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Bradford A. Bruno, Ph.D.
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Schenectady, NY 12308

Subject: Transmittal of Design and Effectiveness of an Environmentally Friendly Heat Pump

Dear Dr. Bruno,

The following contains a detailed proposal for an environmentally friendly heat pump using water sourced from municipal water suppliers in response to Thermotopia's request for assistance with the project.

Using the enclosed design and analysis, we believe that your customers will have continued access to high quality domestic heat pumps while also providing a decreased environmental footprint. Based on our evaluation, the following system will provide customers with the necessary 11.5 kW of power to heat their homes in the winter months with an exceptional EER rating of 12.4. Not only is this rating competitive with other systems, but the annual expected carbon footprint of the system is relatively low at 1.4 tons of CO_2. The initial cost of the system is $6,540 with an annual system cost of $4,150. Additionally, all of the provided restraints and required guarantees have been met by the proposed system.

For any further questions or information, please do not hesitate to contact us. I, Jack Edson, can be reached by phone at (774) 641-1494 or by email at edsonj@union.edu.

Regards,

Jack Edson　　　　Roderick Landreth　　　　Jiawei Liu

Project Summary:

The proposed solution was constructed to be a cost-efficient and environmentally friendly heat pump for residential use within the "cold-belt" of the United States. The designed system operates using a working fluid of R-407a and contains an energy efficiency rating (EER) of 12.4 and seasonal energy efficiency rating (SEER) of 15.2. The compressor within the system requires that 3.18 kW of power be delivered to the unit to properly run the heating process. Additionally, the required areas of the condenser and evaporator within the system are 1.74 m^2 and 1.45 m^2, respectively. As a result of this, the initial cost of the system, inclusive of the three aforementioned components, is $6,510. Additionally, the proposed 10-year system has a present value cost ranging from $43,760 at 2% interest to $31,990 at 10% interest and an annual cost ranging from $4,880 at 2% interest to $5,210 at 10% interest.

As stated in the project description, the goal of this proposal is to provide a design for a cost-effective and energy efficient alternative to the current air exchange style heat pumps. The new design must still deliver the required 11.5 kW of power to adequately heat the residential buildings and must also fall within certain system guidelines based on efficiency and safety. From this, the objective was to design the most cost effective solution based on a comparison of multiple working fluids, an assurance that the requested guarantees are met, and a consideration for both current and proposed legislation.

Within the design methodology, we considered an array of working fluids such as water, cryogenics, and refrigerants. After analyzing an array of potential systems, it was determined that, based on thermodynamic principles and attainable efficiency ratings, a refrigerant was necessary to meet the required conditions. From this, the environmental impact of each available refrigerant was inspected with respect to the environmental impacts (such as global warming potential) and safety for humans. Furthermore, the current and future legality of each fluid was evaluated. This was to ensure the validity of the proposed system not only in the current time but also for the foreseeable future. Following this, the federally mandated efficiencies of heat pumps was considered. Again, this portion of the design process considered not only the presently active legislation but also active proposals and changes to be made in the coming years. Based on the available literature, an EER rating of 12.4 was chosen as it meets all current legal requirements as well as proposed changes for 2023. Following this, the available list of environmentally friendly refrigerants were analyzed within the system at the given EER and were compared based on various economic factors, such as initial costs, the present value of the system after 10 years, and the annual cost of the system for a 10 year lifetime. Based on these calculations, R-407a was determined as the most cost effective working fluid given the constraints of the project.

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Background and Introduction:

Many home heating systems have been found in recent years to have adverse effects on the environment, especially through their choice of refrigerant used as the working fluid. As homeowners have become more conscious of this, companies like Thermotopia, Inc, have started expanding into the market for greener sources of heating control. One such method that is fairly reliable and durable is using the ground as a source of cooling in the summer months and heating in the winter, due to the temperature being almost constant year round after a certain depth. Another similar technique is to use underwater reservoirs to move heat, although several areas have regulations concerning whether you can alter groundwater or return it. Using deep layers of the earth involves heavy construction and often is not the most desired solution. While both of these methods have fairly significant drawbacks, many municipalities have agreed that their water reservoirs can be utilized, returning the water unharmed to the reservoir as opposed to groundwater.

Using the reservoir as a heat source in a heating system may be more environmentally friendly than a combustion cycle, but many refrigerants used in such systems can be very harmful to the environment themselves. In the unlikely case that any refrigerant escapes from the system, use of certain refrigerants, such as R-12 or R-22, has proven very harmful to the ozone layer or, as with the case of methane, prone to causing global warming (SDS). The EPA regulates the use of and is phasing out many refrigerants, recently banning the production and distribution of HCFC refrigerants because they are ozone depleting. As a result of this, R-407a is used as a greener alternative to several refrigerants being banned. Common refrigerants like R-407c and R-134a are also being banned by the EPA in 2024, and R-22 production is banned as of January 1st, 2020, due to the Montreal Protocol (EPA, 2019). R-407a does not deplete the ozone, will not be banned by the EPA in 2024, and has a low toxicity to mammals. Other refrigerants can be harmful to humans, flammable, and many of which are not very efficient to use within the range of temperatures dictated by the project description. Refrigerant choice will determine much of the cycle's efficiency and environmental impact.

A simple heat pump cycle like this requires a refrigerant to have its internal energy greatly increased and be evaporated in the evaporator, enter the electrically driven compressor to raise pressure, condensed into a liquid, supply energy to the air in the house, and then be throttled back down to a lower pressure to begin the cycle again. The initial costs will be the cost of the equipment, and the annual costs are those based off the power and water use in the system. The cost of using the municipality's water reservoirs is larger than the impact of both the initial cost and that of power use, and so water use has to be minimized while maintaining efficiency. However, the power output must also be considered to make this system economically viable. The system has many constraints set by pressure and environment temperature restrictions, but the value that must be minimized is the cost of the system.

Some of the limitations that are less obvious include that heat transfer must be possible, meaning that the temperature of the refrigerant in the evaporator must be below 15°C for heat to be able to transfer from the supply water into the system, and similarly, the refrigerant must be a minimum of 40°C when supplying heat to the house. Guaranteeing the supply water will not freeze is important to the community for the safety of their pipes as ice will severely damage them. The water also must not be contaminated as it will be returned to the water supply for public use.

Problem Definition:

A new heat pump design is required in order to deliver heat to residential houses in deep winters while being both environmentally friendly and cost-effective. The standard vapor compression heat pump cycle is integrated with a water system in the evaporator and must not contaminate or freeze the water. The heat pump must satisfy the heat duty requirement of 11.5 kW with a reasonable cost for equipment and energy. The refrigerant is required to be ecologically compatible while also allowing the system to meet energy efficiency guidelines.

List of Specifications:

- Thermal
    - Deliver 11.5 kW of power to the house
    - A seasonal heat load of 50 million BTUs and an annual heat load of 100 million BTUs
    - 15 °C water supplied to the evaporator with a pressure of 100 kPa gauge
    - Returned water from the system can not be frozen
    - Return air from the house is 20 °C and the heat exchanger must deliver air at 40 °C to the house
    - Condenser has an overall heat transfer coefficient of 100 W/m^2-℃
    - Evaporator has an overall heat transfer coefficient of 410 W/m^2-℃
    - Refrigerant entering and leaving the condenser has to be above 40 °C in order to ensure heat flows from the working fluid into the air
    - Refrigerant entering and leaving the evaporator has to be above 1 °C and below 15 °C to ensure that water is not frozen
- Mechanical
    - The refrigerant pressure must be greater than 30 kPa gauge and less than 5.5 MPa absolute to prevent leaks of the refrigerant
    - Compressor has an isentropic efficiency of 85%
    - Motor has an efficiency of 90%

- Environmental
    - Refrigerant must be environmentally friendly to minimize effects of the system on the environment
    - System must be ensured to have no leaks of the refrigerant into either the local environment or the coupled water system
    - Expected carbon footprint of the system operation (tons of C per year) is required
    - Energy efficiency rating of the system should be greater than 12
- Health and Safety
    - Refrigerant must be safe for humans to be in close proximity with (such as no toxicity or risk of combustion)
- Economic
    - Electric power costs 14 ¢/kWhr
    - Water costs $9.00/1,000 gallons
    - Condenser and evaporator cost $1,500/m^2
    - Compressor costs $550/kW
    - System has a life span of 10 years
    - Interest rates are to be calculated ranging from 2% to 10% and are to be used for non-initial cost calculations
    - Equipment cost (initial cost), present value cost for equipment and energy use for 10 years, and annual cost for a 10 year annuity need to be determined for various system conditions
- Legal
    - Selected refrigerant must be acceptable under EPA regulations
    - System must have an EER rating that meets the federally mandated efficiencies for heat pumps

- Ethical
    - Heat pump must be designed with the intention of providing a cost effective solution that is environmentally friendly and safe for residential use following all moral principles of engineering

Design Description:

The proposed final design includes a heat pump with an EER efficiency of 12.4 (equivalent to a SEER of 15.2) that provides 11.5 kW of power to a residential home using municipal water supplied at 15℃. This choice of EER rating ensures that the system will follow all current and proposed Department of Energy guidelines through 2023 across the entirety of the country. The system operates using a refrigerant of R-407a and requires 3.18 kW to power the compressor for the desired heat output. Additionally, the system requires an initial capital expense of $6,510 with an annual cost of $4,150 for the 10-year lifetime of the system.

Thermodynamic Components:

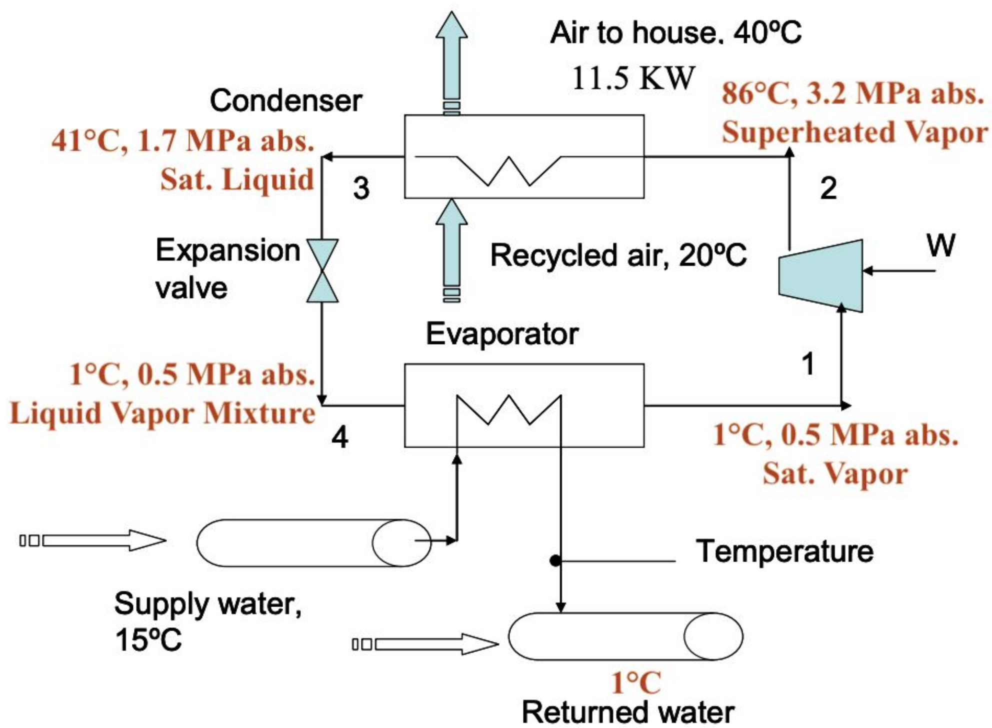

Figure 1: Simplified diagram of the basic components to the heat pump system using a coupled water system connected to the evaporator along with basic state properties at each state of the system.

Figure 1 displays the general states of the working fluid both before and after each component within the system. As shown in the figure, the working fluid is able to constantly provide heat to the recycled air as the temperatures between states 2 and 3 never fall below 40 °C, the desired temperature of the air delivered to the house. Additionally, the water within the coupled system is guaranteed to never freeze. This is due to the working fluid that interacts with the water system never falling below 1℃. Due to this, thermodynamic principles dictate that the water, which enters at 15 °C, will not be able to drop below 1℃.

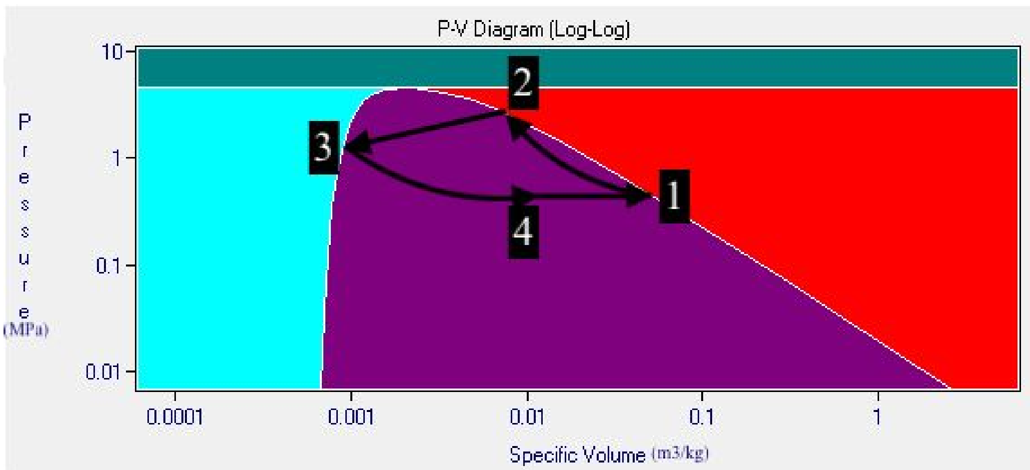

Figure 2: P-V diagram of 4 states used within the heat pump design using R-407a as the working fluid. The states within the diagram correspond to the states in Figure 1.

The above figure details the change in pressure throughout the system. As shown above, the pressure at each states allows for the working fluid to flow without the need of added work, except from states 1 to 2 through the compressor. All pressures are shown in absolute pressure. Additionally, the stated constraints on the pressure within the system are satisfied as the pressure stays between the given bounds. Exact pressure measurements and other thermodynamic values can be found in Appendix A.

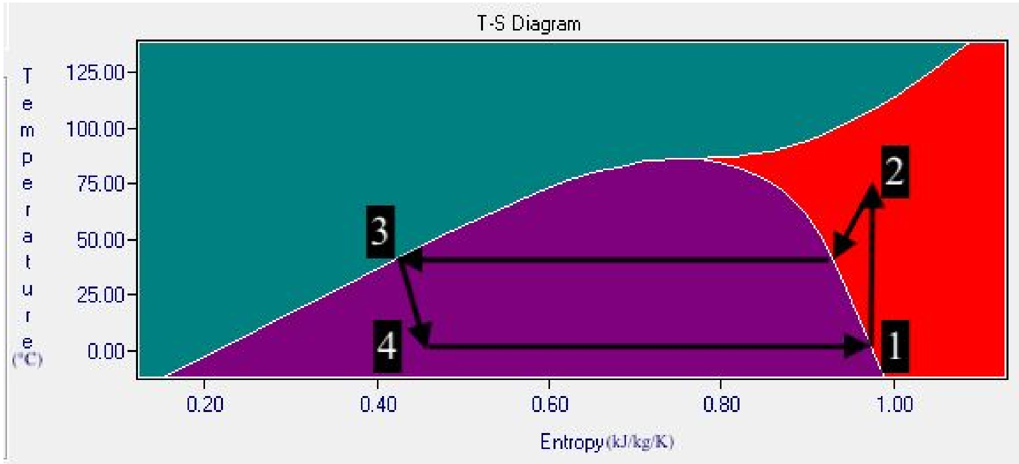

Figure 3: T-s diagram of 4 states used within the heat pump design using R-407a as the working fluid. The states within the diagram correspond to the states in Figure 1.

Figure 3 shows the temperature at each state within the system. Based on the temperatures of the system, the guarantee that water will not freeze upon exiting can be made since the refrigerant itself does not drop below 1℃. This is significant for the proposal as the municipal water suppliers will not agree to work with the system if this condition is not met. Additionally, as previously noted, the working fluid on either side of the condenser maintains a temperature above 40℃ to ensure that the system only adds heat the cross-flowing air. The final states of the systems can be found in greater detail in Appendix A.

Economic Analysis:

Cost	Unit Usage	Total Price	Annual/Initial costs
\$0.14/kwHr	2520 hrs/yr	\$1120	Annual
\$9/1000 Gallons Water	336130 Gal/yr (0.140kg water/s)	\$3030	Annual
\$1500/m^2 Heat Exchanger Sizing	Condenser: 1.75m^2 Evaporator:1.43m^2	\$4770	Initial
\$550/kW Compressor Sizing	3.18kW Compressor	\$1750	Initial

Table 1**:** This is the cost breakdown of the final system, notarizing which values are annual and which are one-time costs.

The initial capital investment is between \$43,760 at 2% interest and \$31,990 at 10% interest, intermediate values found in appendix B. If paid annually, this would be \$4910-\$5250 per year, ranging from an interest rate of 2% to 10% over the 10 year lifetime of the machines. This is working with an average of 50 million BTU's per cold season in similar conditions, extrapolating to 100 million BTU per year of use, for heating in the fall and spring. The areas of the evaporator and condenser heat exchangers were found improperly, assuming that temperature differences would stay constant throughout the heat exchanger. The actual heat exchanger sizes would be larger.

Environmental Aspects:

R-407a is a zeotropic hydrofluorocarbon (HFC) blend that is designed for low and medium temperature refrigeration operations (Linde). It is a replacement for R-22 and R-404a, as reviewed by United States Environmental Protection Agency (US EPA). Our refrigerant, R-407a, has an Ozone Depletion Potential (ODP) of 0, which means it will not cause any degradation to the ozone layer. The 100-years Global Warming Potential (GWP) of R-407a is 2107, indicating that the substance has a medium infrared absorption and a medium atmospheric lifetime (EPA and ca.gov). As for the human health aspect, R-407a is in A1 classification reviewed by the

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This is because R-407a does not have flame propagation nor toxicity at concentrations less than or equal to 400 ppm (ASHRAE). Therefore, it is reasonable to use R-407a for residential heating system as it is not harmful to humans.

Analysis:

Thermodynamic Components:

In order to analyze the system, a multitude of assumptions first needed to be established. First, the system was chosen to have a Steady State Steady Flow behavior. This caused for the analysis to only consider a cycle in which there is no change in the mass flow rate and that the system is stable with respect to time. From this, the startup and shut off periods of the system can not be evaluated. Additionally, this assumption (along with the stated pressure constraints) guarantee that no leaks will be present within the heat pump. This also contributes to a constant mass flow rate throughout the system. Also within the thermodynamic analysis, an assumption that there is no change in kinetic or potential energy was made. From this, it is assumed that the working fluid does not change velocity or height with respect to each individual state. Furthermore, the system components that did not have a specified efficiency were assumed to be ideal, such as an adiabatic and isenthalpic throttling valve and heat exchangers with efficiencies of 100%. Lastly, the atmospheric pressure was assumed to be 101.325 kPa. This was used to compare gage and absolute pressures.

Following the initial assumptions, more constraints were placed on the system design. This included obeying the laws of thermodynamics and heat transfer, as well as ensuring certain guarantees from the project description. The two main factors from this are that heat must flow from high temperatures to low temperatures and that fluid may not flow in an adverse pressure gradient unless work is applied. Also, phases were limited to those that function properly with their corresponding components in the system, such as the inlet for the condenser being a vapor and not a dense fluid. Lastly, temperature restrictions were placed on individual states so that the system would operate correctly. This included setting a minimum temperature of 41℃ for states 2 and 3 as well as setting a minimum temperature of 1℃ for states 1 and 4.

Once the limitations were set, efficiency calculations were performed on multiple systems using various refrigerants. The chosen EER rating was 12.4 (equivalent to SEER of 15.2) as the publically available legislation and proposals indicate that a minimum SEER rating of 15 will be required by 2023 across the country. From this, a select list of refrigerants (as discussed in the following Environmental Aspects section) were analyzed at the given EER rating and their resulting present value costs were compared. This minimization of cost served as our objective function on which we based our final system design and is detailed further in the Economic Reasoning section.

Environmental Aspects:

Refrigerants were chosen from a list of substitutes in residential and light commercial air conditioning and heat pumps from US EPA and a list of common refrigerants from California Air Resources Board (EPA and ca.gov). Only the refrigerants with a global warming potential below 2500 were considered in order to fulfill the ecological compatibility. The list was then narrowed down by determining whether the properties of refrigerants are tabulated in CATT3, as shown in Table 2. The GWP low band includes refrigerants with a GWP below 50, while the medium band has refrigerants with a GWP between 50 and 2500 (Linde).

Refrigerant	GWP band
Ammonia	low
Water/Steam	low
Isobutane	low
Ethane	low
Methane	low
Propane	low
R-134a	medium
R-407a	medium
R-407c	medium
R-410a	medium

Table 2: A list of environmental friendly refrigerants
used for designing new heat pump based (EPA and ca.gov).

Although it is guaranteed that the refrigerant will not leak in or out of the system because of the pressure constraints, refrigerants with high risk hazards were eliminated, as shown in

Table 3 below. As a result, the analysis mainly focused on HFC refrigerants, with brief studies of the natural refrigerants.

Refrigerant	Risk Hazard
Ammonia	Highly toxic (UCL)
Isobutane	Highly flammable (nj.gov)
Ethane	Highly flammable (nj.gov)
Methane	Highly flammable (NASA)
Propane	Highly flammable (EPA)

Table 3: Eliminated refrigerant choices due to their high risk hazards.

Since R-407a has relatively low discharge temperature, there is no need for compressor heat protection, which can reduce the complexity and increase the reliability of the system. Meanwhile, many systems with R-407a have been reported to have an approximately 10% savings in energy efficiency (Linde). Furthermore, as of January 1st, 2024, refrigerants including R-134a, R-407c, and R-410a will be unacceptable for air conditioning and refrigeration usage, according to the Significant New Alternatives Policy (SNAP) Program at US EPA (EPA). As a result, the choice of using R-407a will ensure the system to be legal to operate for both the present and future.

The expected carbon footprint of the system operation was determined by an electricity carbon dioxide conversion factor. Assuming the heat pumps are only used in New York state, the conversion factor was calculated using equation 1 below:

$$\text{Electricity carbon dioxide conversion factor} = \frac{\textit{estimated carbon dioxide emissions}}{\textit{net electricity generation}}. \qquad (1)$$

The estimated carbon dioxide emissions and net electricity generation in New York state are provided by the United States Energy Information Administration (US EIA). The carbon dioxide emission by electric utility produced by all sources was 6,222,373 metric tons of CO_2 in 2018 (EIA). The net electricity generated by all sources in 2018 was 35,659,945 MWh (US EIA). Since these are the latest published values, the conversion factor of 0.00017 metric tons CO2/kWh is assumed to be a constant for the next 10 years. As a result, a compressor with a power of 3.2 kW, running 14 hours a day and 180 days per year, will emit approximately 1.4

tons of carbon dioxide per year. The system generates 40% less carbon dioxide than the average U.S. household generates for electric heating (NYSERDA).

Economic Reasoning:

Based on a household requiring 50 million BTUs of heating per cold season with an output of 11.5 kW, we extrapolated that the heat pump must operate 14 hours a day for the whole year or, more likely, all day during winter and tapering on/off during the fall and spring seasons. This brings the yearly output to 100 million BTUs, making much more sense in the cold belt and with the potential for polar vortices making the cold last longer. Other assumptions made during the economic analysis include no drastic price change due to market fluctuations or shortages within the next 10 years, so the pay-by-rate prices would remain constant (power and water prices). A reasonable assumption is that the compressor sizing and heat exchanger sizing can be bought in the intervals that we need, for example, there are not only 1 and 2 kW compressors, but 1.5 and 1.6 kW compressors on the market if needed. The largest assumption is that the interest rate will be between 2 and 10%, as predicting the future is nearly impossible.

If it were all paid for at once, the investment would be between $43,760 at 2% interest to $31,990 at 10% interest (see appendix B). This is summing the initial costs, and computing the annuity over the 10 year life of the system into a present value cost using equations 2 and 3 (appendix B). The annual cost of this system including power input, supply water, and initial cost of machines is $4910-$5250 per year, ranging from an interest rate of 2% to 10% over the 10 year lifetime of the machines. The detailed price breakdown is included in appendix B. This includes the pay-by-rate costs of powering the condenser and paying for water use, and computes the value of the initial cost if paid annually. This is the price for the full year, not per season, and was computed using equations 2 and 4 (appendix B).

The cost was used as the objective function to determine the states and the refrigerant. The number of variables was greatly reduced by putting bounds on our evaporator and condenser pressures and temperatures, and setting our EER to 12.4. The main driver of price between refrigerants and state values was the mass flow rate of the supplied water, dominating costs as $3030 per year, as shown in Table 1. Limiting ourselves to the lowest EER value we can have based on EPA and DOE guidelines produced a system that had a lower mass flow rate of water, lowering the Q_L to the minimum it can be while still producing a legal EER.

Evaluation of Design and Other Constraints:

Economic:

The main economic constraints rose from the cost of the supplied water and the sizing of the compressor, both driving annual costs and the compressor size which also raised the initial capital expense. The price of the water per year was minimized at the expense of raising power and initial costs of the compressor, and because the water is so expensive, the water price still dominates the price breakdown**.** Additionally, the prices of the evaporator and the condenser are lower than in reality because it was assumed incorrectly that the difference in the temperature of the fluids would remain the same throughout the heat exchangers, instead of the gradient they would actually be. The result is smaller surface areas than the heat exchangers need in reality for both the condenser and evaporator, and a lower initial cost. The proper method for determining the temperature difference for the heat exchangers is to use a logarithmic mean temperature difference.

The cost of heating with this system for a whole year is more than most options, but is within 5% of electric resistance heating annually in nearby regions (Mass.gov. 2019). On both this and electric resistance heating are subsidies and rebates the government gives the installer and the customer in New York. Neither of these are included in the given price of $4880-5210 (based on 2-10% interest) every year. With both the rebates of NYSERDA (*NYSERDA*, 2019) and HEAP (LAW-NY, 2016), the costs would be brought down $350/year for customers in New York, and $550-750 (based on 2-10% interest)/year for the installers in New York. There are other similar electric initiatives in northern U.S. states, but the cycle was designed and is being assessed within New York state bounds.

Environmental:

One of the goals of this task is to use the most ecologically compatible refrigerant. As a result, the selection was chosen from refrigerants with a reasonable environmental impact. Based on how US EPA evaluates the refrigerating substances, there are two major factors to determine how environmental friendly the available substances are: ODP and GWP. The chosen refrigerant, R-407a, is not an ozone depleting substance. It is acknowledged that R-407a has a relatively higher GWP than other refrigerants. However, R-407s is still under the same GWP band with other options, so the difference between the global warming effects done by different refrigerants would not be very significantly.

Ethical:

The entire purpose of this heat exchanger system was to make it was environmentally friendly and affordable. Realistically, if this were the greenest system available but has extremely high costs, no homeowner would have it installed and its environmental benefits would go unused. Tradeoffs that lowered how environmentally friendly this heat pump system is mainly decreased the cost for this reason. For example, setting the EER at 12.4 instead of at the maximum possible value meant that costs would be lower, but also that the condenser had to supply a little more power and its carbon footprint is a little larger. In addition, the use of R-407a was a compromise because it is not the most environmentally friendly material, but because it was among the most efficient and was clean enough to be legal in the lifetime of this system. 40% less of a carbon footprint is very significant, and would greatly impact the yearly emissions caused by home heating.

Health and Safety:

These constraints prevented us from choosing a refrigerant like ammonia or R-12, their detriment to humans are unacceptable for use in a house. Besides the increase in health and safety to the public caused by making an environmentally friendly heating system, this system is guaranteed not to leak because of the refrigerant being within 0.131 MPa and 5.5 MPa, measured in absolute pressure. Even if it were to leak, R-407a is nontoxic and non-flammable, the only danger being asphyxiation, much like fuel burning sources releasing CO_2. Like CO_2 detectors, there are refrigerant detectors that can be installed to lessen the potential risks. The system also operates within a fairly safe-to-touch temperature range, 1℃ to 86℃, and is less hot than a kitchen stove on low heat and than most combustion heating.

Other:

Other aspects that did go into consideration included manufacturability, sustainability, social and political. A few of these have very little to do with designing a way to heat a home, like political, as long as nothing is illegal. We were sure to determine that this is a legal system within its foreseeable lifetime, adding to its sustainability as well. Additionally, some of the assumptions are reliant on other parties, such as the manufacturer. If the evaporator has to be very low in the ground to exchange with the water because of the depth of the water, then the potential energy change may not be negligible. If the system takes a while to reach equilibrium, then the efficiency will not be as high and may not be steady state. None of these aspects were compelling enough to act on because they were unpredictable and outside the scope of the given contract.

Conclusions and Recommendations:

Based on the cost-effectiveness and environmental impact of the proposed system, our recommended course of action is to implement the proposed heat pump system to residential consumers. Firstly, the environmental impact of the refrigerant is classified as having a middle tier global warming potential. While other substances may have a lesser value for this criteria, they fail to attain the same EER rating for a similar cost. Additionally, R-407a is a non-ozone depleting substance which further emphasizes the environmentally-friendly aspect to the system. In addition to this, the refrigerant poses very little risk to humans as it is neither flammable nor toxic. Furthermore, the refrigerant has no direct indication of being banned or phased out in the near future. Other refrigerants, such as R-134a and R-410c, have either had restrictions placed on their usage already or have proposals in place to reduce their application usage. This allows for the proposed system to have an extended lifetime as it will be legally acceptable for the foreseeable future. Additionally, the EER of the proposed system is calculated to be 12.4, which has a Seasonal EER of 15.2. According to current regulations by the Department of Energy, a minimum SEER of 13 is required in northern states and will be increased to 15 by 2024. Again, this change will not affect the availability of the proposed system as the energy efficiency exceeds that of the proposed changes. Also within the environmental aspect to the design, the carbon footprint of the heat pump is a significant reduction to traditional systems. Given the power consumption needs for the compressor, the annual carbon footprint of the design is 1.4 tons of CO_2. When compared to typical CO_2 emissions for heat pumps in residential homes in the United States, this is approximately a 40% reduction from the average 2.4 tons of CO_2. Again, this serves as a meaningful indicator that the system is an environmentally friendly heat pump.

Following the environmental analysis, a cost comparison was also made across all suitable refrigerants. Based on initial costs and the present value costs for all systems using a 10 year lifetime, R-407a has the lowest expenses associated with the system. This served as our objective function with the main goal being to minimize the cost based on the available list of refrigerants and selected EER value.

In addition to this economic analysis, the proposed system is also eligible for multiple rebates, both for the end consumer and Thermotopia, Inc. during the installation process. Firstly, families are potentially eligible for a $350 annual stipend based on their payment method. This would alleviate some of the yearly costs for the system and would potentially attract more customers to switch to the proposed heat pump. For Thermotopia, Inc., there is also an available rebate up to $4,930 based on the heating capacity of the system. This would either help to maximize profits for Thermotopia, Inc. or lower the costs consumers would have to pay and thus make the system more consumer friendly.

Based on the combination of these environmental, economic, and longevity factors, the Private Union of Mechanical Professionals recommends that Termotopia, Inc. begins the manufacture and installation of the proposed heat pump to residential homes within the "cold-belt" of the United States.

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Appendix A:

Fix States R-407a		T °C	P Mpa (abs.)	h kJ/kg	s kJ/kg*K	x	phase
Refrigerant							
	1	1	0.5315	262.8	0.974	1	Sat. Vapor
	2s	86	3.216	305.5	0.974		Superheated Vapor
	2a			318.6169935			
	3	41	1.688	116.6	0.4224	0	Sat. Liquid
	4	1	0.5315	116.6	0.4408	0.2933	Liquid Vapor Mixture
Water							
	1	15	0.201325				
	2	1					

Table 4: States of R-407a used within the heat pump cycle as calculated by CAT3. The state values for R-407a correspond to the state numbers as detailed in Figure X. The state values for water correspond to before the evaporator, state 1, and after the evaporator, state 2.

wideal	42.7		qH	202.0169935
wcompressor	55.81699346		mr	0.05692590412
Wideal	2.430736106		qL	146.2
Wcompressor	3.177432818		QL	8.322567182
			mw	0.142013637
EER	12.39477399			
Condenser area =	Q_H / (h*del T)	1.74242	m^2	
Evaporator area =	Q_L / (h*del T)	1.44992	m^2	
Carbon footprint =	1.39718	ton C/yr		

Table 5: Determined thermodynamic and mass flow rate values for the system based on the states given in Figure X. Required areas of components and the carbon footprint of the system are found using provided values.

Appendix B:

Interest Rate	Annuity Present Cost	Total Present Cost	Annual Cost of Initial Expense	Annual Cost Method
0.02	37250	43760	720	4880
0.025	36290	42800	740	4890
0.03	35370	41880	760	4910
0.035	34480	40990	780	4930
0.04	33630	40140	800	4950
0.045	32810	39320	820	4970
0.05	32020	38530	840	4990
0.055	31250	37760	860	5010
0.06	30520	37030	880	5030
0.065	29810	36320	910	5050
0.07	29120	35630	930	5070
0.075	28460	34970	950	5090
0.08	27820	34330	970	5120
0.085	27210	33720	990	5140
0.09	26610	33120	1010	5160
0.095	26030	32540	1040	5180
0.1	25480	31990	1060	5210

Table 6: Price calculations using equations 1 and 2 below for interest rates between 2% and 10% over 10 years. Highlighted is the difference in final costs for 2% and 10%, paying for the system using both annual cost and initial cost.

Equations:

$$\frac{A}{P} = \frac{i_{eff}(1+i_{eff})^n}{(1+i_{eff})^n - 1}$$

Equation 2: Used to calculate an annuity from a present value or a present value from an annuity

$$P = P_{init.} + A * \frac{P}{A}$$
$$A = A_{p+w} + P * \frac{A}{P}$$

Equations 3 and 4: Equation 2 (top) simplified to calculate the sum total of all costs into one initial cost, and equation 3 (bottom) used to calculate the sum total of all costs into the annual cost. The ratio $\frac{A}{P}$ and $\frac{P}{A}$ are found from equation 1.