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The Design and Economic Optimization of a Warehouse Refrigeration System

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THE DESIGN AND ECONOMIC OPTIMIZATION OF A WAREHOUSE REFRIGERATION SYSTEM

by
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ABSTRACT

HANNAH GRACE TALBOT: THE DESIGN AND ECONOMIC OPTIMIZATION OF A WAREHOUSE REFRIGERATION SYSTEM
(Under the direction of Dr. Adam Smith)

The purpose of this project was to design a cool warehouse refrigeration system for Acme Frozen Foods, Inc located in Newark, New Jersey. The refrigeration system was used to cool eighteen 300,000 ft^3 refrigerated units (200 ft x 100 ft x 15 ft), each requiring 200 cooling tons of refrigeration at a level of 0 °F. The scope of this project included determining the appropriate refrigeration cycle, selecting the most desirable refrigerant, and temperature ranges to optimize the performance of the system. This project also considered the economic cost of the power needed to run the refrigerated units and the pricing of the compressor, evaporator, and condenser and required a preliminary cost estimate. These objectives were met by using thermodynamic analysis, informed consideration of various safety and environmental concerns for numerous refrigerant types, and economical factors. All of these factors contributed to a safe, cost considerate, and optimal refrigeration system.

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1. INTRODUCTION

The School of Engineering at the University of Mississippi was officially established in 1900, making it the oldest engineering school in the state. The School of Engineering is comprised of numerous engineering programs: biomedical, chemical, civil, computer, computer science, electrical, general, geological, and mechanical. Six of the previously named undergraduate engineering programs are currently accredited by the Accreditation Board for Engineering and Technology (ABET), and the three newest degree programs are currently working towards accreditation. The three degree programs currently working towards accreditation are Bachelor of Science degrees in Biomedical Engineering, Computer Engineering, and General Engineering. Students in the Ole Miss School of Engineering take a wide range of courses to gain understanding of core math, scientific, and technical principles needed for an engineering career.

1.1 GENERAL ENGINEERING

General Engineering provides students with flexibly to take a wide range of courses outside the engineering discipline and within other engineering departments to explore a variety of career paths. General Engineering students also select an emphasis tailored to their specific career goals and passions. The choices of emphasis are Aerospace Studies, Business Administration, Manufacturing, Military Science, Naval Science, Pre-Med Studies, or a Standard Option. The Bachelor of Engineering degree is meant to equip students for many engineering, and non-engineering, career paths. During their senior year, General Engineering seniors are given the opportunity to enroll in a Product Design and Development course where they can apply all their undergraduate engineering knowledge into one semester long final project (Capstone). The Capstone varies year to year and can either be centered around designing a physical product or designing a method or hypothetical system.

1.2 THERMODYNAMICS

This year, the General Engineering Capstone was rooted in thermodynamic principles. Thermodynamics deals primarily with heat and energy transfer within systems. Thermodynamic systems are the area of study and are either open or closed. Within an open system, mass can flow into and out of the system's boundaries. Within a closed system, there is no transfer of mass outside or into the system. Applications of thermodynamic knowledge are vast and useful for numerous different processes. Throughout the twentieth century, engineering applications of thermodynamics helped pave the way for significant improvements in our quality of life with advances in major areas such as surface transportation, air travel, space flight, electricity generation and transmission, building heating and cooling, and improved medical practices [1].

1.3 REFRIGERATION SYSTEM OVERVIEW

Refrigeration systems are used both in commercial and home appliances to perform cooling and keep spaces at a desired temperature. Refrigeration systems are evaluated using different thermodynamic values such as entropy and temperature to determine the heat transfer and amount of work done by the system. The work (W) can be calculated by finding the difference between the heat flow at high temperatures Q_H and the heat flow at low temperatures Q_L. The Q_L can be thought of as the 'energy sought' and the Work, W, as the 'energy cost' of a refrigeration cycle. After determining these values, they can be used to calculate the efficiency of the refrigeration system. The efficiency of a refrigeration system is termed the *Coefficient of Performance* (COP) and denoted by β. Mathematically, $\beta = \frac{Q_L\,(energy\ sought)}{W\,(energy\ cost)}$. A high COP is indicative of a highly efficient system with low energy consumption, and therefore low operating costs.

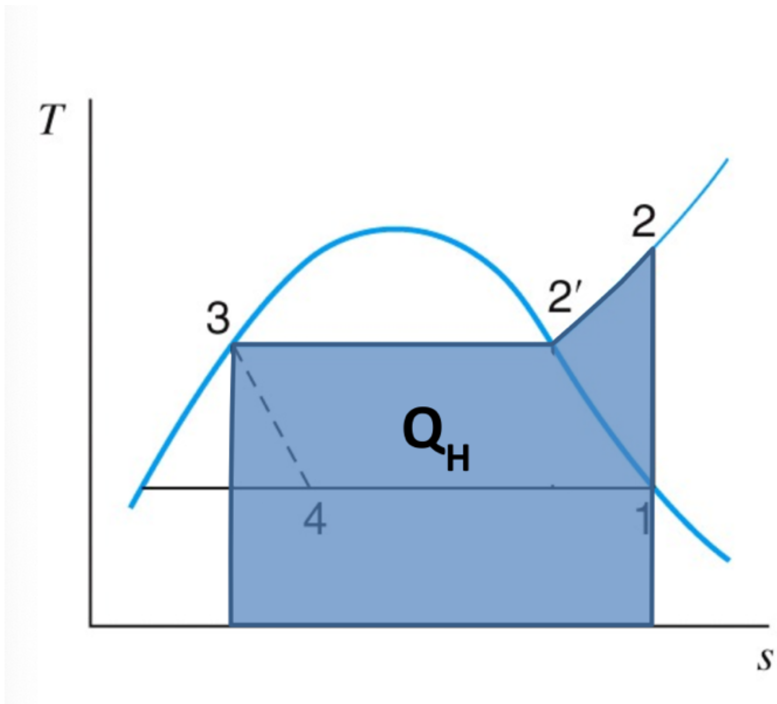

Figure 1: Q_H calculation on a T-S Diagram [14]

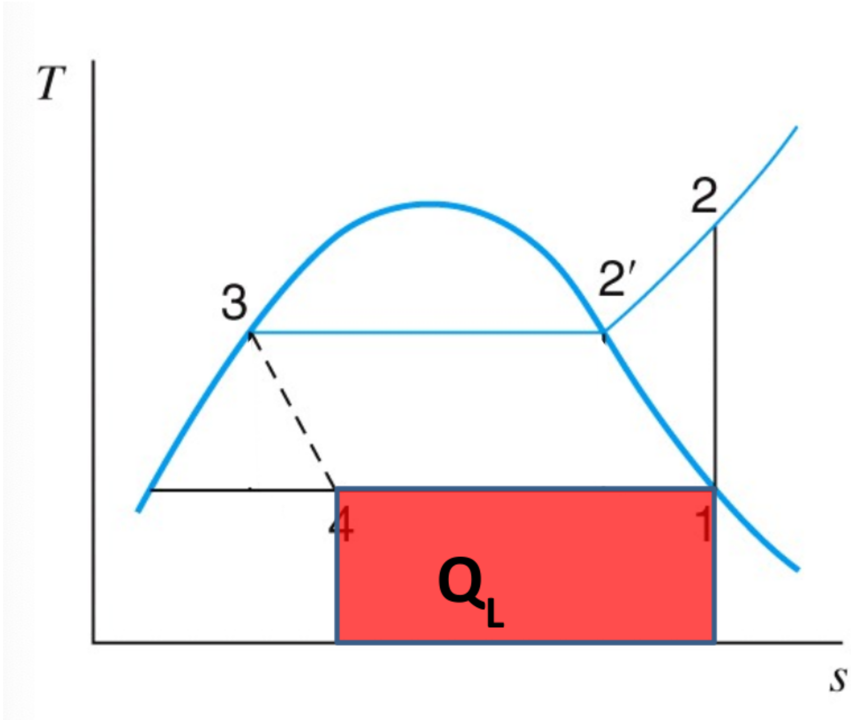

Figure 2: Q_L calculation on a T-S Diagram [14]

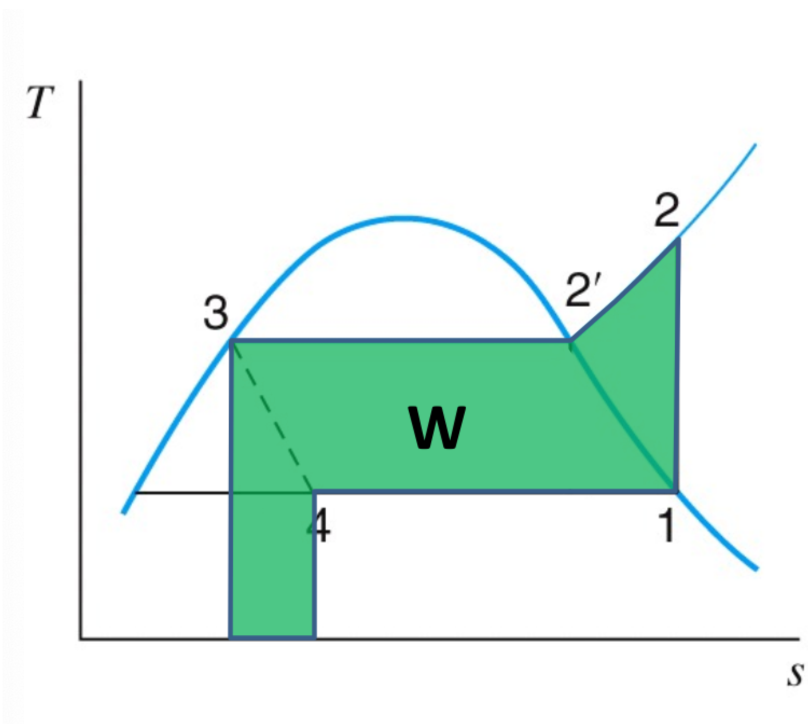

Figure 3: W calculation on a T-S Diagram [14]

1.4 NEWARK, NEW JERSEY

The Acme Frozen Foods cold warehouse is being constructed in Newark, New Jersey. Year-round, Newark experiences both hot and cold weather; the summer high is around 86 °F and the winter low is around 23 °F. While Newark experiences both warm and cold weather, it also averages around 26 inches of snow per year [12]. In an environment where freezing temperatures and snow are common throughout the winter, it is important that any outdoor equipment is easy to maintain and service.

2. REFRIGERATION SYSTEM COMPONENTS

A refrigeration system is composed of four main components: a compressor, a condenser, an expansion valve/device, and an evaporator, as indicated in Figure 4. The size and number of these elements is subject to change depending on the type of system needed. The arrangement of the equipment is based on the pressure and temperature changes of a working system contributing to energy transfer. First, the compressor takes in the working fluid, refrigerant, and transforms it from a low-pressure, low-temperature gas into a high-pressure, high-temperature gas. Leaving the compressor, the high-pressure, high-temperature gas moves into the condenser. The condenser is a heat exchanger that takes heat out of the gas and condenses the refrigerant vapor into liquid. Next, the now saturated liquid fluid moves into the expansion device where the working fluid is changed into a low-pressure, low-temperature mixture. Lastly, the fluid enters the evaporator. The evaporator takes in the low-temperature, low-pressure liquid and it absorbs the heat of the compressed air and vaporizes. After finishing at the evaporator, the cycle continues by sending the working fluid back through the compressor.

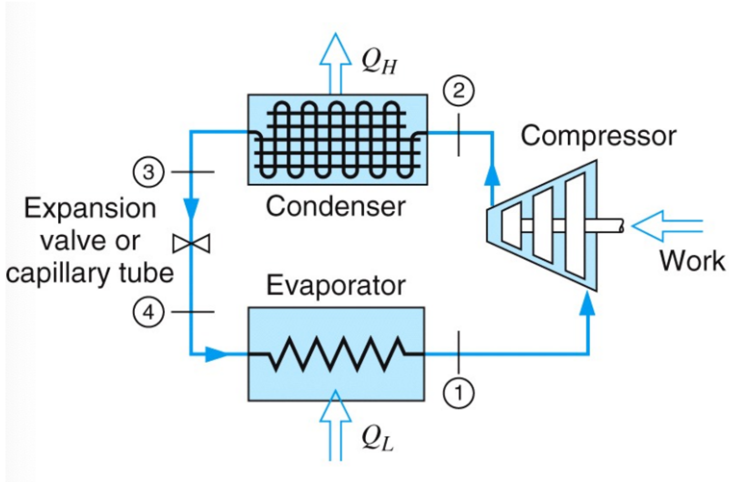

Figure 4: Refrigeration System [14]

2.1 VAPOR-COMPRESSION REFRIGERATION SYSTEM

The vapor-compression refrigeration system is the most used cycle used in refrigerators and air conditioning. Vapor-compression cycles are relatively simple to construct and are cost efficient in terms of construction and operation. This system is comprised of four steps and works by taking heat energy from a cold reservoir and depositing heat into a hot reservoir. In order to generate heat transfer from a cold reservoir to a hot reservoir, work must be done on the system. These systems use varying pressure and temperature values at each step to move the refrigerant through the system. Numerous different refrigerant types can be used in these systems, however, in order to move a fluid from a hot reservoir temperature above room temperature and a cold reservoir held near freezing, the boiling point of the selected refrigerant should be relatively low. The relationship between pressure and volume can be used in conjunction with a graph of temperature and entropy to analyze a system.

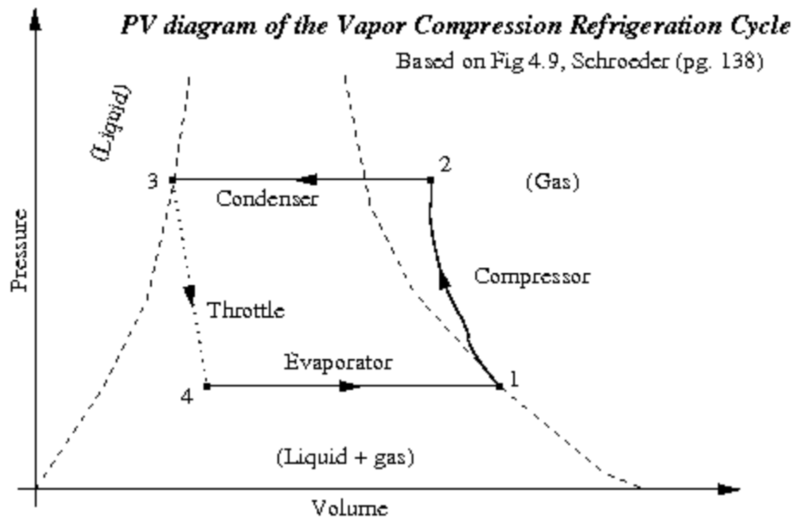

Figure 5: PV diagram of the Vapor Compression Refrigeration Cycle [2]

2.2 CASCADE TWO-PHASE SYSTEM

Cascade refrigeration systems essentially work the same way as vapor-compression refrigeration systems; however, they employ a two-circuit loop. The bottom loop of a cascade system is generally a lower pressure and temperature system. It is composed of an evaporator, expansion valve (throttling device) and compressor. The output of this loop feeds into the high pressure and temperature second loop through a shared cascade condenser. The high pressure and temperature loop is composed of its own expansion valve, compressor, and high-pressure condenser. This goal of this system is to decrease the amount of work required of the system by lowering the temperature differences necessary for heat transfer. Cascade systems can use two different refrigerants through, or one refrigerant at various temperatures. One negative aspect of this specific system is that it is composed of two separate refrigeration cycles, driving the cost and construction complexity upward.

2.3 REFRIGERATION SYSTEM COMPARISON

The vapor-compression and cascade refrigeration systems both have positive and negative attributes. Vapor-compression cycles require fewer pieces of equipment which results in a more economically conservative system to construct and run. However, the work required by these systems is higher than cascade systems, which requires more energy to function. The cascade system requires less energy needed to run; however, the additional equipment makes for a much more costly and complex system. Also, even though the power needed is decreased the COP is reduced due to the heat transfer overlap of the condensing temperature of the lower cycle and the evaporating temperature of the higher cycle [3].

3. REFRIGERANTS

A refrigerant is the chemical compound flowing through refrigeration systems. This is the liquid or gas that moves through the system, absorbing environmental heat and transforming that heat into cool air via the compressor and evaporator of the system. There are many different categories of refrigerants on the market, however, some pose hazardous environmental concerns. In addition to screening for environmental concerns, it is important to select a refrigerant applicable for a particular system because they are not necessarily interchangeable. In commercial refrigeration warehouses the most used refrigerant types are water, Hydrochlorofluorocarbon (HFC) R-134a, Hydrocarbons (HCS), Ammonia (R717), CO2 R744, HCFC -22 (R-22), and R-410a Refrigerants.

3.1 REFRIGERANT SAFETY

Refrigerants are known to be a significant contributing factor to global warming, so recently there has been a push to develop more environmentally friendly refrigerants. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) ranks refrigerant safety based on flammability and toxicity. Refrigerants are also evaluated based on their Ozone Depletion Potential (ODP) and Global Warming Potential (GWP).

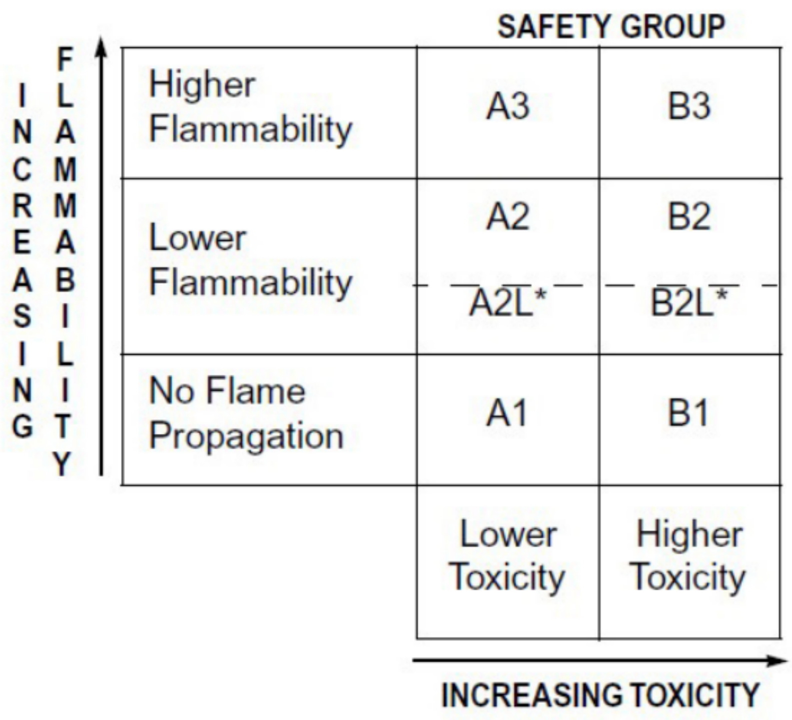

Figure 6: ASHRAE Refrigerant Safety Classification

3.1.1 OZONE DEPLETION POTENTIAL

The Ozone Depletion Potential (ODP) is a way of measuring the amount of damage a refrigerant can cause to the ozone layer. Chlorofluorocarbons and

Hydrochlorofluorocarbons have a range of ODP that goes from 0-1, however, Halons can have an ODP of up to 10. The closer ODP is to 1, the more harm the compound poses to the ozone layer. Refrigerants with an ODP of 0 are deemed environmentally safe, however, GWP is the main indicator of eco-friendliness. Chlorofluorocarbon refrigerants are known to have a higher contribution to ozone depletion [8].

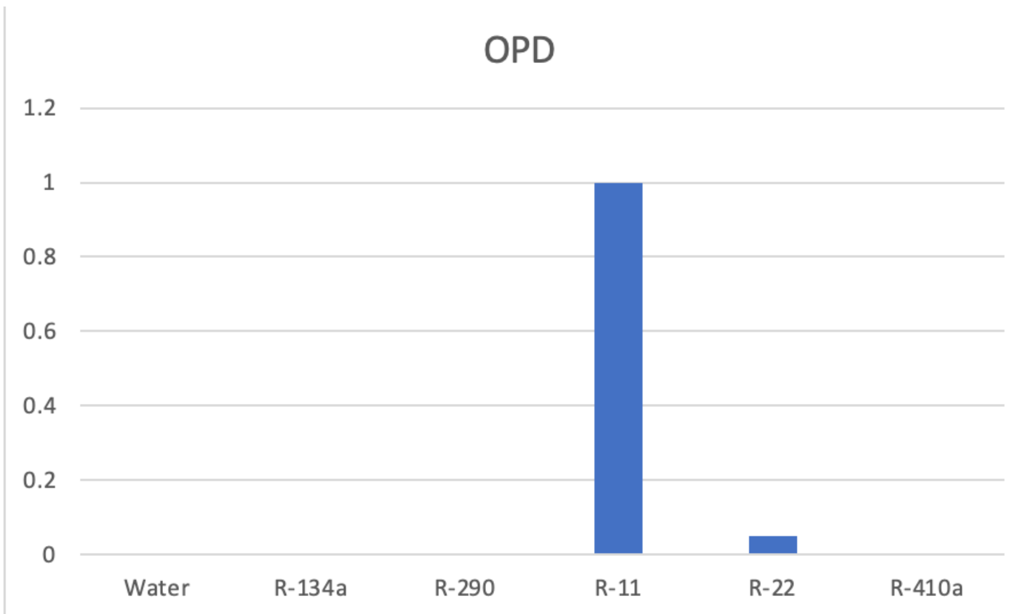

Figure 7: ODP values for various refrigerants

3.1.2 GLOBAL WARMING POTENTIAL

The range for Global Warming Potential (GWP) is significantly higher than the range of ODP. The highest, most dangerous, rating of GWP is anything upward of 2500. Refrigerants with less than 150 GWP are considered safe, 150-2500 is considered moderate, and greater than 2500 is considered a high and dangerous GWP. Hydrochlorofluorocarbons are known for producing highly dangerous GWP values. GWP values indicate the eco-friendliness of refrigerants which is measured predominantly by their potential to contribute to global warming [8].

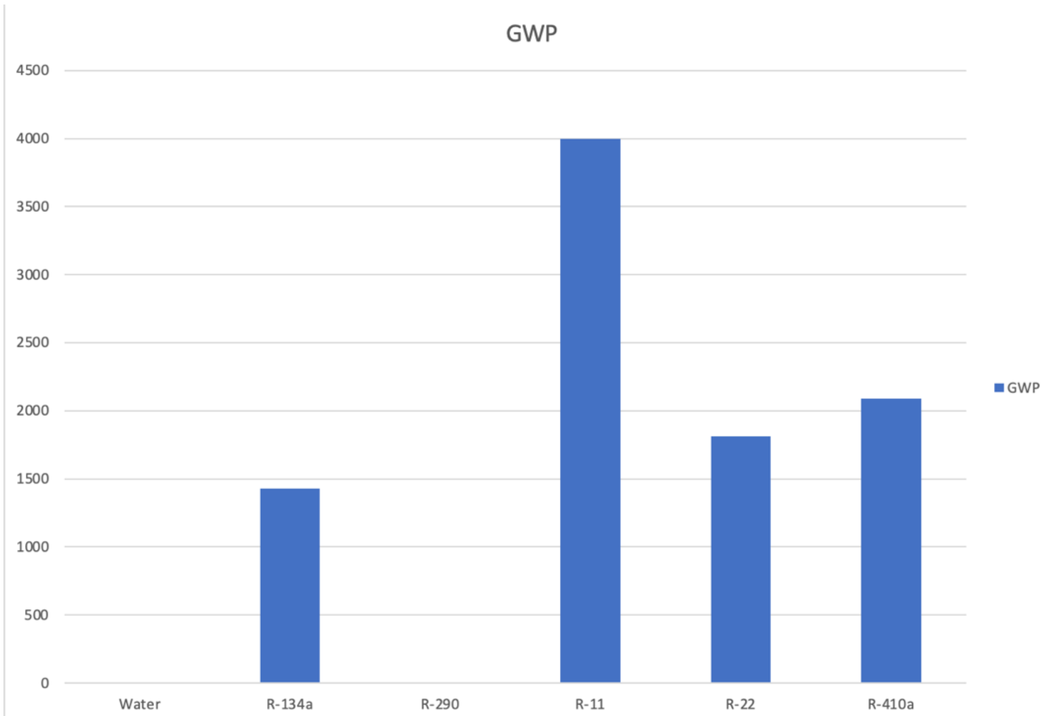

Figure 8: GWP for various refrigerants

3.2 WATER

Water as a refrigerant, R-718, is a natural refrigerant that poses no ozone-depletion potential (ODP), and has very small, if any, global warming potential (GWP) [4]. Some benefits of using water as a refrigerant are that water is environmentally safe, nontoxic, nonflammable, and inexpensive. Another positive attribute of water is that it displays a high latent heat of vaporization, which allows water to absorb greater amounts of heat energy compared to other synthetic refrigerants. Water, however, has a comparatively high freezing point at atmospheric pressure which often requires it to be mixed with other fluids to lower the freezing point. For this system, the running temperature is required to remain at 0°F which is lower than the freezing point of water. Most notably, water when used in vapor-compression systems, displays high specific volumes at lower temperatures. This characteristic raises the pressure ratios and outlet temperatures of the compressor and results in low efficiency and the need for a larger compressor [4].

3.3 R-134A

R-134a, chemically named 1,1,1,2-tetrafluroethane, is widely diverse HFC refrigerant. R134a is suitable for a variety of applications but is most used in vehicle air conditioning and commercial cooling. R-134a has an A1 safety rating from ASHRAE. An A1 rating indicates that R-134a presents no flame propagation and low toxicity. In addition, R-134a has an OPD of 0, but a GWP of 1,430 [5]. The low environmental hazard makes R-134a a safe and effective choice. Contrary to other refrigerants, R-134a has no phase out date set, meaning that this will continue to be a working option for the foreseeable future. R-134a, in comparison to R-410a, is more cost efficient; however, requires a larger compressor to deliver the same amount of cooling [11].

3.4 HYDROCARBONS (HCS)

Hydrocarbons are a branch of refrigerants with no OPD and very minimal GWP. A few examples of HCS are Propane (R-290), Butane (R-600), and Isopentane (R-601a). These characteristics make HCS very environmentally safe. HCS are also natural refrigerants which means that HCS will be used in practice for years to come, potentially replacing chemical refrigerants. Also, HCS are known for being very efficient conductors of heat and result in substantial energy savings and decreased wear and tear on equipment [6]. On the downside, HCS are risky with respect to safety and flammability. The concept of flammable refrigerants makes contractors hesitant to use HCS in large scale projects, however, they are often used in vending machines and other small applications [7].

3.5 R-410A

R-410a, also known as Puron, was introduced into industry due to global concerns of ozone protection. It is composed of equal parts R-32 and R-125. R-410a is ranked A1 on the ASHRAE safety classification chart and has an ODP of zero and a GWP of 2,088. R-410a originated to be a safer refrigerant to replace the hydrofluorocarbon refrigerant R-22 (Freon). With a GWP within the moderate safety range, R-410a is generally thought to be environmentally safe. R-410a is commonly used in chillers and within commercial refrigeration, due to its ability to be used in high-pressure air conditioning systems. R-410a systems are proven to have a high system efficiency, however, it is being phased out by 2024 [11].

3.6 R-22

R-22 is a refrigerant that has been widely used in residential air conditioners and heat pumps, however, in early 2020 the Environmental Protection Agency (EPA) banned the production and import of R-22 [9]. Due to the recent halt in import, R-22 is still circulating in most residential HVAC systems. By law, R-22 can be used when servicing existing systems, however, if a repair requires a new HVAC system, the refrigerant must be switched [10]. R-22 poses environmental concerns given its ODP is 0.05 and GWP is

1,810. Although R-410a has a higher GWP than R-22, the contribution to ozone depletion of R-22 makes it a more harmful refrigerant choice.

4. CONCLUSION OVERVIEW

Based on system, refrigerant, and thermodynamic analysis the final decision for the refrigeration system is a vapor-compression cycle using R-134a as the working fluid. This system contains a balance of efficiency, safety, and cost.

4.1 REFRIGERANT DECISION

Based on the ODP and GWP analysis of the various refrigeration types, I decided that R-134a is the best choice of refrigerant. R-410a is a nonflammable, non-toxic, and environmentally safe choice for commercial cooling. Another benefit of R-134a is that it is not currently being phased out. R-134a is also more cost efficient than R-410a which is important for a project of this size [11]. R-134a is more cost efficient as far as production costs, and it requires a lower pressure environment which reduce operating costs [11]. After selecting R-134a as the working fluid for this project, I used Excel to thermodynamically manipulate this fluid in both a vapor-compression cycle and cascade system to decide on refrigeration system.

4.2 REFRIGERATION SYSTEM DECISION

The vapor-compression refrigeration system is known for being relatively simple and easily constructed and maintained. Given the magnitude of this project, 18 different refrigeration units, maintenance and construction should be heavily considered. Also, given the climate of Newark, NJ it is especially important to consider maintenance during frigid winter months. However, I tested both system types to evaluate their COP and cost.

Using thermodynamic manipulation, I tested both vapor-compression and cascade systems with R-134a and R-410a. Analysis of these two systems resulted in a COP value of 2.77 for the vapor-compression cycle using R-134A, and 2.87 for the vapor-compression cycle using R-410a, as indicated in Table 1. For the cascade system, using R-134a the COP is 2.15 and the COP is 3.22 using R-410a.

Refrigerant	System Type	COP
R-134a	Vapor-compression	2.77
	Cascade	2.15
R-410a	Vapor-compression	2.87
	Cascade	3.22

Table 1: Working fluid, System Type and their COPs

4.3 FINAL SYSTEM

The decision to construct vapor-compression systems using R-134a results in a system that is safe, effective, and cost considerate. This system results in a COP value of 2.77 on a typical scale of 2-4. This value is towards the middle of the range, indicating that it is adequately efficient. The temperature range for the optimal system was -5 °F to 145 °F. Due to the efficiency and environmental safety of R-134a in this system, along with the economic benefits of R-134a this system is the optimal choice. Selecting a vapor-compression cycle is especially beneficial because those systems are easier to maintain. The cost estimate for the total project was constructed using a centrifugal compressor due to their high efficiency and low maintenance requirement.

4.3.1 FINAL SYSTEM PRICING

The 2022 base total cost of centrifugal compressions for 18 refrigerated units is $39,267,785.23 and the cost of power consumption is $1,664,750.18 per year [13]. In order to modernize pricing to 2022 Chemical Engineering Plant Cost Index, outdated values were increased by a magnitude of 1.27. Also, to allow for pricing changes throughout the construction of the project, individual and total project prices are included in Table 3 and Table 4 with +/- 30% offsets.

Pricing for 2022

Base Totals	Per System	Entire Project
centrifugal/r134a	$2,181,543.62	$39,267,785.23
reciprocation/r134a	$945,867.76	$17,025,619.72
centrifugal/r410a	$2,181,557.28	$39,268,031.01
reciprocation/r410a	$945,881.42	$17,025,865.51

Table 2: 2022 Base Total Compressor Pricing

Electricity Cost

power consumption	energy price	usage time (hours)	power consumed	cost per year	Cost for 3 years
703.37	0.27	24	$16,880.88	$1,664,750.18	$4,994,250.54

Table 3: Power Consumption Pricing

Base Totals	Per System	Entire Project
centrifugal/r134a	$1,717,750.88	$30,919,515.93
reciprocation/r134a	$744,777.77	$13,405,999.78
centrifugal/r410a	$1,717,761.64	$30,919,709.46
reciprocation/r410a	$744,788.52	$13,406,193.31

Table 4: 2020 Base Total Compressor Pricing

System Totals w/ Offset	(-)30%	(+)30%
centrifugal/r134a	$1,527,080.54	$2,836,006.71
reciprocation/r134a	$662,107.43	$1,229,628.09
centrifugal/r410a	$1,527,090.09	$2,836,024.46
reciprocation/r410a	$662,116.99	$1,229,645.84

Table 5: 2022 Single System Totals with Offset

Project Totals w/ Offset	(-)30%	(+)30%
centrifugal/r134a	$27,487,449.66	$51,048,120.80
reciprocation/r134a	$11,917,933.81	$22,133,305.64
centrifugal/r410a	$27,487,621.71	$51,048,440.32
reciprocation/r410a	$11,918,105.85	$22,133,625.16

Table 6: 2022 Entire Project Totals with Offset

Compressor

$$-W_c = \hat{h}_1 - \hat{h}_2$$

$$W_c = \hat{h}_2 - \hat{h}_1 = (125.6 - 103) \text{ BTU/lb}$$

$$W_c = 22.6 \text{ BTU/lbm}$$

Condenser

$$Q_H = h_2 - h_3 = 125.66 - 40.2$$

$$Q_H = 85.46 \text{ BTU/lbm}$$

Expansion Valve

$$h_3 = h_4 = 40.2 \text{ BTU/lbm}$$

Evaporator

$$-Q_L = h_4 - h_1$$

$$Q_L = h_1 - h_4 = (103 - 40.2) = 62.8 \text{ BTU/lbm}$$

$$\beta = \frac{Q_L}{W_c} = \frac{62.8}{22.6} = 2.77 = \text{COP}$$

Figure 9: Thermodynamic Analysis of the Final System

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