MAE – 4149: Thermal Systems Design

Term Project Paper

Ahmed Alfaldel, Anton Yanovich, Joanna Ayala-Flores, Mahdi al-Saady, Nii Adotey Sackar, Oscar Southwell

I. Executive Summary

I.I Introduction

This report outlines the approach for the background research, preliminary design, and detailed design performed by the team for the Fall 2022 Thermal Systems Design project at George Washington University (GWU). The project's main objective was to design and analyze a thermally based environmental control system and electrical system for the Science and Engineering Hall (SEH). This system must provide cooling in the summer, heating in the winter and generate electricity all year round for SEH. Secondary objectives of this project included the incorporation of the hydrogen fuel cell, a hydrogen boiler and a hydrogen production plant using catalytic methane pyrolysis. Lastly the tertiary objectives included investigating SEH's LEED rating and the possibility of increasing its LEED score (Leed Score Card, 2015)

The inspiration for the project was drawn from US Patent 3,259,176, also known as the Rice Patent, submitted by N.C Rice on behalf of the United Aircraft Corporation. The patent describes an environmental control system for cooling and heating homes or industrial buildings. It describes a complex and robust control system that will switch over from summer to winter and power generation cycles. Fig. I.I.A - Fig. I.I.C below shows the system of the patent along with its different operating modes (N.C Rice, 1958).

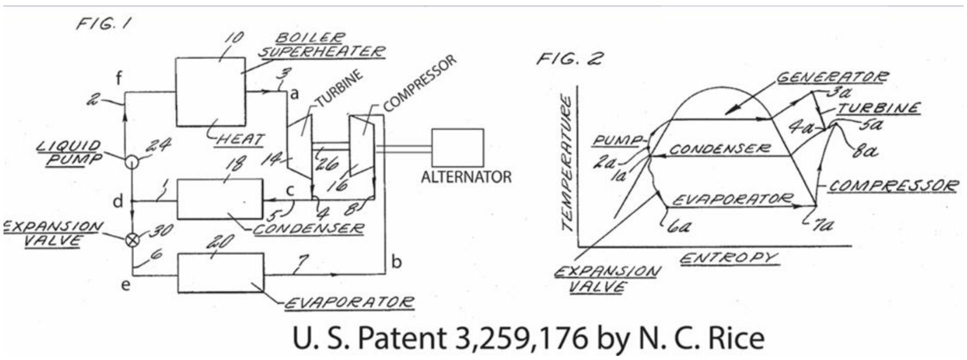

Fig. I.I.A: Rice Patent Overview System Diagrams.

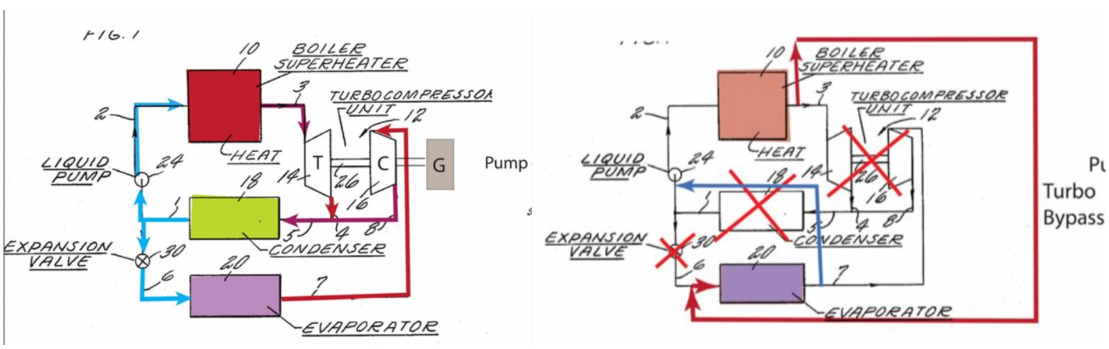

Fig. I.I.B: Cooling Cycle (Left) & Heating Cycle (Right) Annotated System Diagrams

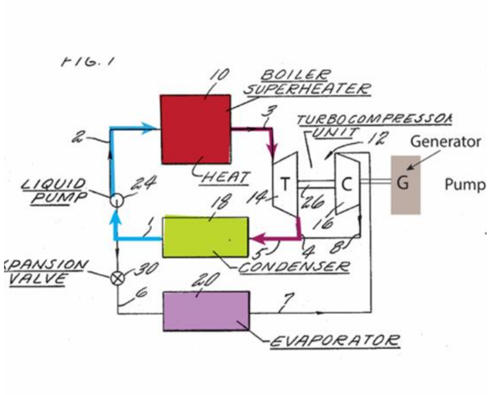

Fig I.I.C: Power Generation Cycle Annotated System Diagram

The requirements for the project derived from the patent and the course instructor were as follows:

The team will be responsible for determining the:

1) Design of the boiler, condenser, evaporator, and electrical power generation

2) Design of piping system and location throughout SEH

3) Design of Compressor and Turbine

4) Working Fluid or Refrigerant of choice

5) Economic Analysis of components and operating costs

6) Viability of the technology being used

I.II Team Structure and approach

To meet these requirements, the team was split up according to the major components, and the major requirements to cover the most ground and make steady progress. The personnel breakdown is as follows in Table I.II:

Table I.II: Team Personnel Breakdown

Team Member	Roles & Responsibility
Ahmed Alfadel	Selecting Refrigerant, Selecting Turbine, Economic Analysis
Joanna Ayala- Flores	Selecting Boilers, Research into SEH utilities, Economic Analysis
Oscar Southwell	Selecting Evaporators, Performance Analysis
Anton Yanovich	Selecting Condenser, Research into LEED rating, Performance analysis on system, Design of overall Layout
Nii Adotey Sackar	Selecting Compressor, Design of overall system layout, Economic Analysis
Mahdi al-Saady	Selection of Power Generator, Selection of Hydrogen Fuel Cell, Assessment of Viability of technology being used

With the roles and responsibilities assigned, the team determined its approach to the design and development of the system to meet the requirements outlined above.

The team approach and overall design motivation can be described as follows:

The team aims to design an environmentally friendly, energy-efficient Heating, cooling, and power generation system for SEH. The design must make use of the components discussed in the patent; however, the design must also prioritize adapting existing systems in SEH that work well. The goal will be to utilize innovative technology to retrofit the existing HVAC system in SEH. This would help to improve the GW SEH Leed rating as one of the scoring criteria is the recycling and reuse of buildings materials and components, as well as the use of innovative technologies in SEH's systems.

This plan and approach allowed the team to proceed with the project and perform the necessary research and design work to fulfill the project objectives.

II. Conceptual Design

The conceptual research phase of the project consisted of Background research, and the preliminary component selection.

II.I Background Research

In the research phase of the design process, the team gathered and evaluated information about the different components that make up an HVAC system. The research phase involved three stages:

1. Science and Engineering Hall (SEH) requirements and constraints assessment: Research into the SEH current system capabilities and constraints and identify any requirements that may impact the HVAC design.

2. Types and functionality assessment: Division of the system components between members, such that each member investigates the different types of an assigned component as well as the functionality and capabilities of each option.

3. Refrigerants Research: Exploration and comparison of refrigerant options, investigating the refrigerants' environmental impact, toxicity, legality, chemical and physical properties, and compatibility with system components.

Ms. Mansi Talwar is executive director of SEH utilities, energy, and engineering. On Nov 21st, 2022, Ms. Talwar provided a detailed presentation summarizing SEH thermal system capabilities and constraints. The following information was concluded from Ms. Talwar's presentation:

A. Overview: SEH was constructed in July 2015 and is a part of Ross Hall campus energy use. SEH total building size is 496,230 ft^2 (about half the area of Chicago's Millennium Park). Its energy consumption is estimated to be 105,170 kBTU/SF and its annual utility cost is estimated to be $2M-$2.5M/year.

B. SEH is considered a sustainable building, with a LEED Gold Certificate (64/100 points). SEH scored 8/10 points in water efficiency, 13/35 points in energy and atmosphere, and 9/15 points in indoor environment quality. Additionally, SEH's carbon emissions, produced from electricity consumed, are mitigated by GW CPSP Project, which is a Solar Farm investment in North Carolina.

C. SEH air conditioning system (cooling and heating) system is powered and provided by Ross Hall's Central Utility Plant. The table below displays a comparison of energy consumption of GWU main campus buildings.

Property/Mini Campus Name	CY19 Source EUI
Ross Hall Campus	598.2
Corcoran School of the Arts and Design	285.5
Academic Center	269.0
Smith Center	259.2
Health and Wellness Center	236.9
Lisner Hall Campus	236.4
Media and Public Affairs	221.1
University Student Center Campus	219.8
South Hall	203.6
Gelman Library Campus	201.1
Milken Institute School of Public Health	186.5
Funger-Duquès-Tompkins	179.7
Elliott School	177.9
Potomac House	174.8
Shenkman Hall	169.3

Fig. II.I.A: Comparison of GWU buildings energy consumption.

The first component looked at was the boiler. The Rankine Power Cycle is a frequently used method for producing heat inside of a boiler by turning water into steam, which then flows through a turbine to provide usable work. With a steam system generator, a boiler is used to add energy to a feedwater supply in order to produce steam (ABMA, n.d.). The water is heated inside a sealed vessel within the boiler which is heated by using gas, fuel, or coal. The main types of boilers that were researched were electric boilers, fire-tube boilers, and water-tube boilers. After further research done on the different types of boilers, the team decided to select a water-tube boiler due to its better overall energy efficiency when compared to the other types of boilers.

With the Power Generation and Steam Diagrams provided by Ms. Talwar, the team used the operating conditions in order to select a model for the system's design. The model chosen was the Universal Steam Boiler UL-SX manufactured by Bosh, shown in Fig. II.I.B (Steam Boiler UL-S - World's Best Selling Bosch Boiler, 2022). The selection was made based on the mass flow rate of 40,000 lbs/hr of the current boiler being used for SEH. With this mass flow rate, the team found a more efficient boiler that integrated the hydrogen fuel cell generator. The fuel source of the UL-SX steam boiler is hydrogen which satisfied the project requirements to design a hydrogen fuel system.

Fig. II.I.B: Selected Hydrogen Ready Steam Boiler

In systems involving heat transfer, a condenser is a heat exchanger used to condense a gaseous substance into a liquid state through cooling. That is, the latent heat is released by the substance, I.e., working fluid, and is transferred to the surrounding environment (Wikipedia Contributors, 2022). The working fluid comes in indirect contact with the surrounding environment, commonly air or water, through utilizing metal coils. The condenser coil can be made of copper tubing with aluminum fins or all-aluminum tubing so heat can be rapidly transferred. A condenser unit is typically used in a refrigeration cycle for air-conditioning systems. The working fluid goes through multiple tube passes during which heat exchange processes occur as covered in detail during MAE 4149 course lecture.

There are three types of condensers including air, water, and air-and-water cooling units. The air-cooled unit is usually a forced convection type and is commonly used in window air conditioners, water coolers, and packaged air conditioning plants. However, one may utilize an unforced convection condenser, where the air naturally flows through the heat exchange fins. Yet, forced convection increases heat exchange while requiring energy input to drive the air through the system. Water cooled condensers, which have been mentioned in the course, include configurations such as a double tube, shell and coil, and shell and tube condensers (Linquip, 2022). These systems circulate fluid as the cooling medium and absorb the heat.

Fig. II.I.C: Horizontal shell and tube condenser.

The shell and tube condenser, specifically the horizontal shell type (Fig. II.I.C), is the most common type in the industry. Vertical shell and tube condensers are usually used in large capacity systems, paired with ammonia as working fluid, so that cleaning of the tubes is possible while the plant is running. Indeed, cleaning is an important aspect for operation of shell and tube systems to guarantee efficient heat transfer. Lastly, air- and water-cooled condensers combine the technologies of the air-cooled and water-cooled condensers (Fig. II.I.D). Such a system is usually used in locations with limited water supply. However, these condensers are efficient through using forced convection and some water to absorb some of the heat energy.

Fig. II.I.D: Evaporative, or air-and-water condenser.

The condenser unit which utilizes fins and tubes for heat flow, uses the following heat transfer model to calculate parameters such as temperature and ultimately efficiency of the condensing system (Wikipedia Contributors, 2022).

$$\Theta(x) = \frac{T_H - T(x)}{T_H - T(0)} = e^{-NTU} = e^{-\frac{hPx}{\dot{m}c}} = e^{-\frac{Gx}{\dot{m}cL}}$$

Equation II.I.A: Heat transfer equation model for condenser tubing.

Where x is the distance from the coolant inlet, T(x) is the coolant temperature, and T (0) the coolant temperature at its inlet , T_H is the hot fluid's temperature, NTU is the number of transfer units, m is the coolant's mass (or other) flow rate, c is he coolant's heat capacity at constant pressure per unit mass (or other), h is the heat transfer coefficient of the coolant tube, P is the perimeter of the coolant tube, G is the heat conductance of the coolant tube, L is the length of the coolant tube.

Chiller units are widely used in commercial HVAC applications. The “all-in-one" units are more compact and efficient than traditional HVAC systems, which allocate individual units to individual thermal zones. Specifically, a chiller unit includes typical subcomponents of the cooling cycle: a compressor, condenser, expansion valve, and evaporator. A refrigerant is used to undergo the cycle and deliver cooling to the building’s water. Refrigerants include commonly used R-134a and more recently introduced alternatives such as R-513a, R-1234ze, and R-1233zd(E). There are various chiller subcomponent types and capacities that are optimal for different HVAC systems. Manufacturers of chiller units, such as Johnson Controls (Johnson Controls, 2021), offer several configuration options.

Compressors receive the cool refrigerant from the evaporator and increase its temperature and pressure above the ambient temperature to achieve a greater temperature differential in the condenser for heat exchange. For large commercial cooling applications, especially in chillers, centrifugal compressors are preferred This is due to the high discharge rate of centrifugal compressors, which is their ability to move substantial amounts of gas through an HVAC system at low-pressure ratio. The centrifugal compressors can be connected to the turbine and disconnected with a clutch mechanism (Lindberg Process Equipment, 2020).

Condensing units cool and condense the refrigerant after it undergoes compression. Most commonly, condensing effect is achieved through using shell and tube heat exchangers paired with water as the cooling mechanism. Additionally, this process requires an installation of cooling towers to cool the water medium after it undergoes heat exchange with the refrigerant.

An expansion valve is a standard component that lowers the pressure and temperature of the refrigerant before going through the evaporator.

Once the refrigerant enters the evaporator, it undergoes another heat exchange. At this point, the refrigerant will provide cooling to the building’s water, which will be cycled through the air-conditioning system. Similarly, to the condenser unit, several types of evaporator configurations may be utilized. As with the condenser, a shell and tube heat exchanger are commonly used. The shell and heat exchanger are often used because of being highly efficient. However, these units require regular maintenance and cleaning to maximize heat exchange parameters and preserve efficiency.

The hydrogen power generator selected for the design is the Empower™ from Renewable Innovations. This device has zero carbon footprint, easy installation, and can be used for primary power and uninterrupted power supply (UPS). Blackouts are prevented as this device is always online, there is a scalable option of desired power output, and custom models are available upon inquiry to fit desired specifications. This component combines the power generator and fuel cell requirement of the system, increasing convenience and budget spending.

For the base industrial model, there are hydrogen fuel cells that supply at least 80 kW per cell adding up to a total output of 1.76 MW. It also includes inverters to deliver the power, heat exchangers that can synthesize with existing building exchanges, a 720-kWh lithium-ion battery array with high efficiencies and continuous power, and the ability to increase energy capacity by adding additional power modules. This component is a good investment because of its reliability, longevity, carbon free power, and its compatibility to existing HVAC computer cooling systems.

II.II Research and Selection of Refrigerant

Refrigerant selection is a crucial decision that requires careful consideration of various factors, including system requirements, refrigerant properties, environmental impact, US legality, availability, cost, and compatibility with other components. In this design, the team researched and analyzed a list of feasible refrigerants which include R32, R134a, R290, R410a, R717, R400, R500, R600a, R1233zd, and R1234ze. These refrigerants were compared based on their Ozone Depletion Factor (ODP), Global Warming Potential (GWP), Safety and Toxicity ratings, Temperature, and Pressure ranges. However, the legality, ODP, and GWP of the refrigerants were prioritized in the investigation. The team narrowed the list of refrigerants down to a list of three refrigerants: R410A, R1233zd, and R717. After further investigation of the refrigerants' compatibility with the available system components, the team found a fourth refrigerant option, R1234ze, which simplifies the design selection process due to its compatibility with a centrifugal chiller system.

R1234ze, also known as HFO-1234ze or R-1234ze, is a type of Hydrofluro-Olefin (HFO) refrigerant that has gained attention in recent years as a potential alternative to traditional hydrofluorocarbon (HFC) refrigerants. R1234ze has a low-global warming potential (GWP) of 7 and ODP of zero, making it a highly environmentally-friendly option compared to other options, which have GWPs in the hundreds or thousands. However, R1234ze has a higher flammability risk compared to HFCs, which will require special handling and storage precautions (Saengsikhiao & Prapaipornlert, 2022).

After confirmation of its availability and legality in the US and compatibility with other system components and requirements, R1234ze was chosen as the system refrigerant.

III. Detailed Design

During the detailed design phase of the project, the turbine, the chiller, and overall system layout were selected. Next, the components were analyzed, and the performance of the system was calculated.

Fig.III.A - Fig. III.C show the overall system layout. The designed system can provide heating, cooling and power to SEH. Some key features to note are the Catalytic Methane Pyrolizer developed by Exxon Mobil. US Patent – US20210331918 outlines the design by Exxon Mobil and the mechanisms it uses to extract hydrogen from the natural gas supply from PEPCO (Exxon Mobil, 2021). The hydrogen gas produced by the pyrolizer will be either sent into the hydrogen tank for storage or through the hydrogen fuel cell to produce the electricity needed to power, the burner, and the chiller. The water produced pyrolysis process is then purified and used as the feedwater for the turbine by the turbine is connected to an alternator to produce the 3.5 MW of electricity needed to power SEH. Fig III.A shows the system layout for air conditioning, Figure III.B shows the system layout for the heating cycle where using control mechanisms the plant will switch over to provide heating to SEH, by bypassing the chiller. Fig III.C shows the methane pyrolizer, the hydrogen fuel cell, and the water supply. In

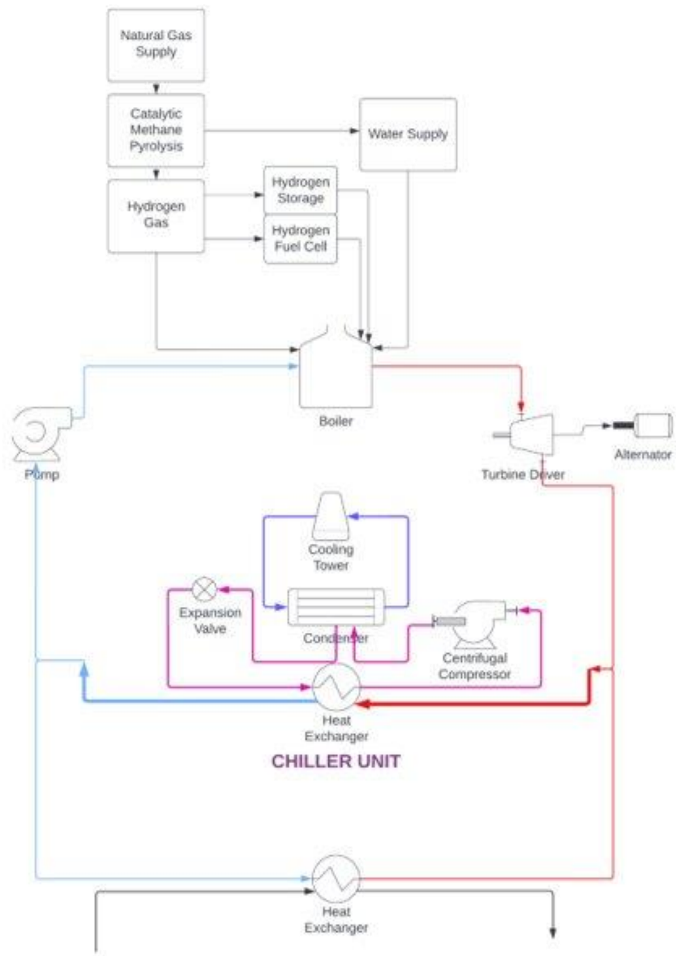

Fig. III.A: Design diagram for power generation and air-conditioning.

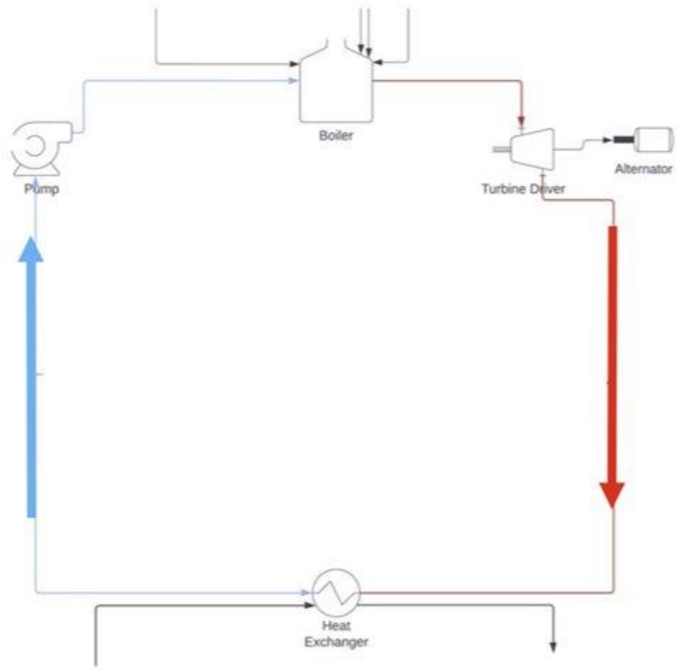

Fig. III.B: Design diagram for power generation and heating.

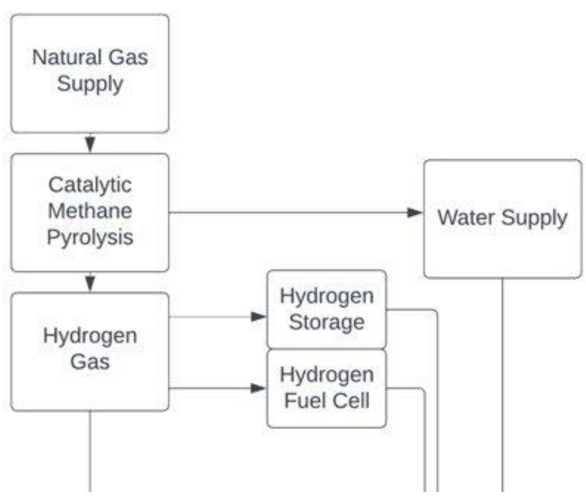

Fig. III.C: Design diagram for methane pyrolysis and hydrogen utilization.

III.I Selection of Components

During the design, it was crucial to choose a turbine that was compatible with the selected boiler capacity, such that it could withstand the thermal loads generated by the boiler. Also, the turbine must be compatible with the selected generator, such that its maximum energy consumption was within the generator's energy capability. Based on the selected Bosch boiler's thermal outlet of 300°F and the generator's maximum energy capacity of 3.5MW, the Dresser Rand Steam Turbine (D-R GAF) from Siemens Energy was selected.

The selected turbine capabilities were evaluated according to Siemens Energy's Dresser-Rand Steam Turbines technical document (Siemens Energy, 2021). The D-R GAF Turbine has a maximum output of 3,500 kW which is consistent with the selected generator. Moreover, the turbine maximum inlet temperature capacity is 825°F which is highly compatible with the boiler's maximum thermal load. Thus, the D-R GAF Turbine is concluded to be compatible with the selected system.

For the chiller unit, a centrifugal liquid chiller model by Johnson Controls was selected (Johnson Controls, 2021). A single unit can provide up to 3,000 tons of refrigerant. Therefore, at least two of these units would be required to supply SEH with chilled water. A third unit may be added as a backup unit. The model featuring centrifugal compressor is an efficient option for a system such as SEH which remains operational on 24/7 basis. The chiller is compatible with R-1234ze refrigerant and uses between 879-10,500 kW of electric energy for operation. The electricity will be fed either from the generator or from the hydrogen fuel cell processes.

III.II Tradeoffs

The main tradeoff carried out throughout the project was to prioritize better performance and efficiency over the price of components. The rationale behind this tradeoff was to implement a system that would be more cost-effective in the long term despite the larger upfront costs. This tradeoff was carried out multiple times, especially during the selection of R-1234ze, the chiller, the boiler, and the use of hydrogen methane pyrolysis to produce hydrogen fuel for the boiler. The refrigerant selected was more expensive than other options such as water, however, the compatibility with the components selected components and the higher cooling capacity led the team to prioritize R1234ze. The boiler selected was also expensive when compared to boilers of similar capacity, however, hydrogen boilers are an innovative technology leading to the high price tag. Hydrogen-fueled boilers use a fuel in hydrogen that does not produce greenhouse gases when burned, which is why it was prioritized. Overall, the technology used in this design while having an upfront cost is more innovative and more cost-effective in the long term than utilizing conventional components.

IV. Analysis

IV.I Analysis of Chiller

For the chiller unit, the team performed analysis by assessing the efficiency of the unit. This was done by calculating the operational energy requirement. The chiller specifications show an energy expenditure range from 879-10,500 kW, depending on the amount of refrigerant circulated.

For the estimates, the team is using the current SEH configuration as the benchmark. Currently, the building utilizes 5,000 tons of refrigerant distributed between two chiller units. The team will assume that the proposed chiller unit will require similar amounts of refrigerant fluid. Assuming energy input and refrigerant mass follow a linear relation, The team has linearly interpolated the provided parameters and obtained 8750.73 kW equivalent to 2,500 tons of refrigerant. This will mean having to utilize multiple hydrogen fuel cell generators to power the chillers, since each fuel cell selected produces 1500 kW. This power requirement from the chillers is quite high, and further analysis will be required to validate the figures.

In this analysis the team did not consider the efficiency of the cooling towers once paired with the chillers. The cooling towers are used to cool down the water that is used to condense the refrigerant undergoing the refrigeration cycle inside the chiller. It is assumed that the cooling towers will perform at the same efficiency level as in the current system.

IV.II Analysis of Heat Exchangers

For the heat exchanger used within the heating and cooling power system, the team selected a hybrid falling film evaporator from Wenzhou ACE Machinery Co., Ltd. This product was chosen with respect to the system's objective function, overall system efficiency, due to the best-in-class thermal efficiency of the hybrid falling film evaporator design. An Evaporator can essentially be seen to function as a large heat exchanger, where the efficiency of an evaporator becomes a function of its tube surface area, how refrigerant interfaces with the outer tube surface, and how the return chilled water interfaces with the inner tube surface. Due to the design of the falling film evaporator, where liquid refrigerant only covers the surface of the upper tubes (as opposed to the tube being completely submerged as in traditional (flooded film) evaporators), the heat transfer in falling film evaporators is very efficient. This increased efficiency comes from the proficiency of the evaporation for the thin refrigerant film covering the tubes, compared refrigerant completely submerging the tubes. This results in a higher heat transfer coefficient for falling film evaporators, which in turn boosts chiller efficiency (Hundy et al., 2016).

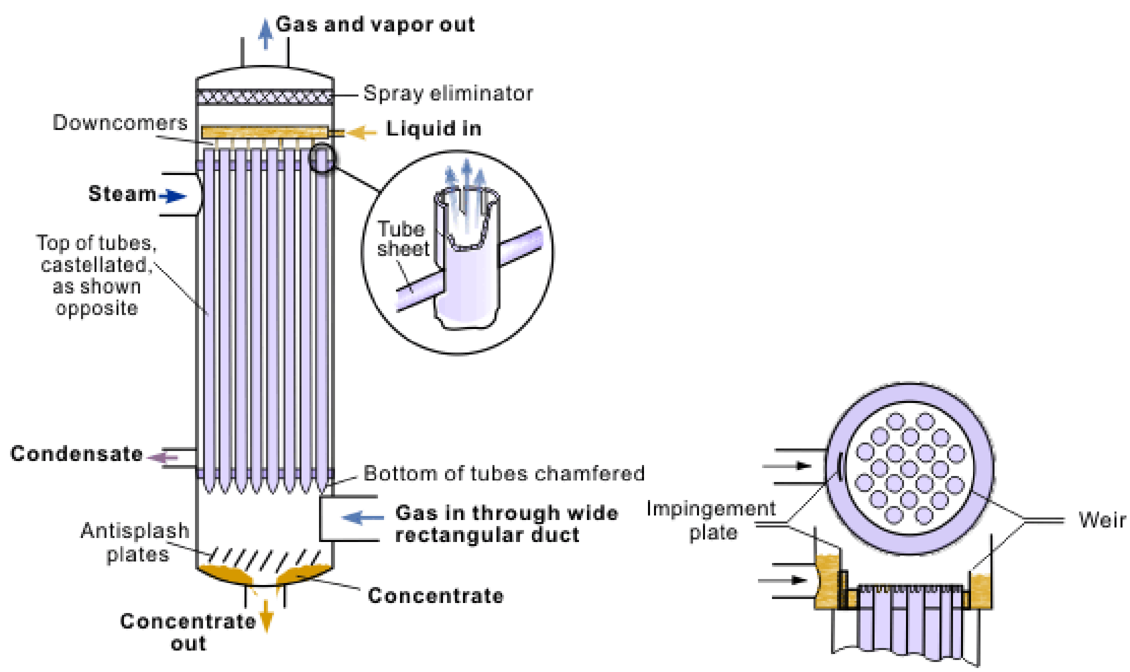

Fig. IV.II.A: Falling Film Evaporator Overview

The specific design selected from Wenzhou ACE Machinery has an evaporation capacity of between 100kg/h and 10,000kg/h, requiring between 0.55kW and 30kW depending on the evaporation rate. The system can be powered by either steam or electric sources, with an operating voltage of between 220V to 480V. Additionally, the design has the capacity to run in single-effect, double-effect, or triple-effect (multi-effect) working effect mode, with an operating compatibility with most available working fluids (refrigerants), including the selected refrigerant for our design (R1234ze). The design is comprised of high-quality 304/316L/TI/2205 stainless steel, negating degradation over long-term system usage. Individually, each unit costs $50,000 USD, though orders of two or more are available at $45,000 USD per unit.

Fig. IV.II.B: Wenzhou ACE Machinery Hybrid Falling Film Evaporator

When considering the specific operating variables for the selected system, the objective is clearly defined as to obtain the required rate of heat transfer from the incoming steam to the working fluid (R1234ze). Given that the mass flow rate of the heated fluid is given as 40,000 lbs. per hour, with the design operating conditions set between 65-75 degrees Fahrenheit, and the specific heat capacity of water and R1234ze known as 4185.5 J/(kg·K) and 1386.3 J/(kg·K) respectively, the mass flow rate of the working fluid must be determined in accordance with the fundamental conservation of energy principles.

$$\dot{Q}_{cv,net-in} - \dot{W}_{cv,net-out} = \sum_{k=1}^{M_{outlets}} \dot{m}_{out,k} \left\{ h_k + \frac{1}{2}\alpha_k v_{avg,k}^2 + g(z_k - z_{ref} \right\} - \sum_{j=1}^{M_{outlets}} \dot{m}_{in,j} \left\{ h_j + \frac{1}{2}\alpha_j v_{avg,j}^2 + g(z_j - z_{ref} \right\}$$

Eq. IV.II.A: Conservation of Energy Equation

Assuming steady flow, no shaft power associated with the heat exchanger ($\dot{W}_{cv} = 0$), zero interaction between the heat exchanger and its surroundings ($\dot{Q}_{cv} = 0$), and negligible kinetic and potential energy changes between inlets and outlets for both the hot and cold streams, Eq. IV.II.A can be described as follows:

$$\dot{m}_H\left(h_{H,in} - h_{H,out}\right) = \dot{m}_C\left(h_{C,out} - h_{C,in}\right)$$

Eq. IV.II.B: Revised Conservation of Energy Equation

Additionally, assuming no change of phase takes place in the heat exchanger, Eq. IV.II.B can be further revised to the following:

$$\dot{m}_H \cdot c_{p,H}\left(T_{H,in} - T_{H,out}\right) = \dot{m}_C \cdot c_{p,c}\left(T_{C,out} - T_{C,in}\right)$$

Eq. IV.II.C: Revised Conservation of Energy Equation (no change of phase)

With respect to the hybrid falling film evaporator used as the heat exchanger in our design, we can use Eq. IV.II.C to calculate the mass flow rate of the working fluid (R1234ze) as such:

$$\dot{m}_C = \frac{\dot{m}_H \cdot c_{p,H}\left(T_{H,in} - T_{H,out}\right)}{c_{p,c}\left(T_{C,out} - T_{C,in}\right)}$$

$$\dot{m}_H = 40{,}000\ \tfrac{lbs}{hr} = 18{,}143.7\ \tfrac{kg}{hr},$$

$$c_{p,H} = 4185.5 J/(kg \cdot K),$$

$$c_{p,c} = 1386.3 J/(kg \cdot K),$$

$$T_{H,in} = 350\ K°$$

$$T_{c,in} = 278\ K°$$

$$T_{H,out} = 338\ K°,\ T_{c,out} = 344\ K°$$

$$\dot{m}_C = \frac{18{,}143.7\ \frac{kg}{hr} \cdot 4185.5 \frac{J}{kg \cdot K°} \cdot (350K° - 338K°)}{1386.3 \frac{JK}{kg \cdot K°}(344K° - 278K°)} = 9{,}959.86 \frac{kg}{hr}$$

This is less than the maximum evaporation capacity of the selected heat exchanger, meaning that the selected operating ranges for the hybrid falling film evaporator design meet the design requirements for the rate of heat transfer from the working fluid. Given that the rate of evaporation is within 1% of the limit of the selected heat exchanger when the cycle is operating at full capacity, it's clear that a second evaporator will need to be added in the case of any additional increased energy demands from the system.

IV.I Overall System Efficiency

The overall efficiency of the system can be evaluated by solving for the thermal efficiency and coefficient of performance for the system's heating and cooling cycles. For the power generation and heating cycle, the thermal efficiency is given by:

$$\eta_{th} = \frac{Net\ work\ Out}{Heat\ In} = \frac{w_{3-4} + w_{1-2}}{q_{2-3}} = \frac{(h_3 - h_4) + (h_1 - h_2)}{(h_3 - h_2)}$$

Eq. IV.II.D: Thermal Efficiency of Rankine Power Cycle

V. Viability of Technology

The viability of hydrogen fuel cell technology is expected to grow exponentially in the next few decades. The International Energy Agency produced a technology report in 2019 assessing the current status of hydrogen energy with findings that strongly support its use. There was a call to action to improve the transition by appointing industrial points as the center of scaling up hydrogen use, repurposing natural gas pipelines for hydrogen, increasing hydrogen as a transportation fuel source, and creating international supply chains and shipping routes for hydrogen (IEA Report, 2019).

The issue of global warming is largely due to greenhouse gas emissions and the impact of the damage is starting to show more as natural disasters are on the rise. Sea level has risen 8-9 inches since 1880, and the rate of increase has doubled from +0.06” change per year to +0.14” per year. The frequency of flooding due to high tides is 900% more frequent today than it was in the 1970s (Lindsey, 2022). The importance of reducing greenhouse gases is the top priority, as most of the world will become inhabitable due to solar flares and flooding.

The economic drawbacks of using hydrogen are high, but only since the industry is currently in the transition phase. With reports from global energy officials and 5-year plans from corporations, the viability of hydrogen technology is not to be underestimated.

V.I Benefits of using Hydrogen Fuel and Methane Pyrolysis

Hydrogen fuel cell technology has the potential to become a zero-emission fuel, but it can only be done if the method of producing hydrogen is clean and energy efficient. Natural gas is currently the main source of hydrogen, but most methods produce carbon dioxide. Methane Pyrolysis is a current temporary solution to the issue of omitting greenhouse gas emissions, producing solid carbon instead of gaseous carbon dioxide. This method not only helps reduce the rapid decline of our environment, but it also can prove to be a valuable change for industries.

V.II Economic Drawbacks of Methane Pyrolysis

Unfortunately, the current infrastructure causes methane pyrolysis to have increased costs in comparison to its alternatives. According to the Department of energy, the cost of producing one kg of H_2 is \$0.72 while coal gasification and steam methane reforming are \$0.24 and \$0.43, respectively (Von Keitz, 2021). This is due to the slow reaction kinetics of the chemical process, Carbon-bond activation is difficult due to methane’s highly symmetrical molecule and CH_3-H bond energy of 440 KJ/mol (International Journal of Hydrogen Energy, 2009). Three tons of carbon are produced per ton of H_2 raising the question of what will be done with the excess carbon. The catalysts of the process, i.e., Nickel and Iron, deactivate relatively quickly.

Methane Pyrolysis is often regarded as a temporary solution as the transition to other methods of hydrogen production is refined, and the drawbacks support this widely accepted claim (Sánchez-Bastardo et al., 2021).

Table V.II.A: Assumed Commodity Prices

Coal	50 $/ton	2.04 $/GJ
Natural Gas	3.00 $/MMBtu	2.84 $/GJ
Electricity	0.07 $/kWh	19.44 $/GJ
Grid Electricity (US, 2019)	**Assumed Carbon Intensity** 0.92 lb CO2 /kWh (116 kg/GJ)	

Table V.II.B: Theoretical Minimum Costs

Name of method	Chemical Reaction		Energy Fuel	$/kg H_2
Methane Pyrolysis	½CH_4(g)	H2(g) + ½C(s)	H_2	0.72
Coal Gasification	½C(s) + H_2O(l)	H2(g) + ½CO2(g)	C	0.24
Steam Methane Reforming	½CH_4(g) + ½H_2O(l)	H2(g) + ½CO2(g)	CH_4	0.43
Water Electrolysis	H_2O(l)	H2(g) + ½O2(g)	Electricity	2.76

VI. Economic Impact

VI.I Overall Cost of Components and Bill of Materials

The economic impact was analyzed as follows; first being the selection of components, then finding an alternative method of gathering costs per component since the information was not available by most manufacturers. Due to the lack of access to pricing information from the manufacturers, the prices found were gathered from research done on the average cost of the specific component correlating with the operating conditions. Once the cost of purchase for each component was determined, the total cost was found to be $2,970,671, not including the steam generator due to lack of resources. The bill of materials for the system is shown in Figure XX.

Although not a lot of information was provided on the cost of the current system that runs SEH, it was determined that it would be more efficient and beneficial to invest in the newer technology necessary to build a standalone plant in SEH. This is primarily because the current system in Ross Hall places GW at the risk of incurring a 7.5 million dollar fine due to their high usage intensity. Therefore, separating the Ross Hall central utility plant from SEH would reduce the overall and average energy usage intensity on the Foggy Bottom Campus.

Table VI.I: Bill of Materials

Component	Type	Manufacturer	Price	Total Cost
Boiler	UL-SX	Bosh	$345k	

Turbine	D-R GAF	Siemens	$38k	
Pump	Centrifugal Pump	Not Found	$2,671	
Chiller	Centrifugal Chiller	Johnson Control York	$875k	
Heat Exchanger	Hybrid Falling Film	Wenzhou ACE Machinery Co., Ltd	$50k	
Hydrogen Fuel Cell	Generator	Renewable Innovations Inc.	$1.6M	
Generator	Turbogenerator	Not Found	Not Found	
Refrigerant	R-1234ze	N/A	$60k	
Whole System				**$2,970,671***

VI.II Cost to operate system comparative to SEH

With the limited time and resources, the team was unable to gather an estimate breakdown of the cost to operate the designed system comparative to SEH. However, information on the utilities of SEH was provided by Ms. Talwar. The average energy readings and usage, shown in Table XX, were used to establish a scale of the utility cost. This was helpful to help the team understand how much GW was spending on the current system.

Table VI.II: Breakdown of SEH Utilities

Meter Reading Date	Average Readings (MWh)	Average Usage (MWh)	SEH Total Utilities Amount Calculated ($)
Jan 22	47,044	596	127,173
Feb 22	47,419	376	98,382
Mar 22	47,874	455	352,965
Apr 22	48,341	467	177,482
May 22	49,045	705	217,846
Jun 22	49,605	561	242,692
July 22	50,113	507	N/A

VI. Conclusions

Regarding risks in implementing the thermal system design, the novelty of proposed technologies, and compatibility with existing system components are areas of concern. The hydrogen methane pyrolysis technologies have limited research and examples of real-world implementation, therefore the method should be carefully examined and crafted in the planning and implementation stages. Secondly, the proposed refrigerant is new and slightly flammable. While the chiller unit is certified compatible with the selected refrigerant by the manufacturer, the fluid should be carefully monitored at the initial stages and ensure stability. In addition, the boiler is also a novel technology, and extra attention and caution should be paid. Lastly, the proposed design does not require the installation of new cooling towers and assumes 100% compatibility with the chiller units. This assumption may not hold true and should be reviewed further before proceeding with the design implementation.

VII. Lessons Learned

Throughout the design process, the team learned that it was often more effective to look at the pre-existing HVAC solutions on the market rather than trying to design a solution from scratch, some solutions have been tried and tested and so trying to replicate what has been done before can often prove to be helpful. This was especially true when it came to designing the piping for SEH. It was discovered that the water piping system already used in SEH would be compatible with the chilled water system designed. Due to this fact, the team elected to stick with the water piping in place currently. Another lesson learned by the team was in relation to the pricing of components. A lot of the catalogs made by the various manufacturers did not have the pricing readily available. This meant the team had to try to get quotes where available and use the average prices for components of similar capacity. Unfortunately, due to time constraints, the team was unable to gain more accurate pricing on all the components. The project provided many opportunities to engage in thermal systems' design and analysis. The demonstrations, presentations, and field trips served to enlighten the team members throughout the process. Overall, the project was highly informative for the whole team and was rich in learning opportunities, challenges, and experience.

Works Cited

ABMA. (n.d.). Boiler 101 | What is a boiler? Www.abma.com. https://www.abma.com/boiler-101

Hundy, G. F., Trott, A. R., & Welch, T. C. (2016). *Evaporators - an overview | ScienceDirect Topics*. Www.sciencedirect.com; ELSEVIER. https://www.sciencedirect.com/topics/engineering/evaporators

IEA. (2019, June 14). *International action can scale up hydrogen to make it a key part of a clean and secure energy future, according to new IEA report - News*. IEA. https://www.iea.org/news/international-action-can-scale-up-hydrogen-to-make-it-a-key-part-of-a-clean-and-secure-energy-future-according-to-new-iea-report

International Journal of Hydrogen Energy. (2009). *International Journal of Hydrogen Energy | Vol 34, Issue 9, Pages 3557-4242 (May 2009) | ScienceDirect.com by Elsevier*. Www.sciencedirect.com. https://www.sciencedirect.com/journal/international-journal-of-hydrogen-energy/vol/34/issue/9

Johnson Controls. (2021). *yk-centrifugal-chiller*. York.com. https://www.york.com/commercial-equipment/chilled-water-systems/water-cooled-chillers/yk_ch/yk-centrifugal-chiller

Johnson Controls. (2022). *Water-cooled Chillers*. Johnson Controls. https://www.johnsoncontrols.com/hvac-equipment/water-cooled-chillers

Lindberg Process Equipment. (2020, January 7). *Picking a Compressor (Centrifugal vs. Reciprocating) - Lindberg Process Equipment*. Lindberg Process Equipment. https://lindbergprocess.com/2020/01/centrifugal-vs-reciprocating/#:~:text=Centrifugal%20compressors%20are%20much%20better,are%20around%20five%20and%20eight.

Lindsey, R. (2022, April 19). *Climate change: Global sea level*. NOAA Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

Max. (2020, July 13). *3 Main Types of Condensers, How Does it Work ? | Linquip*. Industrial Manufacturing Blog | Linquip. https://www.linquip.com/blog/different-types-of-condensers/

Piyanut Saengsikhiao, & Chayapat Prapaipornlert. (2022). Low GWP Refrigerant R1234yf, R1234ze(z), R13I1 as an Alternative to New Zeotropic Refrigerant. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 98(2), 80–89. https://doi.org/10.37934/arfmts.98.2.8089

Renewable Innovations. (2022). Hydrogen Power Modules 1.5MW. Renewable Innovations. https://www.renewable-innovations.com/hydrogen-power-modules-15mw

Sánchez-Bastardo, N., Schlögl, R., & Ruland, H. (2021). Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy. *Industrial & Engineering Chemistry Research*, *60*(32), 11855–11881. https://doi.org/10.1021/acs.iecr.1c01679

Steam boiler UL-S - world's best selling Bosch boiler. (2022). Bosch. https://www.bosch-thermotechnology.com/global/en/ocs/commercial-industrial/universal-steam-boiler-ul-s-ul-sx-669474-p/#null

Siemens Energy. (2021). Efficiency: More value to your facility Dresser-Rand Steam Turbines. https://assets.siemens-energy.com/siemens/assets/api/uuid:333797d8-0fcc-4c63-9599-efc355bf2391/se-brochure-dresser-rand-steam-turbines-2021.pdf?ste_sid=4f1274c0571d6c6544f226eb4f3d0864

Von Keitz, M. (2021, August 31). *Methane Pyrolysis for Hydrogen– Opportunities and Challenges: Hydrogen Shot Summit Thermal Conversion with Carbon Capture & Storage* [Slideshow]. https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-panel2-methane-pyrolysis.pdf

Wikipedia Contributors. (2022, July 8). *Condenser (heat transfer)*. Wikipedia; Wikimedia Foundation. https://en.wikipedia.org/wiki/Condenser_(heat_transfer