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The Design Estimate of a Warehouse Refrigeration System

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THE DESIGN ESTIMATE OF A WAREHOUSE REFRIGERATION SYSTEM

by

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ABSTRACT

The intention of this project was to provide a design and cost estimate for the refrigeration systems within an industrial cold storage distribution center for Magnolia Country Frozen Foods, Inc. in East Rutherford, NJ. The facility includes eighteen 300,000 ft^3 units (200 ft x 100 ft x 15 ft). These units require 200 tons of refrigeration at a maintained temperature of 0ºF. This project's scope included choosing an optimal refrigeration system, selecting a refrigerant for use within the system, and providing a cost estimate for the purchase of the refrigeration system equipment and for the yearly cost associated with running and maintaining the system. In our work researching and preparing to complete the estimate for the system, our top considerations included efficient thermodynamic performance, safety, global warming potential, refrigerant phase-out status, and cost. The refrigeration system equipment for each unit represented in the cost estimate includes a compressor, two heat exchangers, and refrigerant to load each system. The final estimate represents a safe, efficient, cost-effective option to implement in the construction of the warehouse refrigeration complex.

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1. REFRIGERATION SYSTEM

A refrigeration system is made up of four main components: a compressor, a condenser, an expansion device, and an evaporator (Figure 1). The compressor is the first step in a refrigeration cycle, and it functions to increase the pressure of the working fluid to a high-pressure, high-temperature gas. The vapor then enters the condenser where heat is removed until it is condensed into a saturated liquid. Next, the working fluid moves into the expansion valve where the saturated liquid is expanded. Lastly, the evaporator functions as a second heat exchanger that cools the refrigerant so that it can absorb heat from the environment. Research shows that the most commonly used cycles for commercial refrigeration are single-stage vapor compression and cascade vapor compression.

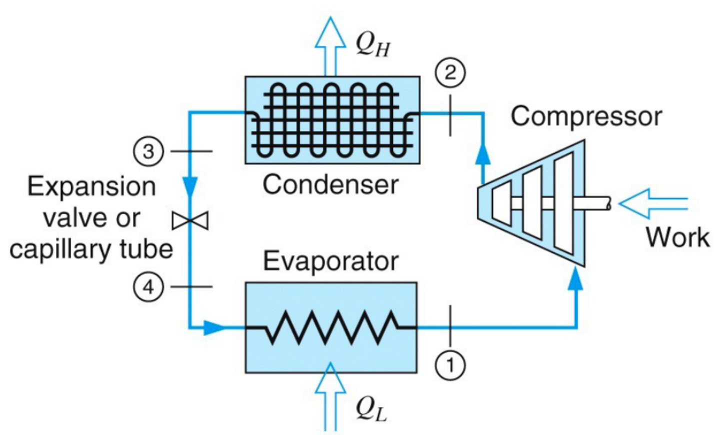

Figure 1. Refrigeration System

1.1. SINGLE-STAGE VAPOR COMPRESSION CYCLE

The single-stage vapor compression cycle is named as such because it only has one stage of compression. The design of the single-stage cycle is relatively simple and economically conservative to construct and is represented by the refrigeration system in Figure 1.

1.2. CASCADE VAPOR COMPRESSION CYCLE

The cascade refrigeration system uses two refrigerants with different boiling points, which run through their own independent freezing cycle and are joined by a heat exchanger [1]. The highest cycle has a condenser, which acts as an evaporator for lower-boiling-point refrigerants. This system is commonly used when the difference between the condenser temperature and evaporating temperature is so large that a single refrigerant with a vapor compression refrigeration system is no longer suitable due to low COP and high compressor discharge [3]. It is also useful for applications where extremely low temperatures are required. In terms of design, the cascade vapor compression cycle is very complex and requires additional equipment to construct.

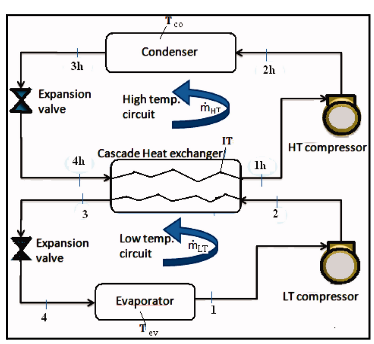

Figure 2: Cascade Refrigeration Cycle

1.3. REFRIGERATION CYCLE PERFORMANCE COMPARISON

When comparing the single-stage and cascade vapor compression cycles, performance is a very important factor to consider. An experimental study comparing the Coefficient of Performance (COP) of the single-stage cycle and the cascade cycle using the same working fluid, R-134a, found that the single-stage cycle performed more efficiently than the cascade cycle. The higher unit of the cascade system requires an increased compression power lowering the COP for the entire system (Figure 3) [2]. When designing a complex system, it is essential to take into account the heating and cooling requirements for the entire process, spanning a wide range of temperatures. The system should also account for the interactions of multiple refrigerants at different pressure levels.

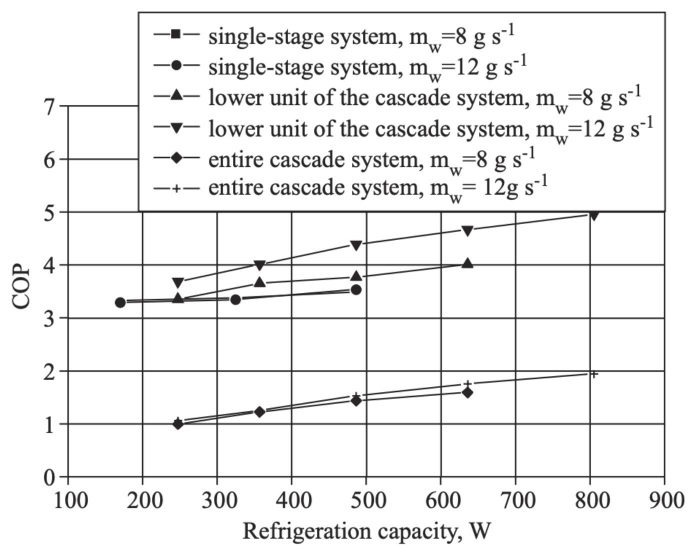

Figure 3: COP Comparison of Single-Stage & Cascade Cycles using R-134a

1.4. REFRIGERATION CYCLE SELECTION

Although both single-stage and cascade refrigeration cycles offer numerous advantages, single-stage vapor compression is the most cost-effective and efficient option that meets Magnolia Country's performance requirements. The selected refrigeration cycle for the system design is the single-stage vapor compression cycle.

2. REFRIGERANT RESEARCH

In a refrigeration system, refrigerants continuously circulate and undergo transformations in form, temperature, and pressure to extract heat from a designated area and replace it with cool air to maintain a specific temperature or temperature range. When selecting refrigerants for industrial cooling, it is crucial to take into account various factors such as safety, environmental impact, energy efficiency, and cost.

2.1. SAFETY

In order to minimize safety risks associated with refrigerants, it is crucial to adhere to proper safety protocols which include appropriate handling techniques, refrigerant storage, and disposal methods. This incorporates wearing personal protective gear, guaranteeing sufficient ventilation, and involves proper knowledge of tools or equipment used to handle refrigerants. Individuals working with refrigerants must also undergo proper training and verification to ensure that they are aware of the associated risks and know how to handle them safely. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) developed Standard 34 to provide a concise method of identifying refrigerants and assigns safety classifications based on data regarding toxicity and flammability.

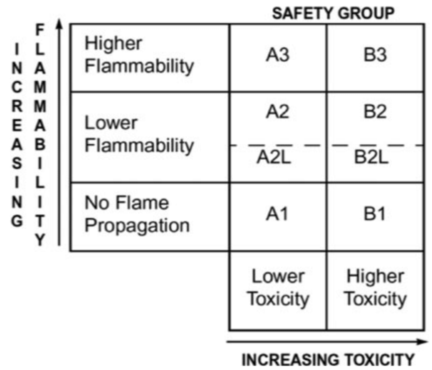

Figure 4: Ashrae Standard 34 - Safety Group Classification

2.1.1. FLAMMABILITY

Some refrigerants can be considered flammable and can pose a fire hazard if they are exposed to an ignition source. Flammable refrigerants are to be handled by experienced technicians and stored away in a secure, ventilated area with specific handling procedures in place. There are three flammability classifications provided in ASHRAE Standard 34, with Class 3 being the most flammable.

2.1.2. TOXICITY

Toxicity refers to the potential for a substance to cause harm to living organisms, including humans when exposed to a sufficient concentration or dose. When released into the environment, certain refrigerants can displace oxygen and lead to oxygen deficiency in enclosed spaces, which can pose a significant risk to human health.

2.2. ENVIRONMENTAL IMPACT

Environmental impact refers to the potential of a substance to cause harm to the environment, including air, water, and soil, when it is released. Refrigerants can have a negative impact on the environment due to their potential to deplete the ozone layer and increase global warming.

2.2.1. **GLOBAL WARMING POTENTIAL** (GWP)

The GWP value of a refrigerant is a measure of its ability to trap heat in the atmosphere over a specified period in comparison to carbon dioxide. When released into the atmosphere, refrigerants such as hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), and chlorofluorocarbons (CFCs) can trap heat and contribute to the greenhouse effect, leading to global warming. Alternatively, hydrofluoroolefins (HFOs) have a significantly lower GWP, making them a more environmentally friendly alternative.

2.2.2. **OZONE DEPLETION POTENTIAL** (ODP)

The ODP is a measure of a substance's ability to cause harm to the ozone layer when released into the atmosphere. The higher the ODP value, the more damage it can cause to the environment and human health. CFCs and HCFCs have been found to have a high ODP, and their use has been phased out in many countries due to their harmful impact on the ozone layer

2.3. PHASE OUT OF OZONE-DEPLETING SUBSTANCES (ODS)

According to the Environmental Protection Agency (EPA), ODS in the United States are classified as either class I or class II controlled substances. Class I substances, including chlorofluorocarbons CFCs, and halons, have a higher ozone depletion potential and have largely been phased out, meaning that their production or import is prohibited. Class II substances, which are primarily HCFCs, serve as transitional substitutes for many class I substances. The production and import of most HCFCs were phased out as of 2020. The EPA has alerted the public to be aware that HFHs are pending phase-out in the US.

2.4. PERFORMANCE

The measurement of the coefficient of performance (COP) is used to determine the effectiveness of a refrigerant. The coefficient of performance (COP) is a measurement of a refrigerant's efficiency, expressed as the ratio of cooling or heating output produced by the system to the energy input supplied to the system, typically measured in kilowatts (kW). A higher COP value signifies superior refrigerant performance.

2.5. COST

The cost of refrigerants can vary depending on several factors such as the type of refrigerant, the quantity purchased, government regulations, and the location of the refrigerant.

3. REFRIGERANT SELECTION

The refrigerants under consideration for the refrigeration system were R-134a, R-404a, R-507a, and R-123yf. Table 1 displays the important aspects of each refrigerant that was considered when making our refrigerant selection. GWP, ODP, Cost, and Class were all known values for each refrigerant. COP was calculated via thermodynamic analysis. An example thermodynamic analysis to calculate COP is shown in the Appendix as Appendix Figure 1. The example analysis is based on R-134a.

Table 1: List of Possible Refrigerants

	R-134a	R-404a	R-507a	R-1234yf
COP	2.55	2.41	2.41	2.67
GWP	1430	3920	3985	4
ODP	0	0	0	0
Cost ($/lb)	$9	$17	$18	$70
Class	A1	A1	A1	A2

*R-717 is not operationally viable within temperature constraints

3.1. R-134a

Refrigerant 134a has been used in numerous cooling systems in large-scale commercial refrigeration projects and is our selection for the system's refrigerant. The COP of all refrigerants was fairly consistent, and the performance cost differences between each refrigerant based on the COP values were minimal. R-134a has a lower GWP than R-404a and R-507a. While it has a much larger GWP than R-123yf, it is far cheaper and is the cheapest refrigerant of the four considered. Ashrae labels R-134a as 1A on their safety table, which is designated as non-harmful or toxic and non-flammable. R-134a was chosen to operate the system based on these factors of safety, environmental impact, performance, and cost. R-134a was compared to other reputable safe refrigerants used in cooling systems below in Table.1

3.2. PHASE-OUT PLAN

With the phase-out becoming a reality for certain refrigerants, it's important to have a plan in the event of a phase-out order. R-1234yf would be a suitable substitution for R-134a. R-1234yf is considered A2 on the Ashrae safety table, so additional steps would need to be taken to ensure system safety upon implementation. R1234yf was developed as a replacement for R-134a due to its lower GWP but is currently priced much higher than R-134a as detailed in Table 1.

4. TOTAL COST ESTIMATE BREAKDOWN

The total cost of the project is broken down into upfront costs related to the system equipment and annual costs that include power consumption and refrigerant recharge.

4.1. UPFRONT COST

The upfront cost of the refrigeration system includes the cost associated with each mechanical component of the refrigeration system. Each system will include a centrifugal compressor, two shell-and-tube heat exchangers, and a preliminary load of refrigerant to run the system. The centrifugal compressor and the shell-and-tube heat exchangers utilized a cost curve for purchased equipment (1) to determine cost. The equation for the cost curve is as follows:

$Ce = a + bS^n$ (Equation 1) [4]. In the equation, Ce represents cost, a and b both represent cost constants, S represents a size parameter, and n represents an equipment-specific exponent.

4.1.1. CENTRIFUGAL COMPRESSOR

For the centrifugal compressor, $a = 580,000$, $b = 20,000$, and $n = 0.6$. The size parameter for the centrifugal compressor corresponds to the driver power of the compressor, which is converted from the work and is calculated to be 276 kW. When entered into Equation 1, the cost per heat exchanger comes out to be $1,163,000. This cost multiplied across the 18 separate units totals up to $20,935,000.

4.1.2. SHELL-AND-TUBE HEAT EXCHANGERS

For the shell-and-tube heat exchangers, $a = 28,000$, $b = 54$, and $n = 1.2$. The size parameters for the shell-and-tube heat exchangers correspond to the surface area of the heat exchangers. This surface area is calculated using the following equation, which utilizes the Q_L or Q_H of the exchanger, the heat transfer coefficient, and the log-mean temperature difference. $A = Q / (U * \Delta Tm)$ (Equation 2) [5]. The condenser surface area was calculated to be 18 ft^2, while the evaporator surface area was calculated to be 3 ft^2. When entered into Equation 1, the cost per heat exchanger came out to roughly $29,800 for each condenser and roughly $28,200 for each evaporator. When multiplied across the 18 separate units, the total cost for all heat exchangers is roughly $1,045,000.

4.1.3. REFRIGERANT

Each system requires 200 tons of cooling power at a level of 0ºF. As a rule, each cooling ton will require 3 pounds of refrigerant. When multiplied, the total refrigerant per system is 600 lbs. Multiplying this by the cost of R-134a ($9/lb), the cost of refrigerant per system equals $5,500 and rounds to $100,000 when all systems are considered.

4.2. ANNUAL COST

The portion of the cost estimate designated as the annual cost includes the energy cost associated with running the refrigeration systems and the maintenance costs associated with refrigerant recharge.

4.2.1. POWER

The power cost was determined by converting the work of the compressor to energy consumption in kWh. The assumptions underlying the cost estimate for power usage are as follows: 24-hour run-time per day, 365 days per year. The average commercial electric cost in New Jersey, as of April 2023, was $0.1357/kWh [6]. Table 2 below shows the energy cost yearly breakdown.

Table 2: Annual Energy Costs

Power/unit (kWh)	Operating Hours/day	Power cost ($/kWh)	Annual Cost/Unit	Total Annual Energy Cost
275.84	24	$0.1357	$330,000	**$5,940,000**

4.2.2. REFRIGERANT MAINTENANCE

Each year, refrigeration systems will need to be recharged with refrigerant due to leakage. The range for refrigerant recharge rate in commercial refrigeration systems ranges between about 4%-10% [7]. Assuming the higher end of the recharge rate, 10% of the total refrigerant pool results in a cost of around $10,000 per year.

4.3. PROJECTED ANNUAL CHARGES

The constructed complex is planned to be operational for 15 years. The yearly costs will fluctuate with the changing value of the dollar due to inflation. Table 3 details the projected annual power cost change over the next 15 years as a result of inflation. The estimated inflation rates are based on previous annual trends. It is important to note that the numbers in the figure are the unrounded calculations based on average power costs and are not intended to represent specific predicted costs, but rather serve as a guideline for cost planning as it relates to inflation. The estimated average energy cost per year considering inflation over the next 15 years is around $6.8 million.

Table 3: 15-Year Energy Cost

Year	Energy (kWh)	Power/Unit	Total Power	Total Annual
1	$0.1357	$327,900	$5,902,197	**$5,903,547**
2	$0.1384	$334,458	$6,020,241	**$6,021,591**
3	$0.1412	$341,147	$6,140,646	**$6,141,996**
4	$0.1440	$347,970	$6,263,459	**$6,264,809**
5	$0.1469	$354,929	$6,388,728	**$6,390,078**
6	$0.1498	$362,028	$6,516,502	**$6,517,852**
7	$0.1528	$369,268	$6,646,832	**$6,648,182**
8	$0.1559	$376,654	$6,779,769	**$6,781,119**
9	$0.1590	$384,187	$6,915,365	**$6,916,715**
10	$0.1622	$391,871	$7,053,672	**$7,055,022**
11	$0.1654	$399,708	$7,194,745	**$7,196,095**
12	$0.1687	$407,702	$7,338,640	**$7,339,990**
13	$0.1721	$415,856	$7,485,413	**$7,486,763**
14	$0.1755	$424,173	$7,635,121	**$7,636,471**
15	$0.1791	$432,657	$7,787,824	**$7,789,174**
	Total Annual Cost for 15 years			**$102,089,404**
	Average Annual Cost			**$6,805,960**

5. CONCLUSION

This project aimed to design a comprehensive, cost-effective refrigeration system for Magnolia Country Frozen Foods' cold storage distribution center located in Rutherford, NJ. Following a thorough evaluation of key factors, including efficiency, safety, and environmental impact, it became clear that the single-stage cycle utilizing R-134a is more efficient and cost-effective for the customer than the cascade cycle. Installing each refrigeration unit will require a centrifugal compressor, two shell & tube heat exchangers, and R-134a refrigerant. For the complete installation of all 18 units, the estimated total upfront cost for the project is $22.1 million, with an estimated average annual cost of $6.8 million over the next 15 years stemming from power consumption and refrigerant recharge.

APPENDIX

Appendix Figure 1: R-134a COP Calculation

R-134a COP Calculation

Compressor:

$Wc = \hat{h}_2 - \hat{h}_1$
$Wc = 125 - 101$ BTU/lb
$Wc = 24$ BTU/lb

Condenser:

$Q_H = \hat{h}_2 - \hat{h}_3$
$Q_H = 125 - 39.9$ BTU/lb
$Q_H = 85.1$ BTU/lb

Evaporator:

$Q_L = \hat{h}_1 - \hat{h}_4$
$Q_L = 101 - 39.9$ BTU/lb
$Q_L = 61.1$ BTU/lb

COP:

$COP = Q_L / Wc$
$COP = 61.1$ (BTU/lb) / 24 (BTU/lb)
$COP = 2.55$

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