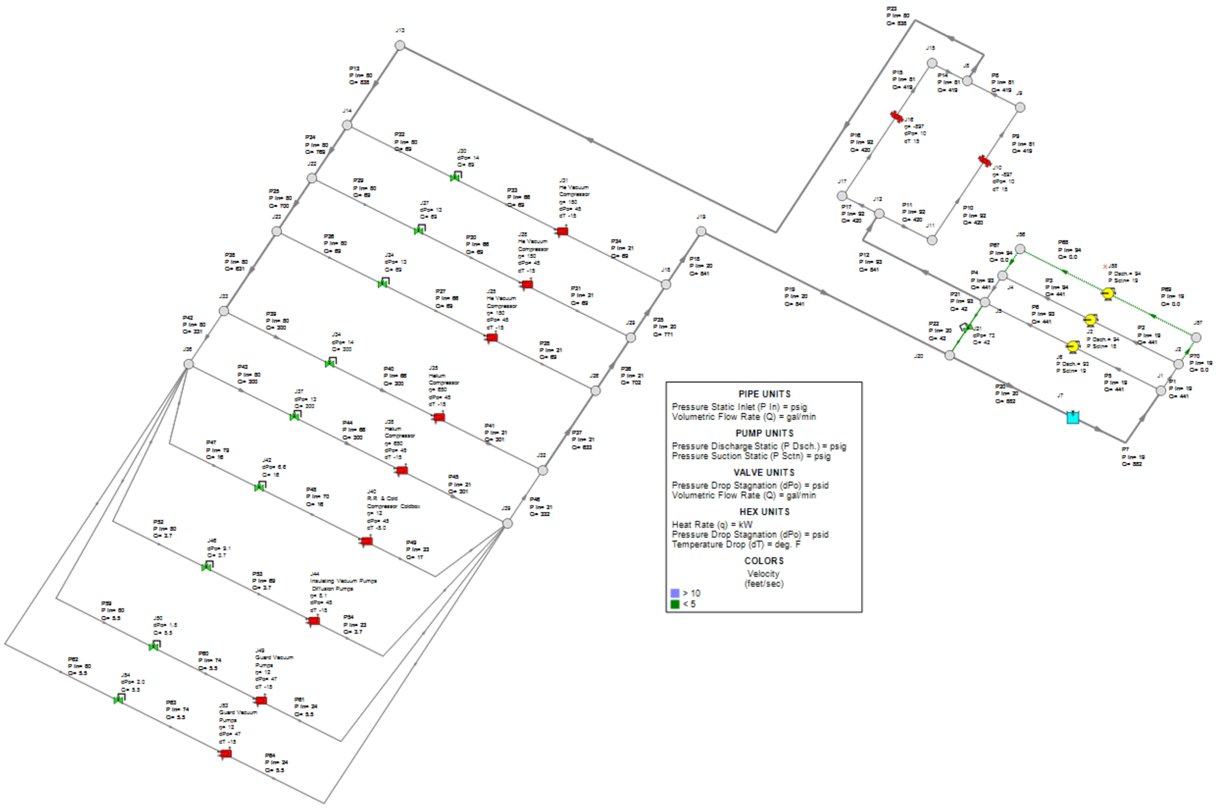

Figure 16: 1010 Cryo building with manifolds and pumping system

VI. Conclusion

By designing large-scale models in a simulation software, we were able to create a modeling tool that can be used to reduce the cost and improve effectiveness of the cooling system, thus lowering the carbon footprint by reducing the power consumption. The team utilized principles of fluid dynamics to design a cooling system model that would handle the heat rejection requirements for the EIC accelerator support systems. Recommendations would be to get real pump and manufacturer data to update the model to replicate real-life cooling systems. The model also should be updated to replicate design changes to the EIC. Additionally, the model should continue to be used for cost savings and carbon emission savings. Ten systems were created during the summer program. We were able to fully complete our project for such complex cooling systems that would contribute meaningful results to the EIC.

VII. References

[1]"Frequently Asked Questions (Faqs) - U.S. Energy Information Administration (EIA)." *Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)*, 15 Dec. 2020, www.eia.gov/tools/faqs/faq.php?id=74&t=11.

VIII. Acknowledgements

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