Molten Salt Reactor (MSR) for Worcester Polytechnic Institute (WPI) Steam Generation

A Major Qualifying Project Report

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ABSTRACT

An increased world energy demand coupled with decreasing sources of coal, natural gas, and oil have sparked innovation in the energy industry the past decade, including revisits to old technologies. Molten Salt Reactors (MSR) were studied in the 1960s and 70s as an experiment at the Oak Ridge National Laboratory (ORNL) in Tennessee, but research stopped on this nuclear technology for financial and technological reasons. This project revisited the Oak Ridge Design to design a steam generation system for Worcester Polytechnic Institute. For this project, a system including a primary heat exchanger and steam generator were designed using ORNL's reactor design, accommodating for WPI's steam needs, and taking into consideration the special physical, chemical and thermal properties of the special materials used in an MSR. This project will serve as a starting point for a cleaner, more efficient source of steam production at WPI, and will be a step-by-step guide for the design process.

ACKNOWLEDGEMENTS

EXECUTIVE SUMMARY

Background

The 21st century has presented scientists and researchers with several new problems. One of the most pressing issues facing today's innovators is the energy problem: the issue of increasing energy demand, intensified by a decreasing resource supply and increasing environmental concerns. The challenge of the 21st century is to find clean, cheap, and long-lasting energy. Current technologies include hydrogen fuel cells and biofuels, but a promising option seems to be nuclear power.

The first proof of energy production from nuclear fission was shown by Enrico Fermi in 1942 (Wood, 2007). From this discovery, the world gained and interest in using nuclear power as an advantage in World War II. Nuclear power gained popularity in the military not only for weapon use, but also for powering submarines and aircrafts.

From the research of nuclear power in the military came the development of pressurized water reactors (PWRs). The technology powered submarines for extended periods without refueling. After seeing the success with PWRs in the submarines, Shippingport Atomic Power Station opened a nuclear power plant in 1957 for the creation of commercial power (Kok, 2009). As research continued, boiling water reactors (BWRs) were developed. In the 1950s, nuclear research began to turn from a military focus to civilian energy focus, and research began on a new type of reactor using molten salt (Wood, 2007). The Molten Salt Reactor Experiment (MSRE) began at Oak Ridge National Laboratory in Tennessee in 1961.

This new technology had all the environmental benefits of nuclear power, but in addition, presented improvements in fuel efficiency, stability, and safety (Robertson, 1965). MSRs differ from PWRs and BWRs in that the fuel leaves the reactor and flows throughout the reactor system, transferring heat directly. In PWRs and BWRs, water flows through the reactor and transfers heat from the reactor to another loop. MSRs can reduce costs because of they don't require a complex fuel rod design in the reactor core, and they don't require extensive shutdown procedures like PWRs and BWRs (Shultis & Faw, 2002).

The MSR also presents incredible safety benefits. Even though nuclear material travels outside of the reactor, nuclear material can be separated from the heat generation loop by the insertion of an intermediate loop of coolant salt. On top of this, the system does not operate at nearly the same pressures as PWRs and BWRs. The MSRE was stopped in 1969 due to economic reasons, but the results of the experiment proved the MSRs were a promising technology. Though current MSR technology does not exist, it is one of the main considerations in Generation IV reactor technology because of its added benefits and because ORNL has already proved that it can work (Generation IV International Forum, 2013).

Because of MSRs promise, this project used applied ORNL's reactor design to create a steam generation system to provide steam to the Worcester Polytechnic Institute campus. To prove and MSR was better than both the current WPI steam generation system and other nuclear technologies, this project focused on the thermal properties and heat transfer related to the steam generation systems.

Goals, objectives, and methods

The goal of this project was to design a steam generation system for the steam needs of Worcester Polytechnic Institute using the Oak Ridge National Laboratory Molten Salt Reactor Experimental reactor design as a heat source. The methodology and results of this project will be a starting point for designing an MSR steam generation system at WPI, ultimately being more thermally efficient, more environmentally friendly, and potentially more beneficial to educational programs at WPI. In designing the steam generation system, the following steps were taken:

1. Determine campus heating needs from given steam production information
2. Evaluate steam generation loop using the design from the Oak Ridge National Laboratory Molten Salt Reactor Experiment.
3. Evaluate steam generation loop and determine steam production from the thermal output of the MSRE using Aspen Plus Simulation software.
4. Use heat transfer calculations to compare steam generation from a Molten Salt Reactor to that of a Pressurized Water Reactor (PWR).
5. Design the heat exchanger network used with a molten salt reactor for campus heating, taking into consideration special requirements for the molten salt system.

Step 1:
Using the description of current campus steam production, the energy content of the steam was used to determine the overall heating needs of campus.

Step 2:
Using the design from ORNL's MSRE, a steam generation loop was developed and evaluated. The original MSRE design only consisted of a radiator to dissipate heat. For this project, the first step was to make this system capable of producing steam by utilizing the heat from the reactor.

Step 3
After the steam generation potential was evaluated, detailed data from the MSRE was used to validate the steam output from the MSRE's specific design Aspen Plus Simulation Software.

Step 4:
Heat balance calculations were used to evaluate steam generation from a pressurized water reactor-based system and a similar molten salt reactor-based system to show the advantage of MSRs.

Step 5:
Once the thermal properties of the steam generation loop were determined, the heat exchanger network was designed, taking into consideration the thermal duties of each unit, as well as the necessary materials for the special chemical, physical, and thermal properties of the molten salt.

Results

The steps above showed that the MSRE design does not exactly meet campus heating needs. Then it was found that the PWR and MSR systems can both meet campus needs with a reactor output of 12.55 MW for the PWR and 12.16 for the MSR. The MSR fuel was determined to have a higher specific power of 44 kW/kg uranium, compared to 33 kW/kg uranium in the PWR fuel. Lastly, the

heat exchanger network required was found to be a four exchanger set-up with one economizer, one evaporator, and two superheaters. The overall design was compared to data found about industrial boilers which showed that the heat exchanger network took a total floor space of 44 square feet, while the current boiler system at WPI would take about 256 square feet, showing the heat exchanger network would be four times more space efficient.

Conclusion and Recommendations

In conclusion, the research of this project showed that a molten salt reactor steam generation system would be an advantageous campus update for WPI to consider implementing for continued leadership in environmental impact, sustainability, and technological innovation. However, as a Generation IV technology, actual reactor usage is likely still a few decades in the future. This extended timetable allows for future research into optimization of materials, design of the containment and equipment that was not considered here, and more accurate heat transfer analysis. Once these projects are completed, final studies could include a cost analysis for system installation and operation, licensing considerations, and determination of the optimum campus location for this system.

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1 INTRODUCTION

Since the industrial revolution, the world has seen an increasing need for energy. The U.S. Energy Information Administration (EIA) estimates a 56 percent increase in energy consumption between 2010 and 2040. The growth is mainly due to population and economic growth in underdeveloped countries (U.S. Energy Informatio Administration (EIA), 2014). Coupled with an increased energy demand is a decreased and unreliable supply of many of the world's energy resources like coal, natural gas, and oil. These resources have also gained a reputation for their harmful effects on the environment. The world is now on a search for renewable and low-emission energy sources.

Nuclear power may be what the world is looking for. Many countries, including the United States, already utilize nuclear power. "On a global scale, nuclear power currently reduces carbon dioxide emissions by some 2.5 billion tonnes per year", had the same amount of power been produced by coal, and nuclear power only accounts for about 12% of the world's electricity (World Nuclear Association, 2014). Utilizing nuclear power could drastically decrease the environmental impact of energy use.

The majority of light water reactors, which are the most prevalent type of reactor currently in use, generate their power through Uranium fission reactions, meaning Uranium is the principle fuel used in nuclear reactors. Uranium is typically obtained from mining, and is "approximately as common as tin or zinc" (World Nuclear Association, 2014). The World Nuclear Association reported the total known recoverable Uranium as almost 6 million tons in 2013. It is possible that with continually improved mining methods, this amount could increase. Energy production by uranium also requires much less fuel. A ton of uranium produces 7.4×10^{16} Joules. The same amount of coal only produces 3.2×10^{10} Joules (Holdren, 1991).

Despite Uranium's energy and availability promise, like any energy source, there are potential flaws. To produce energy, the Uranium fuel absorbs a neutron, and begins to fission. The heavy and unstable nucleus, given a neutron absorption event, begins to break into smaller, radioactive fission products. Fission events also produce a large energy release. The radiation from fission products, gamma rays, and alpha and beta particles, make nuclear reactions dangerous. Overexposure to these high-energy particles can cause health issues such as cancer. Nuclear waste from uranium reactors is also a concern as the spent fuel still contains radioactive nuclides. There are many ways to condition or reprocess the fuel, but current U.S. policy is to store spent fuel for ultimate disposal rather than for reprocess, leaving potential energy unused (Nuclear Regulatory Commission, 2014).

Yet again, there is a potential solution to the energy problem. Molten salt reactors, which appeared in the 1950s, present a much safer and economical approach to nuclear power. Molten salt reactors use the same material as both its fuel and coolant. This permits the use of spent LWR fuel, fresh low-enrichment uranium-based fuel, or thorium-based fuel. Molten salt reactors were studied for a short period of time in the 1950s to the 1960s, but major research in Oak Ridge National Laboratory in Tennessee was shut down and the United States focused more on implementation of the pressurized water and boiling water reactors (Wood, 2007).

This project re-opened molten salt reactor research. With help from the Oak Ridge experiment, current research, and chemical engineering plant design concepts, this project aimed to create a

modern, feasible design for a pilot reactor to produce steam to meet campus heating needs. Successful installation of such a unit may reduce energy and labor costs for the University, and will also act as a research and learning tool for future students. While this project focused on determining a feasible design for a steam generation system, future research may include cost and logistics of building and installing the reactor, as well as materials and thermal considerations not taken into account for these initial calculations. The purpose of this project was to outline a process for analyzing and designing the steam generation loop from given thermal energy needs.

2 BACKGROUND

2.1 The World Energy Problem

Global warming and energy use have become increasingly popular topics in the 21st century. The energy problem is nearly unavoidable. The worlds of research, media, and literature have all taken notice to the issue. The energy problem consists of two main issues: the supply and demand of energy resources and the environmental impact of energy production.

Holdren's study on "Population and the Energy Problem" from the University of California Berkley claimed that "[t]he problem is not that we are running out of energy. It's that we have nearly run out of the low-cost energy that has fueled the industrial development of today's rich countries." (Holdren, 1991). Increased demand and depletion of these sources has increased energy costs as new sources may be harder to find, harder to transport, and require more investment. Coupled with supply issues is an increasing population and demand, the effect of depleting resources is intensified. Between 1950 and 1990, the world population doubled. Energy use, however, quadrupled (Holdren, 1991). "If the cumulative consumption of [gas fuels] continued to double every 20 years, the initial endowment would be 80% depleted in another 40 years' (Holdren, 1991).

As mentioned, the energy problem is a two-part conundrum. Energy generation also poses a threat to the environment. Emissions from burning coal and fossil fuels have a direct impact on the environment, and are a principle cause of global warming because they affect how much energy the atmosphere absorbs (Environmental Protection Agency, 2013). The increased heat created by global warming has a direct impact on habitats, water supply, crop production, and infrastructure (Environmental Protection Agency, 2013).

2.2 Current Energy Technology and Research

The energy problem has sparked several developments in the energy industry. From recovery technologies to renewable sources and scrubbing technologies, there have been several efforts to solve the energy problem.

The National Academy of Sciences identifies several "emerging technologies". It notes that "[s]ome will require substantial improvements-or even research breakthroughs- to have a major impact on our energy market." However, research in these areas create hope for improvements to the energy industry. Nuclear power, hydrogen fuel cells and biofuels are just a few of the technologies being researched today (The National Academy of Sciences, 2014).

2.3 Nuclear Power History and Main Reactor Types

Just as atoms can interact with other atoms by forming or breaking bonds, the nuclei of said atoms can also interact with other nuclei as well as subatomic particles. In these interactions, neutrons collide with a nucleus with just the right level of kinetic energy to either be absorbed by the nucleus, or to cause the nucleus to break apart. These interactions, where the nucleus splits into separate nuclei, are called fission reactions. In these reactions, the amount of energy released is significantly higher than that produced in chemical reactions. According to Shultis and Faw, the amount of energy released in a fission reaction is approximately 50 million times the energy produced in the formation of carbon dioxide via combustion (Shultis & Faw, 2002).

The potential for energy production from nuclear fission was first shown by Enrico Fermi in 1942 when Chicago Pile 1, the first nuclear reactor, reached the point of producing enough neutrons to sustain continuous fission reactions (Wood, 2007). This construction of graphite and uranium exemplified the ability of a nuclear reaction to become self-sustaining by producing excess neutrons with each fission. It was soon after this discovery that the Manhattan Project began with the goal of constructing a weapon using nuclear energy for the United States to use in World War II.

Research into harnessing nuclear energy for military use continued when the United States government began research into powering military submarines and aircraft with nuclear reactors. This led to the start of the Aircraft Reactor Experiment (ARE), undertaken by Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee in 1954. The aim of this experiment was to design a small reactor capable of powering a military aircraft, but it was determined that a nuclear reactor with the proper amount of shielding to contain radioactivity would need to be far too heavy to make flight possible.

The research into powering naval submarines with nuclear power was far more successful. Under the leadership of Admiral Hyman Rickover, the US Navy developed the pressurized water reactor (PWR) for use on submarines. These vessels were capable of producing enough power to propel an entire submarine for extended periods of time without requiring air like a combustion engine. This concept used solid uranium oxide pellets as fuel in a highly pressurized reactor vessel. Water served as both a moderator and a coolant in these reactors and was kept at extremely high pressures to allow it to absorb the heat energy produced by the fission in the fuel rods without boiling. This high pressure water would then pass through a heat exchanger where the heat was transferred to lower pressure water causing it to boil and produce steam that powered a turbine. The first prototype of these reactors first went critical in 1953, and in 1955 the *USS Nautilus* became the first submarined to operate propelled using a PWR (Fishlock, 2006). Soon after, in 1957, the first commercial nuclear power plant started up in Pennsylvania using the same type of pressurized water reactor at the Shippingport Atomic Power Station near Pittsbirgh in Pennsylvania, as shown in Figure 1 (Kok, 2009).

Figure 1: Shippingport Atomic Power during installation;
http://en.wikipedia.org/wiki/Shippingport_Atomic_Power_Station

Using the same concepts as the PWR, the Boiling Water Reactor (BWR) was developed using similar clad solid uranium oxide fuel rods. In BWR reactors, however, the reactor vessel remains at low enough pressures to allow the water in the reactor to boil when it absorbs heat from the fuel rods. The steam generated by this boiling water turns a turbine directly out of the reactor without heat transfer to another stream. The first commercial-scale nuclear power plant to use this type of reactor, Dresden I, opened in Dresden, Illinois in 1960 (Theriault, 2009).

In 1946, with the passing of the McMahon Act, the nation's research goals for nuclear energy changed from military to civilian energy production (Wood, 2007). The Aircraft Reactor Experiment at Oak Ridge National Laboratory concluded unsuccessfully, but a new reactor technology was developed through ARE research. In this new reactor concept, a fissile material mixed into a molten salt fuel circulated throughout the reactor, as opposed to the solid fuel elements used in the pressurized water reactors investigated through submarine power research. Oak Ridge National Laboratory converted the Aircraft Reactor Experiment facility to hold a new experiment, the Molten Salt Reactor Experiment (MSRE), to test the power-production capability of this new reactor type. The 10-MW$_{th}$ reactor of the Molten Salt Reactor Experiment demonstrated that a fluid-fueled reactor was feasible for power production, pending research and development to eliminate materials-related issues encountered during its operation (Haubenreich & Engel, 1970), scale-up to reach size required to be feasible for commercialization, and continuous fuel reprocessing and removal of fission poisons.

The nation continued research into many different reactor concepts from this point forward, but only reactors that are similar to PWR and BWR designs have been constructed at the commercial scale throughout the United States. Due to both the vast experience already obtained with these reactors and the current state of nuclear regulation, research into Generation IV reactors has focused mainly on modifying and improving the PWR and BWR concepts. With the occurrence of accidents at nuclear power plants such as Chernobyl, Three Mile Island, and Fukushima, public support of nuclear power production has fallen over the years making it difficult to garner funds needed for further research and development into commercialization of the Molten Salt Reactor type.

2.4 Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs)

Currently the only commercial nuclear power plants in operation in the US are PWRs or BWRs (Power Reactors, 2013). In both of these reactor types, water is used as both the moderator and coolant within the reactor core where the fission occurs and generates heat. The moderator is a component in the core that neutrons can bounce off of in order to lose enough kinetic energy to reach the ideal energy level to cause fission to occur within the fuel. The coolant in a reactor serves to absorb the energy given off by the fission reactions to transport it out of the reactor. The fuel is uranium oxide in the form of solid pellets stacked into long rods wrapped in a layer of zirconium alloy. The water passes between these rods and absorbs the heat generated from the fission. In the case of a PWR, the reactor vessel is kept at pressures of approximately 2250 psi to prevent the water from boiling in the reactor (Shultis & Faw, 2002). The water then passes through a steam generator where it heats a coolant stream that is also composed solely of water. This coolant water boils and the steam produced powers a turbine, converting the heat energy to mechanical energy. In the case of a BWR, the water is allowed to boil within the reactor and the steam goes directly from the reactor to a similar turbine to generate electricity.

The safety system of a PWR or BWR relies mainly on the insertion of control rods or blades into the reactor core in situations where the reactor has reached limits of safe operation. These control rods are made of materials, such as boron or a silver-indium-cadmium mixture, that absorb neutrons to prevent them from colliding with fissile atoms to continue the chain reaction. In addition, containment is a main consideration in initial reactor design to prevent any escape of radiation or materials in such situations. Pressurized and boiling water reactors are housed within containment buildings with thick concrete walls to keep any leaked reactor contents or radiation emissions from escaping into the surrounding environment. If any part of the reactor or coolant circulation system failed for any reason, the containment building would hold the leak and keep surrounding personnel, buildings, and plant and animal life safe from exposure to the radioactive fuel, fission products and byproducts, and any other components that may produce harmful radiation particles.

Throughout the operation of the reactor, isotopes of different elements are produced to form the reactor waste. When a uranium atom undergoes fission, neutrons collide with the atom's nucleus and cause it to break unevenly, forming fission products with mass depending on how the protons and neutrons split between the new nuclei, as well as well as more neutrons. Fisison products are radioactive or unstable and decay to more stable elements by giving off energy or charged particles.

In some cases, the neutron doesn't have enough energy in the collision so it is just absorbed by the nucleus and a different isotope of uranium is formed. In any reactor, all of these things will be occurring with many isotopes of different elements. This leads to the production of a variety of waste byproducts that are classified as either high level, transuranic, intermediate level, or low level waste based on their radioactivity and components (Shultis & Faw, 2002).

High level waste is highly radioactive and contains the fission products that build up within the reactor fuel. Transuranics are actinide elements with atomic numbers greater than 92 that are formed in reactor fuels by neutron absorption and radioactive decay and remain highly radioactive for thousands of years (Kok, 2009). Low level wastes include contaminated materials that are not part of the reactor, and are much less radioactive than the high level and transuranic waste (Shultis & Faw, 2002). Low level waste can generally be sent away and stored for disposal, but high level waste and transuranics cause more problems. The United States does not currently have a long-term solution for the ever-growing quantities of high-level and transuranic waste produced by these reactors, though options are being considered.

2.5 Molten Salt Reactor Experiment (MSRE)
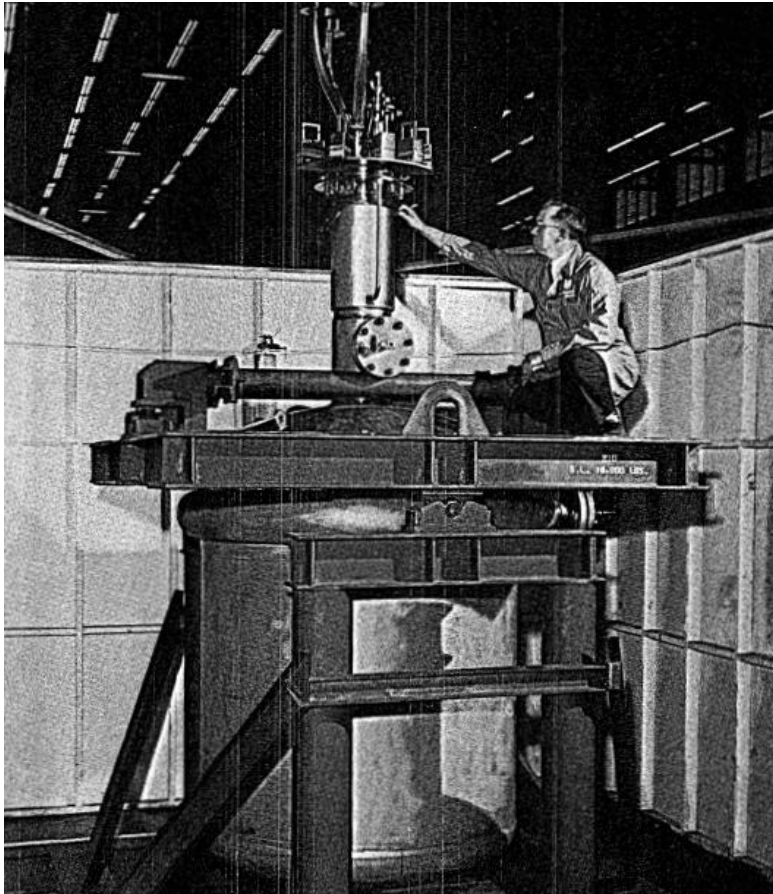
Figure 2: MSRE Reactor Vessel during Installation (Robertson, 1965)

The Molten Salt Reactor Experiment (MSRE) was approved by the Atomic Energy Commission in 1961 with the goal of studying the molten salt-fuelled reactor concept developed through research for the Aircraft Nuclear Propulsion Experiment. The MSRE was not used for power generation, but to demonstrate general feasibility of someday using the molten-salt reactor technology for commercial power production. A small-scale reactor capable of producing a maximum of 10MW was constructed on the Oak Ridge National Laboratory site in the building previously dedicated to aircraft propulsion studies. Actual operation of the molten salt reactor began in 1964 and continued for approximately five years. Throughout operation, the reactor was operated at different power levels, allowing for analysis of different operating conditions, development of equipment improvements, and studies of the fuel and reactor component behavior (Haubenreich & Engel, 1970). A picture of the reactor during installation is show in Figure 2.

The most promising aspects of molten salt reactors were related to fuel efficiency, stability, and costs, as well as safety features, and neutron economy (Robertson, 1965). In a molten salt reactor, unlike PWRs and BWRs, the fuel flows throughout the reactor system in liquid form. This eliminates many costs incurred with solid fuel rod design, development, and implementation. This also eliminates the cladding needed for solid fuel rods, which are disposed in high level waste, further saving costs in the fuel cycle. Fuel can also be added or processed as part of reactor operation (Robertson, 1965), unlike PWRs and BWRs which require shut-down periods throughout every one or two years throughout the life of the reactor for fuel reloading and removal for eliminating fission products that impede reactor operation (Shultis & Faw, 2002). Molten salt fuel also allows for savings in pumping costs because the reactor operates at high temperatures and does not require pressurization.
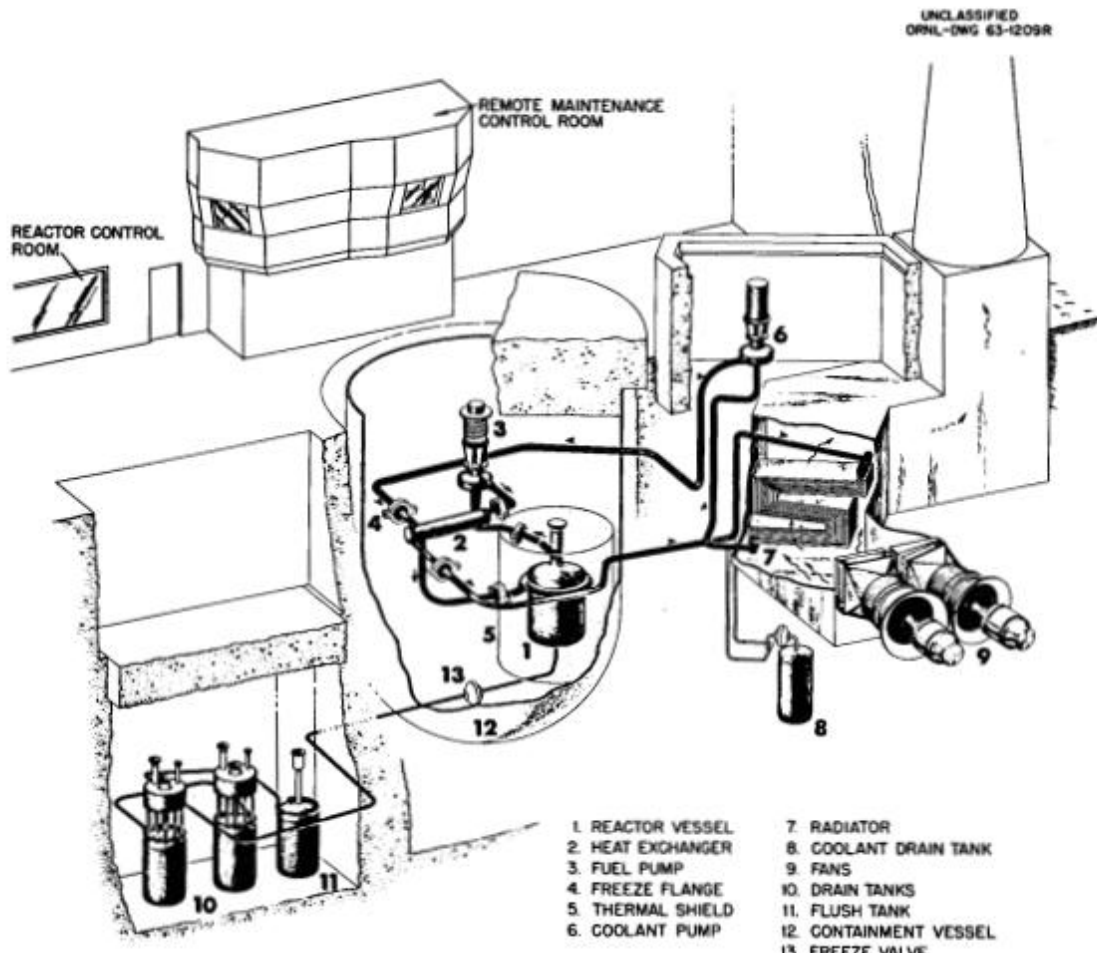
Figure 3: MSRE Flow Diagram

The reactor developed for the MSRE studies consisted of two main circulation loops, as shown in Figure 4.
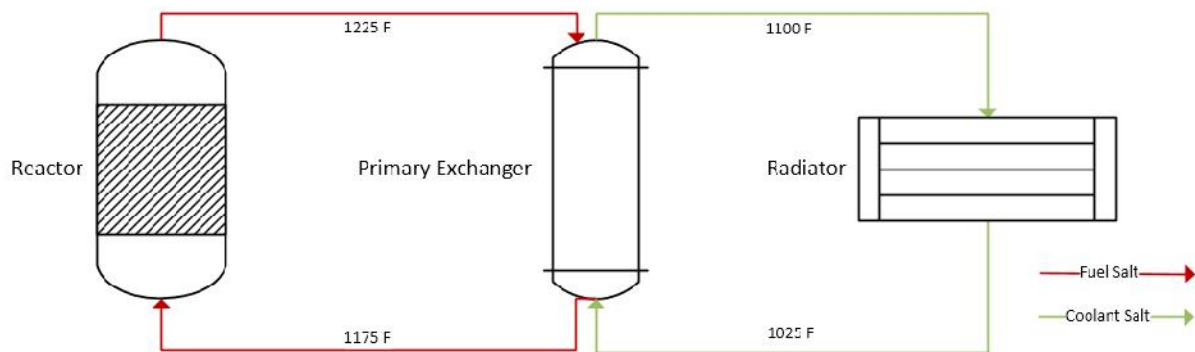
Figure 4: MSRE Fuel and Coolant Loop Designs

In one loop, the reactor fuel passed through the reactor, then was pumped to a shell and tube heat exchanger. The secondary loop contained a coolant fluid salt mixture with similar composition to the reactor fuel. This coolant passed through the same heat exchanger as the fuel salt, then was pumped to a radiator where air cooled the fluid before returning it to the heat exchanger. If this reactor configuration was to be used for power generation, the radiator on the coolant salt loop would be replaced by a steam generator which, similar to the PWR and BWR cycles, would produce steam that would turn a turbine to generate electrical energy.

Both circulation loops of the system were heated throughout the equipment to prevent the liquid salt mixture from cooling to its freezing point. The system also included several drain tanks where the coolant and fuel salts would cool when not being circulated through the reactor system. Pumps allowed transport of reheated salts from the drain tanks back into circulation.

The fuel salt consisted of UF_4 dissolved in a mixture of LiF, BeF_2, and ZrF_4 (Robertson, 1965). This mixture was chosen because it provided the ideal combination of stability when interacting with radiation, low melting point, and minimal issues when put in contact with water or oxygen. When this fuel mixture comes in contact with air or water, the different fuel component molecules will break apart and form oxides, but the inclusion of zirconium fluoride lowers the probability of the fissile uranium precipitating out of the mixture as uranium oxide. Stable operation was first established with this initial fuel using partially enriched uranium, meaning it had an increased concentration of fissile ^{235}U as opposed to naturally-occurring uranium which contains about 0.7% ^{235}U and about 99.3% ^{238}U, a non-fissile isotope. After a few years of operation with this mixture, the fuel was treated to remove the uranium and replace it with ^{233}U obtained from a separate fuel processing unit (Rosenthal, Kasten, & Briggs, 1970). The purpose of this change was to evaluate the thorium-uranium fuel cycle to demonstrate the feasibility of using this reactor configuration as a breeder reactor. A breeder is a reactor in which the fuel generates far more neutrons than it uses.

The reactor vessel was constructed of a nickel-molybdenum alloy and surrounded by a 16-inch thick stainless steel and flowing water shielding layer to prevent radiation from leaking into the laboratory space (Robertson, 1965). Within the reactor vessel is a core made of graphite with

grooves cut out where fuel flows and reaches a critical configuration. Within these grooves, the uranium within the fuel salt mixture underwent fission to produce heat energy, which built up until the fuel stream reached the heat exchanger. There the fuel salt passed on the shell side of the heat exchanger, where the heat created within the reactor was transferred to the coolant salt. Because the reactor was not used for power production, the heat was allowed to radiate from the coolant salt into the air.

Upon completion of the MSRE in 1969, several conclusions could be drawn relating to the feasibility of commercial power production by molten salt-fueled reactors. It was found that the fuel remained chemically stable, corrosion of the reactor materials was low, and that complete containment of radioactivity was attainable (Haubenreich & Engel, 1970). These conclusions showed that design and operation of a molten salt-fueled reactor was indeed feasible, increasing the promising outlook of this technology.

2.6 Current Molten Salt Reactor Technology

Today, the Molten Salt Reactor is one of six main designs being considered in the Generation IV class of reactors and is currently being researched mainly by Russia, France, and the European Union (Generation IV International Forum, 2013). The MOSART reactor concept currently being researched in Russia is a molten-salt reactor able to process transuranics (long-lived, highly radioactive by-products created during fission of uranium) and thus reduce the amount of dangerous waste produced by currently operating PWR and BWR type reactors (Ignatiev, et al., 2014).
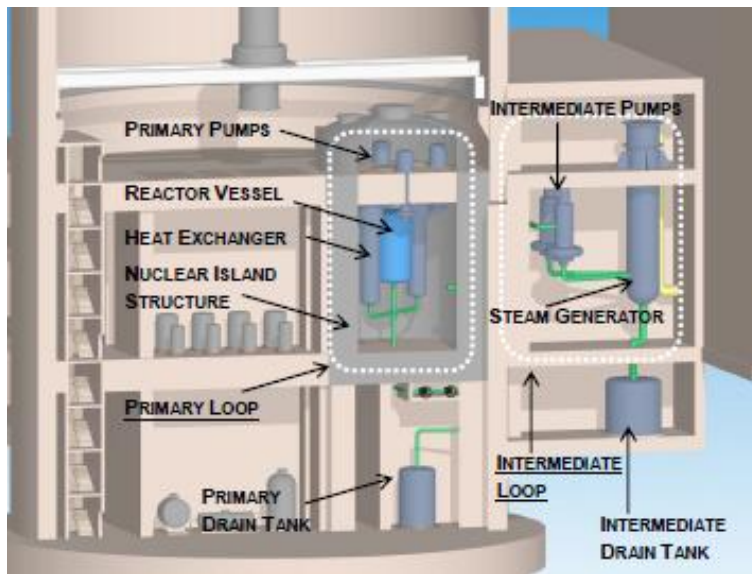
Figure 5: TAP MSR Reactor Vessel and Power Generation System Design

While the majority of Generation IV reactor technology in the United States is focused on small modular reactors and high temperature gas-cooled reactors, smaller teams are continuing research into molten salt-fueled reactors (Generation IV International Forum, 2013). One notable start-up company is the Cambridge, MA-based Transatomic Power (TAP) Corporation. The company includes nuclear professionals from various national laboratories and universities across the country and is focused on mass-producing molten salt reactors powered by a fuel mixture that includes spent-fuel from PWR and BWR reactors (Generation IV International Forum, 2013). The TAP design, like that studied here, is based on the Oak Ridge National Laboratory's MSRE design. In their design, however, TAP uses a metal hydride moderator as opposed to the carbon used in the MSRE design, and the fuel is based on lithium fluoride-heavy metal fluoride fuel salt mixture (Transatomic Power Corporation, 2014). TAP's system design can be seen in Figure 5.

2.7 Use at WPI
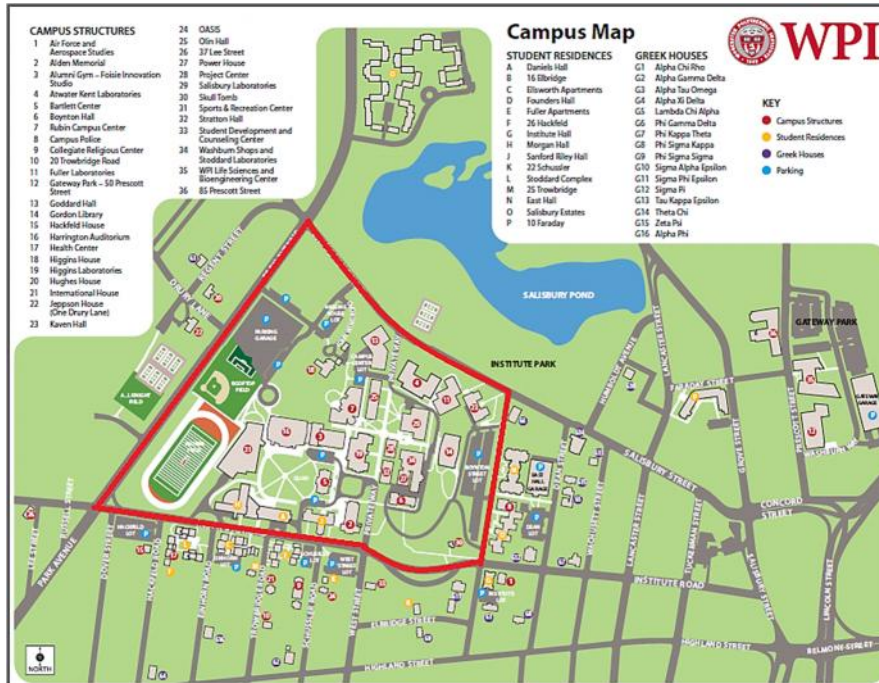
Figure 6 WPI 2-D campus map obtained from wpi.edu. Red outline added to demonstrate buildings heated with steam from the Power House boilers (Worcester Polytechnic Institute, 2014).

Steam generation for the WPI campus is currently accomplished using large boilers in the campus Power House. In the cold season, these boilers generate between 8,000 and 32,000 lb/hr of steam that is transported throughout the main campus to heat the academic and residential buildings located in the area bordered by Institute Rd., Salisbury St., Boynton St., and Park Ave., as indicated in red in Figure 6. (Grudzinski, Further Power House Information, 2014). In the warmer months, however, the boilers run at a small fraction of their capacity to supply steam only to the Sports and Recreation Center and the Goddard Hall Unit Operations Lab, causing a decrease in efficiency and increase in the wear on the boiler (Grudzinski, WPI Power House Steam Production Information, 2014). These boilers are heated using natural gas and require the purchase of fuel as well as labor costs for the boiler operators, which totals to over $3000 per year to supply solely the lab in Goddard Hall for approximately 17 days of operation in the warm months (Grudzinski, Further Power House Information, 2014). In addition to this cost, there are also increased maintenance costs of the boilers because the equipment experiences excessive wear from running at partial capacity to provide steam for a small portion of campus. There is also potential of decreased costs with the use of a molten salt reactor for campus heating because the reactor can run for long periods of time on a single charge of fuel, fuel inventory or enrichment could be adjusted throughout operation in order to produce just the amount of thermal energy required for seasonal heating needs while preventing the energy waste and excessive equipment damage that occurs when running the boilers at low capacity, and a MSR is capable of producing highly superheated steam that would allow campus heating to be accomplished using a much lower flow rate of steam than what is needed using saturated steam.

3. METHODOLOGY

The goal of this project was to evaluate the feasibility of using a molten salt reactor similar to that used in Oak Ridge National Laboratory's Molten Salt Reactor Experiment of the 1960s for steam generation on the WPI campus to be used for heating in the winter. In order to evaluate this, a series of objectives were met, as follows:

1. Determine thermal energy required for WPI campus heating based on steam conditions and flow rate obtained from interviews with the campus Power House Chief Engineer
2. Evaluate steam generation that can be accomplished using the same conditions used in the Molten Salt Reactor Experiment and model MSRE steam generation system using Aspen Plus to validate calculated results
3. Calculate the reactor thermal power output required from a PWR and a MSR to produce superheated steam with the energy content required to meet campus needs, and model PWR and MSR steam generation
4. Design heat exchanger network for steam generation using a molten salt reactor to produce steam to meet campus heating needs and simulate design in Aspen Plus to verify design calculation results

3.1 Step 1: Campus Heating Needs Calculation

Heat for the majority of WPI campus is currently provided by saturated steam generated in natural gas-fuelled boilers in the Power House. Because the steam generated is saturated, the enthalpy, H, was determined from steam tables. This enthalpy value was used in Equation 1 to calculate the total thermal energy required for heating campus at the maximum steam production rate.

$$Q_{needed} = \dot{m}H \tag{1}$$

This energy needed value was used in further calculations to evaluate the ability of the MSRE design for campus heating, as well as to calculate the reactor thermal output required from a PWR and from an MSR to heat campus. These calculations are shown in Appendix A.1.

To validate the calculations done, an Aspen Simulation was run using a furnace or fired heater block.

3.2 Step 2: MSRE Steam Generation Assessment

3.2.1 Steam Generation Loop Design
The MSRE set-up consisted of a reactor attached to a fuel circulation loop, a primary heat exchanger where heat is transferred from the fuel to a coolant salt loop where heat was removed through a radiator and expelled to the atmosphere through a heat stack (Robertson, 1965). The purpose of this project was to design a process that would utilize the heat production from a molten salt reactor. This was a simple process design that involved the addition of a steam generator in the place of the radiator.

For steam generation calculations, a three-exchanger system was adopted for the steam generator design. Per Teir's suggested calculations in "Basics of Steam Generation", the generator calculations approximated a heat recovery steam generator as a series of heat exchangers (Teir,

2003). The components in the heat exchanger network represent the three main portions of a steam generation boiler, known as an economizer, an evaporator, and a superheater. In this design, the coolant salt passed through the tubes of the exchangers to heat water running through the exchanger shells. A diagram of this exchanger network implemented in the MSRE system is shown in Figure 7.
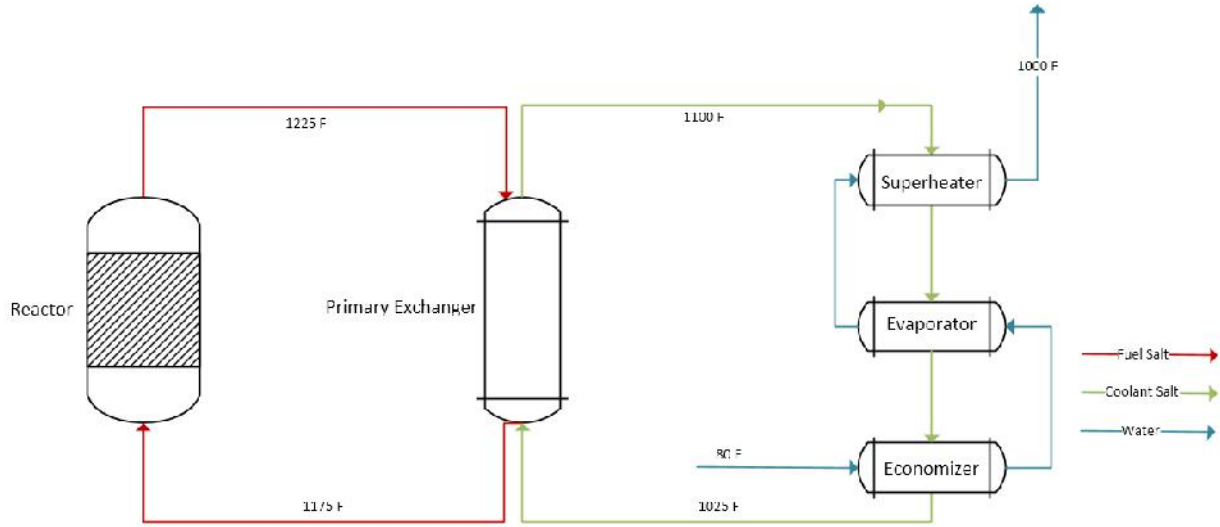
Figure 7: Steam Generation Heat Exchanger Series Block Diagram

3.2.2 Calculation of MSRE Steam Generation Potential

In order to determine whether the MSRE system was capable of meeting maximum campus heating needs, heat transfer within each exchanger was evaluated using Equation 2.

$$Q = \dot{m} C_p \Delta T \qquad (2)$$

Heat loss across the primary heat exchanger was determined as a percentage of heat given off by the fuel and a series of electric heaters within the exchanger using Equation 3. In Equation 3, Q_f represents the sum of the heat given off by the fuel and heaters, and Q_c is the heat absorbed by the coolant salt.

$$Q_{loss} = \frac{Q_f - Q_c}{Q_f} * 100\% \qquad (3)$$

Calculations were then performed under the assumption that this heat loss percentage would be the same across the steam generator. Equation 2 was again used to determine the heat given off by the coolant stream in the steam generator, which was approximated as a series of heat exchangers, based on the temperature change across the radiator in the original MSRE design. Equation 3 was rearranged to form Equation 4, then used to determine the heat absorbed in the water stream, Q_w.

$$Q_w = Q_c(1 - Q_{loss}) \qquad (4)$$

Q$_w$ represents the sum of the heat absorbed by the water in each of the heat exchangers used to approximate the steam generator. The overall heat transferred to the water/steam stream within the steam generator was modeled by Equation 5. The three heat exchangers used to approximate the steam generator were the economizer, where the water was heated to saturation temperature, the evaporator where the latent heat of vaporization, , was added to convert the saturated water to saturated steam, and the superheater that heats the saturated steam above the saturation temperature to 1000°F.

$$Q_w = \dot{m}_w (C_{pw} \Delta T_{economizer} + \lambda + C_{ps} \Delta T_{superheater}) \tag{5}$$

Equation 5 was used to calculate the flow rate of steam that could be produced from this system as follows in Equation 6:

$$\dot{m}_w = \frac{Q_w}{(C_{pw} \Delta T_{economizer} + \lambda + C_{ps} \Delta T_{superheater})} \tag{6}$$

One of the main benefits of the molten salt reactor is that it is capable of producing highly superheated steam because of the high temperatures of the fuel and coolant salts. The enthalpy of superheated steam is greater than that of saturated steam, so equivalent heating can be accomplished with a lower flow rate. The enthalpy of 1000°F and 100 psig steam and the calculated flow rate that could be produced were used in Equation 1 to determine the thermal energy content of the steam produced to compare to the calculated campus heating need.

3.2.3 Aspen Plus Simulation of Steam Generation Using MSRE System
Aspen simulations were performed using the specifications from the Oak Ridge MSRE. This was done to validate parameters given in the Oak Ridge reports and give more information on the design loop. Information from the simulations was also used in proceeding simulations.

The simulation was run to obtain heat duties of the exchangers and steam production, as well as to verify the use of Aspen and heat transfer calculations to optimize the steam generation loop design in future steps.

3.2.3.1 Simulation Using Furnace/Fired Heater Block
The first simulation used a furnace or fired heater block to simulate the steam generator. A simple flow sheet of the system created in Aspen is shown in Figure 8.
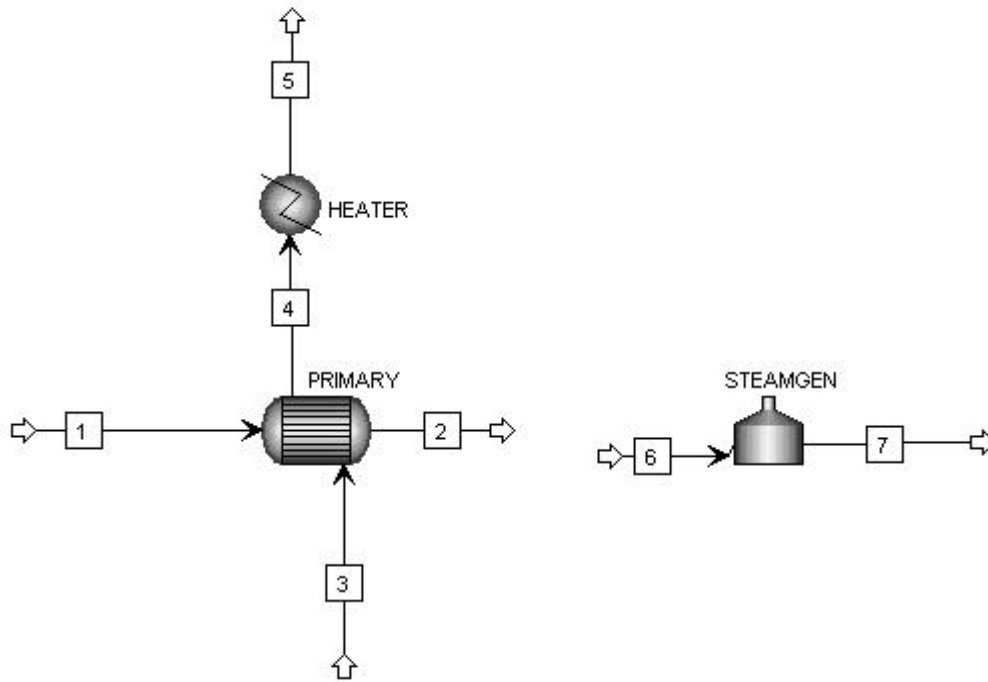
Figure 8: Aspen Plus Flow Sheet for MSRE Steam Generation

A heat exchanger unit and the heater come together to simulate the primary heat exchanger in the steam generation loop. In the MSRE design, a series of heaters, totaling to 30 kilowatts, were part of the primary heat exchanger to keep the salt mixture in liquid form, so this was considered in simulations (Haubenreich & Engel, 1970).

A furnace, or fired heater, block is used to simulate the steam generator. According to AspenTech, "Aspen Shell & Tube Exchanger, Air Cooled Exchanger, and Aspen Fired Heater offer capabilities that can allow modeling of heat recovery steam generators" (AspenTech, 2014)., The first options require detailed design input. Since this project aimed to design a steam generator, these detailed data were not available. The best option was a fired heater, where only a water flow rate must be input to attain a steam outlet flow rate and conditions.

As the fired heater block only allows water input, a full connection of the system could not be simulated in Aspen as Figure 8 shows. Instead, information from simulations in the primary heat exchanger was used to continue simulations in the steam generator.

The streams were defined as given in Table 1 and Table 2, where information highlighted in gray was given in the Oak Ridge reports (Robertson, 1965). 80 degrees Fahrenheit was chosen for the utility water temperature base on a chemical engineering design heuristic, and pressure was assumed to be the same as the steam produced (Turton R. , Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2013).

Stream No.	1	2	3	4	5	6	7
Material	Coolant Salt	Coolant Salt	Fuel Salt	Fuel Salt	Fuel Salt	Water	Steam
Flow rate (gpm)	850	850	1200	1200	1200	--	--
Temp. (°F)	1025	1100	1225	--	1170	80	--
Pressure (psig)	47	77	35	55	55	100	--

Table 1: ORNL Stream Data used for Aspen Input

Material	Fuel Salt	Coolant Salt
LiF4	0.7	0.66
BeF2	0.291	0.34
UF4	0.009	0

Table 2: Salt Stream Compositions in mol%

Note that in the full connected system, stream 2 would be entering the steam generator to provide heat to the utility water, and stream 1 would be the coolant salt return to the primary heat exchanger. Stream 3 would be the exit from the reactor, and stream 5 would be the return. It is also important to note that the primary heat exchanger functions as a normal heat exchanger, transferring heat between two fluids. The steam generator creates a phase change in the water stream, which was specified in Aspen.

Another purpose of this simulation was to find the steam flow rate provided by the thermal output of the MSRE design, as done in the previous section. To validate the calculations done in section 3.2.2, a Sensitivity Analysis was run to find the steam flow rate that correlated with the steam generator heat duty calculated in the previous section. The calculated flow rate was compared to the flow rate output from Aspen.

3.3 Step 3: MSR vs PWR Steam Production Comparison

3.3.1 MSR and PWR System Comparisons

To demonstrate the benefit of using a nuclear reactor capable of producing superheated steam over natural gas fired boilers, Equation 1 was used to determine the flow rate of steam required for campus heating when superheated to 700°F by a PWR and 1000°F by a MSR. Based on these flow rates, Equation 5 was solved to determine heat absorbed by the water in the steam generation portion of the coolant salt loop. This total heat quantity was then used in Equation 3 with calculated heat loss percentages to determine the heat given off by the coolant stream across all 3 heat exchangers. In the MSR case, the heat loss percentage used was that calculated in section 3.2.1, and for the PWR the heat loss was calculated based on available data for a representative commercial PWR system, the Westinghouse 414 (Westinghouse Electric Corporation Water Reactor Divisions, 1984). The heat given off by the coolant was used in Equation 2 to calculate the total flow of coolant in each reactor system.

In the MSR-based system, the heat given off by the coolant salt was used in Equation 3 to determine the heat transferred from the fuel salt. In this case, the thermal power of the reactor is the same as the heat given off by the fuel because the power is generated within the fuel salt itself as it passes through the reactor. In the PWR system, water serves as the coolant, and heat is transferred to it from the stationary fuel rods within the reactor core. This means that heat loss occurs not only in the steam generator, but also within the reactor. Therefore, Equation 3 must be used to evaluate the thermal output of the reactor using a heat loss percentage calculated based on Westinghouse 414 PWR data. The reactor output calculations for the PWR system are given in Appendix A.3 and MSR thermal output calculations are given in Appendix A.4.

Another comparison of the two systems was made using thermal efficiency, which is a ratio of energy produced by the steam to the energy output of the reactor. In other words, the measure of thermal energy lost to the environment in each system was compared. Thermal efficiency was found using Equation 7:

$$Thermal\ Efficiency = \frac{Energy\ content\ of\ Steam}{Thermal\ output\ of\ reactor} \qquad (7)$$

Lastly, the reactors were compared using specific power, which is calculated by dividing the thermal output of the reactor by the mass of Uranium in the fuel:

$$Specific\ Power = \frac{Thermal\ output\ of\ reactor}{Mass\ Uranium\ in\ fuel} \qquad (8)$$

3.3.2 Aspen Plus Simulation of MSR and PWR Steam Production

To simulate the steam production differences in a PWR and the MSR in Aspen, only the fired heater block was used, as pictured in Figure 8. To compare each system, a sensitivity analysis was done in Aspen to determine the mass flow rate of steam needed for each reactor to meet the energy needs of WPI, the energy of steam required by WPI, 38,090,000 Btu/hr (Grudzinski, WPI Power House Steam Production Information, 2014). For the different processes, the fired heater block required different input. A PWR can only produce saturated high pressure steam (Westinghouse Electric Corporation Water Reactor Divisions, 1984). In the PWR simulation, only a vapor fraction of 1 and outlet pressure of 100 psig were specified, which would output saturated steam at 100 psig and 338°F. The use of an MSR allows for steam at much higher temperatures and creation of superheated steam. In simulating MSR steam generation, degrees of superheat were specified instead of vapor fraction, keeping in mind that the exiting coolant salt temperature is 1025°F, and the steam could therefore not exceed around 1000°F. The mass flow rates of steam from the MSR and PWR loops obtained from Aspen were compared.

3.4 Step 4: Designing MSR Steam Generation Loop for WPI Campus Need

3.4.1 Design Calculations

Based on the calculated campus heating needs, a MSR system was developed using a network of heat exchangers, as shown in Figure 7, to transfer heat from the reactor fuel salt, to coolant salt, and finally to steam to generate the necessary quantity of 1000°F superheated steam. The reactor output was determined in section 3.3.1, but specific reactor sizing would involve nuclear physics and engineering concepts that were beyond the scope of this project. Therefore the design aspect of this project focused on sizing of the primary exchanger for heat transfer between fuel and

coolant salts, and sizing of the heat exchangers that made up the steam generation section of the coolant salt loop.

3.4.1.1 Inner Heat Transfer Coefficient Calculation

In order to effectively design each heat exchanger, Equation 9 needed to be evaluated to determine A, the total surface area required to transfer the calculated amount of heat. This total surface area represents the outer area of all of the tubes within the heat exchangers.

$$Q = UA\Delta T_{LM} \tag{9}$$

Q in Equation 7 is the same as the Q value calculated using Equation 2 for the hot stream in each exchanger. T_{LM} in Equation 6 is the log mean temperature difference across the exchanger, and U represents the overall heat transfer coefficient. Equation 10 gives the definition of T_{LM}, where the subscripts h and c indicate the hot and cold streams, respectively, subscripts i and o indicate inlet and outlet, respectively, and F is a correction factor that accounts for the fact that flow in heat exchangers of 2 or more passes are not truly countercurrent, which the T_{LM} assumes. A correction factor of 0.97 was given in the MSRE report and was assumed to be a suitable approximation to use throughout exchanger sizing calculations (Robertson, 1965).

$$\Delta T_{LM} = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln\left(\frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}}\right)} * F \tag{10}$$

The overall heat transfer coefficient, U, represents the resistance to heat transfer across the film of fluid immediately adjacent to the inner boundary of the tube walls, through the pipe itself, and across the film of fluid immediately adjacent to the outer wall of pipe. The equation form of this overall heat transfer coefficient is given in Equation 10. Again, subscripts i and o indicate inner and outer, respectively, while A_{ave} is the average between the total inner area and total outer area of the tubes, t_p is the thickness of the pipe and k_p is the thermal conductivity of the pipe material.

$$\frac{1}{UA_o} = \frac{1}{h_i A_i} + \frac{t_p}{k_p A_{ave}} + \frac{1}{h_o A_o} \tag{11}$$

The inner and outer heat transfer coefficients, h_i and h_o, are factors to describe heat transfer via convection in the inner and outer film regions along the pipe. These coefficients are dependent on the fluid on the corresponding side of the tube, geometry of the space the fluid is flowing through, and the velocity of the fluid. Figure 9 shows how the inner and outer heat transfer coefficients related to flow through a shell and tube exchanger. In the MSRE report, the coolant salt was specified as the tube side fluid in the primary heat exchanger (Robertson, 1965). Therefore, h_i could be determined based on data given in the MSRE Design and Operations Report, and could be
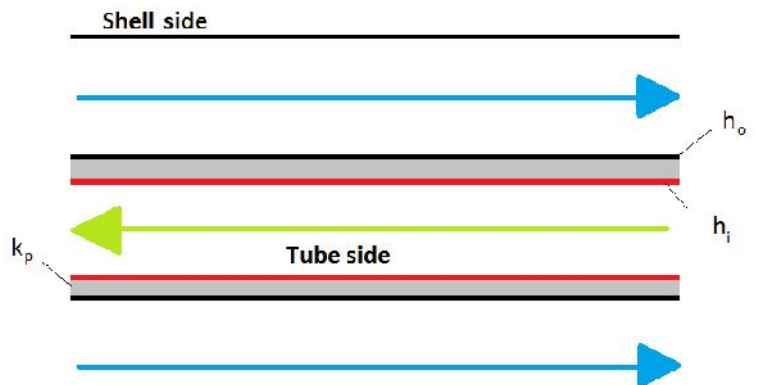
Figure 9: Diagram of Heat Transfer Coefficiens through a Shell and Tube Exchanger

used in sizing calculations for this design as long as coolant salt was specified to be the tube side fluid throughout the system.

The value of h_i was calculated using properties of the coolant salt given in the MSRE Design and Operations Report and Equations 12-15. Equation 12 is the dimensionless parameter known as the Nusselt number, Re is the Reynold's number, defined by Equation 13, and Pr is the Prandtl number, defined by Equation 14. Equation 15 defines the relationship between the three parameters for turbulent flow, and is known as the Dittus-Boelter Equation (Clark, 2014). The calculated value of h_i from MSRE data, as well as the pipe thickness and thermal conductivity, were taken to be constant throughout heat exchanger sizing calculations.

$$Nu = \frac{h_i d_i}{k_c} \tag{12}$$

$$Re = \frac{\rho_c d_i v_c}{\mu_c} \tag{13}$$

$$Pr = \frac{C_{pc} \mu_c}{k_c} \tag{14}$$

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \tag{15}$$

3.4.1.2 Outer Heat Transfer Coefficient Calculation

The outer heat transfer coefficient depends on the flow characteristics, properties, and flow geometry of the shell side fluid. In the case of the primary heat exchanger, the shell side fluid was the same as in the primary exchanger in the MSRE, so the overall heat transfer coefficient was assumed to be the same for simplicity of design calculations. In the steam generation exchangers, however, the outer heat transfer coefficient would be different due to the shell side containing water instead of fuel salt, and the difference in phases between the exchangers containing water. In these cases, the outer heat transfer had to be calculated separately. Equations 16 and 17 were obtained from *Fundamentals of Heat and Mass Transfer* by Bergman et al and was used to estimate the outer film heat transfer coefficient for the economizer and superheater, where no phase change occurs (9.6 Empirical Correlations: External Free Convection Flows; 9.6.3 The Long Horizontal Cylinder, 2011).

$$Ra_D = \frac{g\beta(T_s - T_{bulk})d_o^3}{\nu\alpha} \tag{16}$$

$$Nu = \frac{h_o d_o}{k} \left\{ 0.60 + \frac{0.387 Ra_D^{\frac{1}{6}}}{\left[1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2 \tag{17}$$

For the evaporator, however, Equations 16 and 17 cannot be used to calculate the outer film heat transfer coefficient because there is a phase change that needs to be accounted for differently.
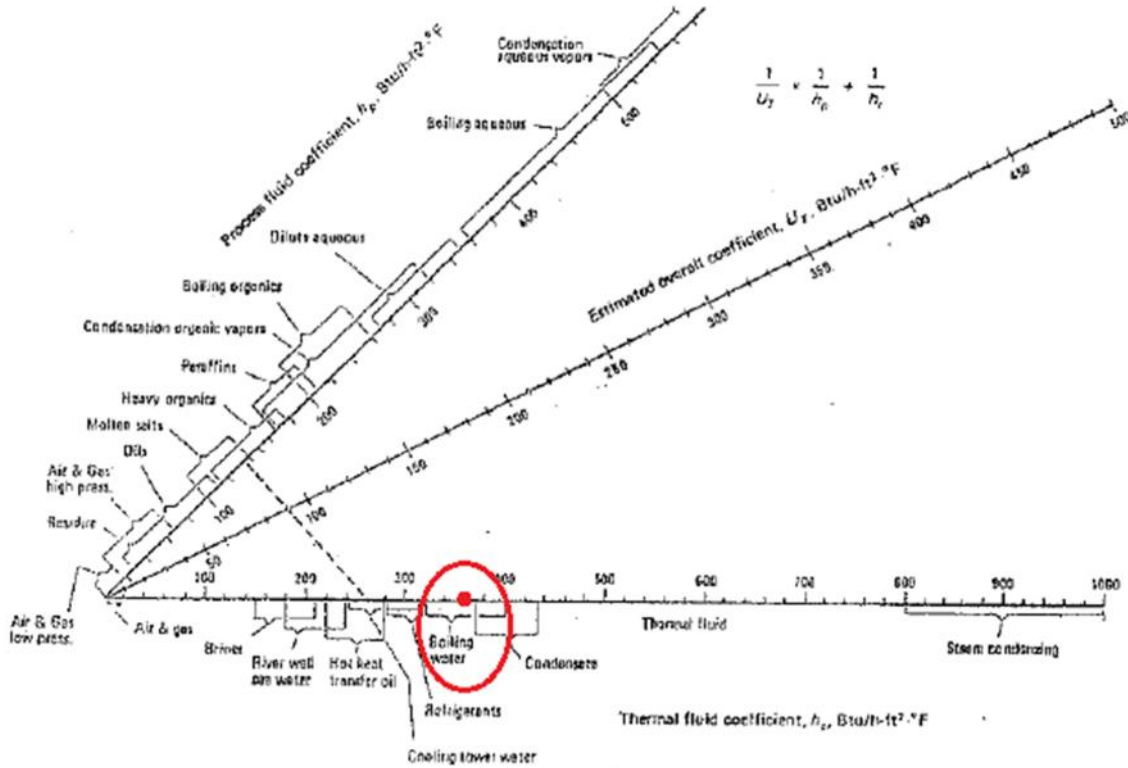
ESTIMATING OVERALL HEAT TRANSFER COEFFICIENTS

Figure 10:"Estimating Overall Heat Transfer Coefficients"

Figure 10 shows a chart from the CHE 4404 class at WPI that was used to estimate the outer heat transfer coefficient for use in evaporator sizing calculations. Because only the outer coefficient was unknown, the value was taken from the x axis in the range labeled "Boiling water" (Starr, 2014).

3.4.1.3 Exchanger Sizing
The primary heat exchanger was sized using the fuel salt heat transfer calculated in section 3.3.1, the temperature difference and correction factor given in the MSRE report, and the overall heat transfer coefficient was determined using Equation 6 and the heat, area, and temperature difference defined in the MSRE report (Robertson, 1965). The tube diameter was chosen and the number of tubes required to provide the necessary area was calculated. The exchanger shell diameter was chosen based on the number of tubes calculated and the charts given in Appendix D, and a safety factor of 10% was added to the area, based on a general exchanger design heuristic (Starr, 2014). The length of the straight section of tubes, where heat transfer is most efficient, was calculated to obtain the total area needed at the calculated number of tubes.

The economizer and superheater sizing methodology was similar to that used in the primary heat exchanger calculations. Instead of using the overall heat transfer coefficient calculated from the

MSRE data, though, Equations 16 and 17 were solved for a chosen diameter and given flow and temperature conditions in each exchanger that did not cause phase change. These heat transfer coefficients were then used to solve a system of equations including inner and outer area formulae and Equations 11-15 for the areas, tube straight length, and number of tubes. Similar to the primary exchanger sizing, the shell diameter was determined using the charts in Appendix D and the actual tube length was found based on an additional 10% heat transfer area. The evaporator was sized the same way using the estimated outer film heat transfer coefficient from Figure 10 in place of Equations 16 and 17.

3.4.2 Material Considerations

After designing the size of the heat exchangers in the steam generation loop, materials were chosen for each one. Since the exchangers use molten salts, "[t]he high operating temperatures limit the range of possible candidate materials for the construction of the heat exchanger[s]" (Adames, 2010). Corrosion, creep and thermal loads are three characteristics to take into consideration when choosing a material of construction (MOC). Molten salts can be very corrosive. And because they operate at high temperatures, the tendency for creep and oxidation greatly increase (Adames, 2010). Therefore, special steels or "superalloys" were considered for use wherever molten salt exposure would occur. ORNL's MSRE used hastelloy, a nickel-based alloy, with the ability to resist corrosion and oxidation, and avoid creep at high temperatures. Hastelloy and other nickel alloys will be important considerations for the heat exchangers' material (Haynes International, 2008).

3.4.3 Comparison to WPI's Current Boiler System

After the heat exchanger network was designed for an MSR meeting campus heating needs, the designs were compared to WPI's current set up in the Power House. To compare the two systems, floor space of each was evaluated. The design calculations for each exchanger in the MSR system included shell diameters and lengths. Assuming each exchanger's width was equivalent to its diameter, a floor space area was calculated:

$$A = Length \; x \; diameter \tag{18}$$

The exact floor space of the boilers in WPI's Power House were not known, so their size was estimated using data from an industrial boiler manufacturer, which provide base length and width, thus floor space can be determined by:

$$A = Length \; x \; width \tag{19}$$

4. RESULTS AND DISCUSSION

4.1 Campus Heating Need

Currently, heating needs on the majority of WPI's campus are met by 100 psig saturated steam produced by the boilers in the campus Power House. This steam is transported along a fuel loop that heats approximately 1.2 million square feet of academic and residential spaces (Grudzinski, Further Power House Information, 2014). During the cold season, the production need of this steam is between 8,000 lb/hr and 32,000 lb/hr, but on average the required flow rate is approximately 25,000 lb/hr. At a certain pressure and temperature, steam contains a specific amount of energy per pound, known as the enthalpy of the steam. At the conditions used on campus, the enthalpy was assumed to be constant at 1190 BTU/lb of steam, meaning saturation temperature and pressure was assumed to be maintained at maximum, minimum, and average production rates (Spirax-Sarco, 2014). At minimum steam production of 8,000 lb/hr, the heating energy usage was found to be approximately 9.52 million BTU/hr. At maximum heating need, the total energy need was found to be approximately 38.1 million BTU/hr, and the average heating energy need for campus was found to be 29.8 million BTU/hr. These calculations are provided in Appendix A.1.

An Aspen simulation was performed to validate these calculations. The simulations yielded an energy output of 9.2 million BTU/hr, 29 million BTU/hr, and 37 million BTU/hr for minimum, average and maximum steam needs, respectively. The Aspen results compare well to the energy balance calculations, confirming that Aspen and the furnace/fired heater block can simulate steam generation from a boiler system. Although future calculations did not focus on the boiler system, they did investigate the steam generation system of other heat sources.

These energy calculate levels of energy need were considered the standards from which to determine whether campus heating needs could be met using nuclear reactors as heat sources. The WPI Power House boilers produce saturated steam, but if the heat source of the steam production could heat the steam beyond the saturation temperature then campus heating could be accomplished more efficiently. As the steam temperature increases further and further above saturation temperature, in this case 338°F, the enthalpy of the steam increases and therefore the same quantity of heating can be accomplished using less water. This is the first way in which switching to a nuclear reactor as the heat source for campus steam generation would be beneficial. The outlet temperature of steam, and therefore the quality of that steam, from a natural gas-fired boiler is limited by the combustion energy obtainable from natural gas, furnace efficiency and boiler efficiency. The systems examined in this report, however, are based solely on heat exchange between two fluids, which can be accomplished using typical shell-and-tube heat exchangers, allowing efficiency to be estimated based on the calculated heat loss across the primary exchanger in the MSRE Design and Operations Report (Robertson, 1965).

4.2 MSRE Energy Potential Calculations and Simulation

The first candidate system to be evaluated for its ability to meet campus steam needs was the Molten Salt Reactor Experiment design used in Oak Ridge National Laboratory. For these calculations, the system was considered to contain a 10 MW_{th} reactor for nuclear power generation, a fuel salt flow rate of 1,200 gallons per minute, and a coolant salt flow rate of 850 gallons per minute, identical to the conditions used in the MSRE. The primary heat exchanger and all

temperatures were assumed to be identical to the MSRE design as well, but the air-cooled radiator was replaced with a theoretical heat recovery steam generator. The steam generator was approximated by three heat exchangers where heat was transferred between the coolant salt loop and the feed water/steam generation stream. Based on the temperature change in the coolant salt across the radiator, it was assumed that superheated steam could be produced at 1,000°F because this is reasonably close to the minimum coolant temperature of 1,025°F. Heat transfer calculations determined a heat loss in the primary exchanger of approximately 5% of the heat given off by the fuel salt. This was used as an estimate for heat loss across the steam generator to determine the overall heat absorbed by the water to generate the steam.

The inlet and outlet temperatures of the water stream in each exchanger were known because the steam was assumed to be 1000°F, as mentioned previously, and the economizer inlet temperature was chosen as 80°F based on a chemical engineering design heuristic and the assumption that Worcester city water supply would be at a similar temperature (Turton R. , Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2012). The remaining unknown temperatures, the evaporator inlet and outlet, are by definition the saturation temperature of 100 psig water because the economizer heats the feed water to saturation, phase change occurs within the evaporator, and the superheater heats the steam from saturation to the outlet temperature. From the known information in the MSRE report, both heat balances and an Aspen simulation were performed.

For the heat balance, known total heat transferred and temperature change values for each exchanger, as well as heat capacity and latent heat values obtained from steam tables (Spirax-Sarco, 2014), the set of three heat balances and the sum of the 3 heat values were solved simultaneously to find the heat transfer in each exchanger and the flow rate of superheated steam produced. The overall flow rate of superheated steam produced was found to be 20,521 lb/hr. The enthalpy of steam at 100 psig and 1000°F is 1532 BTU/lb, meaning the total heating energy in the calculated steam production is 31.4 million BTU/hr. The Aspen simulation yielded similar results, finding that an energy need of 3.1 BTU/hr of would require 20,660 lb/hr of steam.

These results indicate that the MSRE design would be able to meet the minimum and average heating needs of the buildings on the campus steam heating loop, but only 82.5% of maximum campus heating needs. Based on this finding, a molten salt reactor-based steam generation loop would require a slightly greater reactor thermal power output than that of Oak Ridge National Laboratory's MSRE. Calculations for the MSRE evaluation are provided in Appendix A.2

4.3 PWR vs. MSR Comparison

The next set of calculations aimed to determine the reactor thermal output that would be required to satisfy even maximum campus heating needs. For this evaluation, the goal was twofold – to show the water savings that can be seen from using a nuclear reactor instead of the natural gas-fuelled boilers currently used on campus, and to show the advantages of using a molten salt reactor as opposed to a pressurized water reactor similar to those used in many commercial nuclear power plants in the United States. To meet these goals, a steam generation system was first evaluated that resembled a scaled-down version of a Westinghouse 414 PWR power generation plant to determine the degree of superheating that can be attained at 100 psig and the reactor thermal output that would be required to produce enough steam at this temperature to meet the maximum campus heating needs of approximately 38 million BTU/hr. This was then compared to a design similar to the MSRE, with the radiator again replaced by a series of heat exchangers for steam generation.

4.3.1 Steam Generation by a PWR

The Westinghouse 414 is an example of a typical commercial PWR reactor capable of producing approximately 3800 MW_{th} (Westinghouse Electric Corporation Water Reactor Divisions, 1984). The first step in evaluating a system like this to be adapted for use in steam generation was to determine heat losses within the reactor and within the steam generators. Based on data available for the Westinghouse 414, the reactor was found to have approximately 11% of the thermal energy generated in the core not transferred to the coolant water, and 6.7% of the heat from the coolant water is lost across the steam generator to the environment. These percentages were then used in the design of a steam generation system for WPI.

Based on the temperatures given in the Westinghouse 414, heat exchange between the coolant stream and steam generation stream could potentially produce steam at a temperature of 500°F because this is reasonably close to the minimum coolant temperature of 558°F. Superheated steam at 100 psig and 500°F has an enthalpy of 1277 BTU/lb, which means that 29,800 lb/hr of steam would need to be produced in order to meet maximum campus heating needs (Spirax-Sarco, 2014). The Aspen Simulation estimated a need of 31,370 lb/hr. The Aspen and heat balance results are comparable, helping to verify each result. The Aspen simulation yielded a higher steam need by mass, which can be explained by one of two things. First, Aspen may use a higher heat loss across the generator. If all of the heat from the reactor isn't transferred to the steam generator, more steam will be required to service the same energy need. Second, heat transfer calculations become complex with boiling and phase change. Aspen may assume slightly different heat capacities or other values than those found for the heat transfer calculations.

Continuing a heat balance around the steam generator it was found that there would need to be a flow rate of approximately 455,000 lb/hr of coolant water at the same operating temperatures described in the Westinghouse 414. Another heat balance performed around the reactor determined that a PWR with similar heat loss to the Westinghouse 414 design would need to produce 12.55 MW_{th} in order to produce enough steam at 500°F to meet maximum heating needs on campus. A reactor this size producing steam at 500°F would allow for an overall water saving in the steam generation loop of 6.8% over the saturated steam produced by the boilers on campus at maximum heat production. Aspen Plus was not capable of simulating these calculations because of the extreme pressures required by a PWR, and because the fired heater/furnace block was not capable of connecting to another system or heat source.

By dividing the energy content of the outlet steam by the reactor thermal efficiency, the system was found to have an overall thermal efficiency of 89%, using Equation 7. Shultis and Faw provide a PWR summary table showing that the fuel used in a PWR has a specific power of approximately 33 kW/kg uranium (Shultis & Faw, 2002). Based on this specific power estimate, it was calculated that a 12.55 MW_{th} PWR would require approximately 380 kg of uranium to operate, rearranging Equation 8.

4.3.2 Steam Generation by an MSR

The 5% heat loss calculated in evaluation of the MSRE for steam generation was used as the approximate heat loss across the primary exchanger and steam generation exchangers in the MSR system evaluation. As mentioned in section 4.2, a molten salt reactor system at the temperatures given in the MSRE Design and Operations report is capable of producing steam superheated to 1000°F at 100 psig. This results in a steam flow rate of approximately 24,900 lb/hr required to

meet maximum campus heating needs. An Aspen simulation estimated the 38 million BTU/hr would require 25,674 lb/hr in an MSR. This corresponds to an average water savings of 20.1% over saturated steam need.

In order to produce this quantity of 1000°F steam from coolant salt at temperatures equal to those in the MSRE, the coolant flow rate required was found to be 991,600 lb/hr, and the fuel flow rate required was found to be 1.77 million lb/hr, an increase of 21.2% in coolant flow rate and 36.9% in fuel flow rate over the MSRE design. At these flow rates and the temperature changes from the MSRE, the total reactor thermal output required was found to be 12.16 MW and the thermal efficiency of the system was found to be 91.8%. Again, an Aspen simulation was not done on this part of the calculations because of the limitations of the furnace/fired heater block.

At 10 MW_{th} operation of the MSRE system, the primary (fuel circulation) loop contained 73 ft^3 of fuel. According to the fuel composition given in the Design and Operations Report, 0.009 mol % of the fuel was uranium tetrafluoride (Robertson, 1965). Using Equation 8, the specific power of the fuel was approximately 43.9 kW/kg uranium. Assuming this same specific power, the 12.16 MW reactor required to produce steam to meet campus needs would require approximately 276 kg of uranium of uranium to operate. Detailed calculations can be found in Appendix A.4.

4.3.3 Benefits of the MSR

The calculations above prove that using a nuclear reactor as the heat source in a steam generation loop for heating the majority of campus would indeed allow for water savings in the steam generation. These calculations also show that not only can greater water savings be achieved with a molten salt reactor, but at a lower power production rate and with a lower uranium inventory. In addition to these benefits, a pressurized water reactor requires high pressure operation at approximately 2250 psia in order to prevent the water in the coolant loop from boiling (Shultis & Faw, 2002), however the molten salt fuel and coolant salts allow operation at pressures between 5 psig and 55 psig. This eliminates the need for equipment capable of withstanding such extreme pressures. Also, in a commercial PWR it is necessary to shut the reactor down completely approximately once a year to replace a portion of the fuel rods due to the buildup of fission poisons. The fluid nature of the fuel in a molten salt reactor enables some of these fission poisons to be removed throughout typical reactor operation by a helium off-gas system within the pump bowl (Robertson, 1965). For poisons that can't be removed by the helium gas, additional chemical processing unit operations can be added to the fuel loop to allow for continuous reprocessing without shutdown, or small quantities of fuel can be removed or added through a sample port in the reactor housing (Robertson, 1965). This would allow for continuous operation over long periods of time, which is especially important during the winter months when campus would rely on a consistent heating source to prevent pipe freezing or discomfort of students, staff, and faculty members. Table 3 shows a summary of the benefits related to an MSR over a PWR.

	PWR	MSR
Water need (lb/hr)*	29,820	24,870
Reactor thermal output (MW)*	12.5	12.1
Operation pressure (psi)	2250	Atmospheric
Specific Power of U (kW/kg U)	33	44

*Table 3: MSR vs. PWR; *Indicates value calculated from WPI campus energy need*

4.3.4 Exchanger Network Design and Sizing

Calculations from section 4.3 showed that the molten salt reactor was the more attractive option for campus steam generation than a PWR. Next, the final heat exchanger network design portion of this project was completed to fit into a molten salt reactor-based system to generate the amount of 1000°F required to meet WPI's maximum heating needs. Based on previous calculations this was found to be a flow rate of approximately 24,900 lb/hr of superheated steam at 100 psig and 1000°F, where the coolant flow rate required was found to be 991,600 lb/hr and the fuel flow rate 1.77 million lb/hr. The heat exchanger network was then sized based on these flow rates and the temperatures defined in the MSRE Design and Operations Report. All of the heat exchangers in the network were designed as shell and tube exchangers because that is the exchanger type successfully demonstrated in the MSRE primary exchanger. Sizing was determined using systems of equations in combination with handouts from the WPI ChE 4404 course to help estimate part of the heat transfer coefficient and to determine shell diameter sizes needed to fit the calculated number of tubes and passes (Starr, 2014). In order to facilitate heat transfer coefficients, the coolant salt was maintained as the tube side fluid in all of the exchangers, and the tubes were consistently considered to be made of Hastelloy N, the same material used in the MSRE primary exchanger. In addition to helping with heat transfer coefficient determination, using the same tube material allows for heat exchanger design to be supported by proven operation throughout the entire duration of the MSRE.

4.4.1 Primary Exchanger Sizing Calculations

In order to determine the total heat transfer area required within the primary exchanger, an overall heat transfer coefficient needed to be determined. The overall heat transfer coefficient is the sum of the inverse of three resistances, as described by Equation 10. The first resistance is a measure of heat transfer through a thin layer of tube side fluid immediately adjacent to the tube wall. The second is the resistance to heat transfer through the tube material itself, and the last is the resistance to heat transfer through a thin layer of shell side fluid immediately adjacent to the outer wall of the tubes. In order to calculate the heat exchange area required in the primary exchanger in the system designed for this project, the heat transfer coefficient needed to be determined. Because of the similarity in material and geometry between this exchanger and the MSRE primary exchanger, the overall heat transfer coefficient can be assumed to be the same between both. This was determined using the heat transfer, log mean temperature difference, and total area defined in the Design and Operations Report, and was found to be 1027 BTU/(lb*hr°F). In designing the primary exchanger

for this project, the log mean temperature difference and overall heat transfer coefficient were the same as in the MSRE, and the heat transferred was the same as that calculated in section 4.3.2, so the area required for heat transfer was found to be 303.6 ft^2. By choosing 1" diameter 2 pass U-tubes with a straight length of 10 feet, the total number of tubes required was found to be 58. Adding a 10% extra area as recommended by design heuristic, the actual heat transfer area was found to be 334 ft^2, which corresponds to 58 1"-diameter U-tubes with a straight length of 11 feet. A U-tube set up is shown in Figure 11.
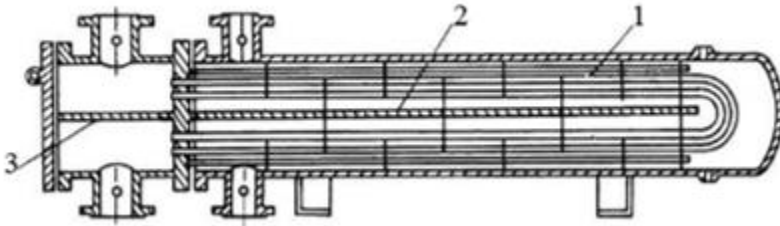
Figure 11: U-tube Set Up for Exchanger Design

Hastelloy N was chosen as the material of construction for its ability to resist corrosion and creep at high temperatures (Haynes International, 2008). Furthermore, this was the material used in the MSRE's primary exchanger, so it has shown its ability to withstand the harsh conditions of a molten salt environment (Haubenreich & Engel, 1970).

Figure 12 displays general design aspects of each exchanger:

Primary Exchanger
- Length: 10 ft, Diameter: 12"
- Floor Space: 10 ft^2
- MOC: Hastelloy N

Economizer
- Length: 11 ft, Diameter: 10"
- Floor Space: 7.33 ft^2
- MOC: Hastelloy N

Evaporator
- Length: 11 ft, Diameter: 8"
- Floor Space: 9.17 ft^2
- MOC: Hastelloy N

Superheater A
- Length: 16 ft, Diameter: 8"
- Floor Space: 10.66 ft^2
- MOC: Hastelloy N

Superheater B*
- Length: 11 ft, Diameter: 8"
- Floor Space: 7.33 ft^2
- MOC: Hastelloy N

Figure 12: MSR Exchanger System Design

4.4.2 Superheater A/B Calculations

The superheater is the last portion of the steam generation section where the saturated steam is heated to 1000°F. Sizing calculations for this exchanger were similar to those for the economizer and utilized the same equations for outer film heat transfer coefficient determination. A variety of diameters were tested but none gave reasonable length or area results. The log mean temperature difference was then adjusted to allow for more reasonable results. In order to do this, the superheater was split into two separate units in series with respect to the water stream. In order to maintain the temperature profile of the coolant salt loop, the coolant stream was split so that the exchangers were in parallel with respect to the coolant salt. A diagram of this layout is shown in Figure 13.
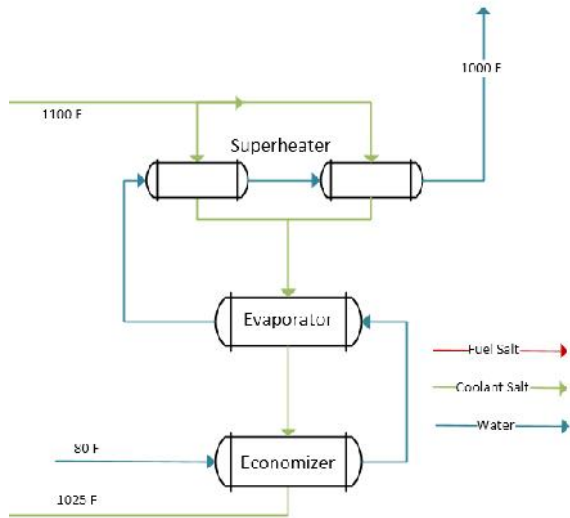
Figure 13: Split Superheater Steam Generation Design

Once this adjustment was made, the results were much more reasonable. Outer film coefficients were again calculated using Equations 11-15, and the system of equations previously described was used to solve for the area required for each heat exchanger and the number of tubes to make each area. For the first superheater, where the steam was heated from saturation to 639°F, the required heat transfer area was 198 ft^2, which led to a need for 36 two-pass tubes with diameter 0.75 inches and a triangular 1 inch pitch. With the 10% additional area the final tube length for the first superheater was found to be 15.4 feet. For the second superheater where the steam was heated from 639°F to the outlet 1000°F, the initial calculations again gave unreasonable areas, but this was a small enough problem that it was remedied by increasing the number of tube passes from 2 to 4. With 4 passes, the required area was calculated to be 283 ft^2 which required 36 four-pass 0.75-inch diameter tubes. These tubes required a shell diameter of 8 inches and a triangular pitch of $\frac{17}{18}$ inches. With the 10% additional area, the final tube straight length required was found to be 11 feet.

4.4.3 Evaporator Sizing Calculations
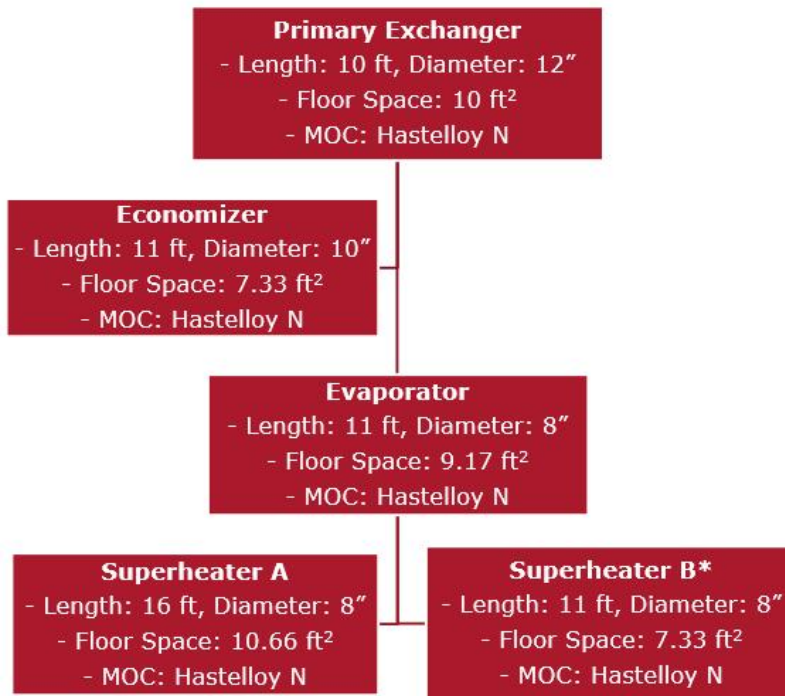
In the evaporator, the latent heat of the saturated water is transferred from the coolant stream to the saturated feed water, vaporizing it to form saturated steam. Because of the boiling that occurs within the evaporator, determination of the outer film coefficient was more complicated than with the economizer. When dealing with boiling water, one has to consider the different phases of evaporation that the water goes through. First is nucleate boiling, in which small bubbles of vapor begin to appear one by one then rise away from the tube surface. Then is transition boiling where larger bubbles form more quickly and evaporate out of the liquid, and lastly film boiling where a full layer of vapor replaces the liquid along the tube surface. Because of the different phases of boiling, the heat transfer film coefficient can't be evaluated the same way as in the economizer. In the interest of time, a film coefficient was estimated from the chart in Figure 10 to be 360 BTU/(hr*ft^2*°F). Using this film coefficient and an assumed tube diameter of 0.75 inches, the system of equations used for economizer sizing was set up to find the required heat transfer area

of 141 ft^2 and the number of tubes required, which was found to be 36. In order to fit 36 tubes of 0.75 inch diameter on a triangular pitch of 1 inch, the shell diameter required was found to be 8 inches. With the 10% safety factor area increase, the total straight tube length was determined to be 11 feet.

4.4.4 Economizer Sizing Calculations

The economizer is the first section of the steam generation heat exchanger series. In this exchanger, the feed water is heated from 80°F to its saturation temperature of 338°F. This exchanger utilizes the coolest part of the coolant salt stream because it requires the least heat. The heat exchanged is approximately 4.73 million BTU/hr, and the corrected log mean temperature difference is 224°F. In order to calculate the area required for heat exchange, the overall heat transfer coefficient was determined. Unlike the primary exchanger, the value calculated from MSRE data could not be applied to this exchanger because the shell side fluid is not fuel salt and therefore the film coefficient will be different. *Fundamentals of Heat and Mass Transfer* provided Equations 13 and 14 to determine the outer film coefficient for a fluid flowing in a cross-flow configuration across cylindrical horizontal tubes (9.6 Empirical Correlations: External Free Convection Flows; 9.6.3 The Long Horizontal Cylinder, 2011). From these equations and a chosen outer tube diameter of 1.75 inches, the outer film coefficient was found to be 522.13 BTU/(hr*ft^2*°F). A system of equations was set up using Equations 6, 8-12, and the equations for inner and outer tube areas to solve for the number of tubes and the straight length of those tubes that would allow the inner film coefficient to be the same as that in the primary exchanger while simultaneously making Equation 6 true. The heat exchange area required was found from this system of equations to be 142 ft^2, which corresponded to 22 two-pass tubes on a 1 5/8 inch triangular pitch. This many tubes at this size require a 10 inch shell based on the charts provided from ChE 4404 (Starr, 2014). After adding a 10% safety factor to the area, the final straight length of these tubes was found to be 10.8 ft.

4.4.5 Floor Space Comparison to Current Boiler System

To compare the designed MSR steam generation system to the current system used at WPI and prove the impact of using an MSR, the floor space of each layout was compared. Using the shell diameters determined from the design calculations as a width, and tube lengths as length, the floor space needed for each MSR exchanger was calculated. It was found that the primary exchanger, evaporator, economizer, superheater A and superheater B would require 10, 7.33, 9.17, 10.66, 7.33 ft^2, respectively. This totals to 44.5 ft^2 of floor space required for the entire MSR exchanger system, not taking into account the space needed for accessing the equipment for maintenance.

The floor space taken up by the current boiler system at WPI was unknown, so an estimation was calculated using information from an industrial boiler manufacturer, Hoval. In Hoval's manual of industrial boiler options, the base length and width are listed for each type, along with other data. Hoval's smallest boiler, which has a capacity of 7.8 BTU/hr, has base dimensions of 3480 mm by 1700mm (11.42 ft by 5.6 ft) (Hoval, 2013). Thus, the floor space required for the boiler is 63.9 ft^2. A minimum of four of these boilers would be required to meet WPI's campus heating needs, meaning it would require about 256 ft^2 of floor space, over 5 times more floor space than the entire MSR system. . There are currently only three boilers in the WPI Power House, but this serves as a general understanding of the space requirement for each kind of steam generation system. The difference in the floor space requirements for each system is impactful for future analysis and implementation. Since the MSR system doesn't require as much space, the possibilities for installation location on campus are much greater than those of a boiler system.

CONCLUSION AND RECOMMENDATIONS

After determining WPI heating need and evaluating and designing a steam generation system, a molten salt reactor would be an attractive solution to WPI's steam generation issues. Using an MSR would be an economic, technological, and environmental advantage. This project was the first step in evaluating an MSR for steam generation and the possibility of a nuclear reactor of such a large scale on a university campus. There are several research and implementation steps ahead. Recommendations for future work can be broken into two categories: continued loop design and campus implementation. Research on continued loop design would focus on refining the MSR system designed in this project by looking at all aspects of the reactor and steam generation loop. Campus implementation would include research on economic and political aspects of building a new reactor, as well as the eventual installation and operation plans.

As mentioned before, this project was the first step in designing a steam generation loop for WPI, using an MSR as a heat source. Future research should focus on building upon the proposed design and designing all other aspects of the reactor and steam generation loop. Since the MSRE design would not meet WPI's heating needs, a new reactor would need to be designed for use at WPI. The required thermal output of the reactor and the fuel and coolant salt flow rates were determined in this project, but extensive research should be done on the core design itself and scaling up to over 12 MW from the 10 MW MSRE design. Furthermore, the MSRE concluded in the 1960s, less than 20 years after nuclear power research began. Over 50 years later, there are certainly technological improvements to be made on the core design. Future research should also focus on the design of the entire system: containment tanks, freeze valves, pumps, pipes, etc. A potentially unique aspect of an MSR design would be pump design. A study presented at the 12th annual International Conference on Optimization of Electrical and Electronic Equipment in 2010 investigated the possibility of pumps self-operating from the convective and electromagnetic nature of molten salts (Etay, Fireteanu, Fautrelle, & Roman, 2010). This would add another benefit to the MSR system by improving safety and reducing electricity costs.

In addition to the equipment design, there are possibilities for improvements in fuel technology and material of construction for equipment in the MSR system. An important aspect of bringing an MSR to campus would be determining most efficient and cost effective fuel compositions and materials of construction. The MSRE investigated multiple fuel types before it was shut down, each with varying compositions of beryllium fluoride, lithium fluoride, zirconium fluoride, thorium fluoride, and uranium fluoride (Haubenreich & Engel, 1970). This research should continue to determine the best fuel from his application. Research could also continue on materials for both the core and other equipment. Although Hastelloy N was used in the MSRE successfully, it is a very expensive alloy. There may be cheaper or more effective materials that could be used for the design on WPI campus.

Lastly, to aid research of continued loop design, it would be important to use a simulation software capable of simulating nuclear chemistry, high temperatures, and the unique properties of molten salts. Aspen Plus Simulation software was able to give a basic understanding on some of the heat transfer properties of steam in the steam generator. However, there were difficulties in simulating the molten salt heat transfer, and Aspen was unable to simulate the full connected MSR system. To best design the future system for WPI's campus, it would be important to use a more advanced simulation software to test designs.

Once the full system has been designed, WPI can begin the process of bringing the reactor to campus. This would also require extensive research. Before the reactor could actually be built on campus, research should focus on several aspects of implementation. First, once system materials and equipment have been designed, it will be important to complete a cost analysis of the project, including construction, installation and eventual labor costs. A cost analysis would also serve as a comparison to WPI's current steam generation system to determine how beneficial the MSR would be economically. Furthermore, there are extensive safety and licensing requirements for chemical plants, especially for nuclear reactors. Once the reactor is sized, research should look into where the system can be placed on campus, how it can be connected to the current system, and what licensing and regulations standards WPI will need to meet. Since actual implementation of the project is several years in the future, there is plenty of time for current Power House operators and staff to receive the proper training.

Overall, the MSR is a promising technology for steam generation a WPI. Though there are several future steps and research necessary before an actual reactor can be brought to campus, this project has proven that MSR technology is an important option to consider for improving WPI's steam generation. Most importantly, implementing a nuclear reactor for steam generation on a college campus would make a significant impact in the technology world. WPI has a long tradition of innovation, and striving to be at the forefront of technological advancements. Bringing an MSR to campus would continue this tradition.

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APPENDIX A: Heat transfer and energy calculations

A.1 Campus energy requirement

Steam characteristics

Saturated Steam

$P := 100$ psi

$T := 338$ °F

$H := 1190.22$ $\dfrac{BTU}{lb}$

Steam production rates during cold season

$w_{min} := 8000$ $\dfrac{lb}{hr}$

$w_{max} := 32000$ $\dfrac{lb}{hr}$

$w_{ave} := 25000$ $\dfrac{lb}{hr}$

Thermal energy requirements on campus

$Q_{min} := w_{min} \cdot H$

$Q_{min} = 9.522 \times 10^6$ $\dfrac{BTU}{hr}$

$Q_{ave} := w_{ave} \cdot H$

$Q_{ave} = 2.976 \times 10^7$ $\dfrac{BTU}{hr}$

$Q_{max} := w_{max} \cdot H$

$Q_{max} = 3.809 \times 10^7$ $\dfrac{BTU}{hr}$

A.2 MSRE steam production

*MSRE System Specifications as defined in MSRE Design and Operations Report
(Robertson, 1965)*

Fuel Characteristics

$$V_f := 1200 \qquad \frac{gal}{min}$$

$$\rho_f = 134 \qquad \frac{lb}{ft^3}$$

$$C_{pf} := 0.47 \qquad \frac{BTU}{lb \cdot \,^\circ F}$$

Coolant Salt Characteristics

$$V_c := 850 \qquad \frac{gal}{min}$$

$$\rho_c = 120 \qquad \frac{lb}{ft^3}$$

$$C_{pc} := 0.53 \qquad \frac{BTU}{lb \cdot \,^\circ F}$$

Reactor (r) Specifications

$$Q_{rMW} := 10 \qquad MW$$

$$T_{in.rf} = 1175 \qquad \,^\circ F$$

$$T_{out.rf} = 1225 \qquad \,^\circ F$$

Primary Heat Exchanger (px) Specifications

$$Q_{hkW} := 30 \qquad kW$$

Fuel on shell side

$$T_{in.pxf} = 1225 \qquad \,^\circ F$$

$$T_{out.pxf} := 1175 \qquad \,^\circ F$$

$$Q_{fMW} := 10 \qquad MW$$

Coolant on tube side

$$T_{in.pxc} := 1025 \qquad °F$$

$$T_{out.pxc} := 1100 \qquad °F$$

Steam Generator (sg) Specifications*

$$T_{in.sgc} := 1100 \qquad °F$$

$$T_{out.sgc} := 1025 \qquad °F$$

* In the original Molten Salt Reactor Experiment the coolant salt passed through a radiator where the heat was allowed to dissipate from the stream into air. To acheive steam generation, we are replacing the radiator with a steam generator but maintaining the same inlet and outlet conditions.

Steam Generation Specifications
Superheated Steam

$$T_s := 1000 \qquad °F$$

$$P_s := 100 \qquad psi$$

$$H_{s.1000} := 1531.75 \qquad \frac{BTU}{lb}$$

$$Q_{need} = 3.809 \cdot 10^7 \qquad \frac{BTU}{hr}$$

$$C_{psat.steam} := 0.59 \qquad \frac{BTU}{lb \cdot °F}$$

$$C_{psup.steam} := 0.52 \qquad \frac{BTU}{lb \cdot °F}$$

$$C_{psteam} := \frac{C_{psat.steam} + C_{psup.steam}}{2}$$

$$C_{psteam} = 0.555 \qquad \frac{BTU}{lb \cdot (°F)}$$

$$C_{pfeedwater} := 0.998 \qquad \frac{BTU}{lb \cdot (°F)}$$

$$\lambda_w := 881.04 \qquad \frac{BTU}{lb}$$

$$T_w := 80 \qquad °F$$

$$T_{sat} := 338 \qquad °F$$

Unit Conversions

$$Q_{BTU} := 3412142 \qquad \frac{\frac{BTU}{hr}}{MW}$$

$$V_{ft3\_hr} := 8.021 \qquad \frac{\frac{ft^3}{hr}}{\left(\frac{Gal}{min}\right)}$$

$$Q_r := Q_{rMW} Q_{BTU}$$

$$Q_r = 3.412 \times 10^7 \qquad \frac{BTU}{hr}$$

$$Q_f = Q_{fMW} Q_{BTU}$$

$$Q_f = 3.412 \times 10^7 \qquad \frac{BTU}{hr}$$

$$Q_{hMW} := \frac{Q_{hkW}}{1000}$$

$$Q_{hMW} = 0.03 \qquad MW$$

$$Q_h = Q_{hMW} Q_{BTU}$$

$$Q_h = 1.024 \times 10^5 \qquad \frac{BTU}{hr}$$

$$m_f := V_f \cdot V_{ft3.hr} \cdot \rho_f$$

$$m_f = 1.29 \times 10^6 \qquad \frac{ft^3}{hr}$$

$$m_c := V_c \cdot V_{ft3.hr} \cdot \rho_c$$

$$m_c = 8.181 \times 10^5 \qquad \frac{ft^3}{hr}$$

Heat Loss in Primary Heat Exchanger

$$Q_c = m_c \cdot C_{pc} \cdot \left(T_{out.pxc} - T_{in.pxc}\right)$$

$$Q_c = 3.252 \times 10^7 \qquad \frac{BTU}{hr}$$

$$Q_f = 3.412 \times 10^7 \qquad \frac{BTU}{hr}$$

$$Q_{loss} := \frac{\left(Q_f + Q_h\right) - Q_c}{Q_f + Q_h}$$

$$Q_{loss} = 0.0498 \qquad \frac{BTU}{hr}$$

Steam Generated

$$Q_c = 3.252 \times 10^7 \qquad \frac{BTU}{hr}$$

Assume same heat loss as in primary heat exchanger

$$Q_{loss} = 0.05$$

$$Q_w = Q_c \cdot \left(1 - Q_{loss}\right)$$

$$Q_w = 3.09 \times 10^7$$

Guess

$$m_w = 20000$$

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Given

$$Q_{econ} := m_w \cdot (C_{pfeedwater}) \cdot (T_{sat} - T_w)$$

$$Q_{evap} := m_w \cdot \lambda_w$$

$$Q_{super} := m_w \cdot (C_{psteam}) \cdot (T_s - T_{sat})$$

$$Q_w = Q_{econ} + Q_{evap} + Q_{super}$$

$$\text{Find}(Q_{econ}, Q_{evap}, Q_{super}, m_w) = \begin{pmatrix} 5.15 \times 10^6 \\ 1.762 \times 10^7 \\ 8.133 \times 10^6 \\ 2 \times 10^4 \end{pmatrix} \qquad \begin{pmatrix} \dfrac{BTU}{hr} \\ \dfrac{BTU}{hr} \\ \dfrac{BTU}{hr} \\ \dfrac{lb}{hr} \end{pmatrix}$$

$$m_w = 2 \times 10^4$$

$$Q_{steam.MSRE} := m_w \cdot H_{s} \cdot 1000$$

$$Q_{steam.MSRE} = 3.063 \times 10^7 \qquad \frac{BTU}{hr}$$

$$Q_{need} - Q_{steam.MSRE} = 7.455 \times 10^6 \qquad \frac{BTU}{hr}$$

MSRE can not meet current campus needs.

50

A.3 PWR steam production

Westinghouse 414 PWR System Design

Reactor

$Q_{r.MW.414} := 3819$ $\dfrac{BTU}{hr}$

$T_{in.c.r} := 557.5$ $°F$

$T_{out.c.r} := 618.5$ $°F$

$m_{c.r} := 138400000$ $\dfrac{lb}{hr}$

$C_{p.c} := 1.37$ $\dfrac{BTU}{lb·°F}$

Steam Generator

$T_{in.c.sg} := 621$ $°F$

$T_{out.c.sg} := 558$ $°F$

$T_{w.414} := 462$ $°F$

$T_{s.414} := 561$ $°F$

$m_{c.sg} := 35075000$ $\dfrac{lb}{hr}$

$m_{s.414} := 3813000$ $\dfrac{lb}{hr}$

$C_{pw414} := 1.13$ $\dfrac{BTU}{lb·°F}$

$\lambda_{1100} := 628.13$ $\dfrac{BTU}{lb}$

$C_{ps414} := 1.31$ $\dfrac{BTU}{lb·°F}$

$T_{sat.414} := 558$ $°F$

Unit Conversions

$$Q_{BTU} := 3412142 \qquad \frac{\frac{BTU}{hr}}{MW}$$

$$V_{ft3.hr} := 8.021 \qquad \frac{\frac{ft^3}{hr}}{\left(\frac{Gal}{min}\right)}$$

$$Q_{r.414} := Q_{r.MW.414} \cdot Q_{BTU}$$

$$Q_{r.414} = 1.303 \times 10^{10} \qquad \frac{BTU}{hr}$$

Westinghouse 414 heat losses
  Reactor

$$Q_{r.414} = 1.303 \times 10^{10} \qquad \frac{BTU}{hr}$$

$$Q_{cool.r} = m_{c.r} \cdot C_{p.c} \cdot \left(T_{out.c.r} - T_{in.c.r}\right)$$

$$Q_{cool.r} = 1.157 \times 10^{10} \qquad \frac{BTU}{hr}$$

$$Q_{loss.r} := \frac{Q_{r.414} - Q_{cool.r}}{Q_{r.414}}$$

$$Q_{loss.r} = 0.112 \qquad \frac{BTU}{hr}$$

Steam Generator

$$Q_{cool.sg} := m_{c.sg} \cdot C_{p.c} \cdot \left(T_{in.c.sg} - T_{out.c.sg}\right)$$

$$Q_{cool.sg} = 3.027 \times 10^{9} \qquad \frac{BTU}{hr}$$

$$Q_{steam.sg} := m_{s.414} \cdot \left[C_{pw414} \cdot \left(T_{sat.414} - T_{w.414}\right) + \lambda_{1100} + C_{ps414} \cdot \left(T_{s.414} - T_{sat.414}\right)\right]$$

$$Q_{steam.sg} = 2.824 \times 10^{9} \qquad \frac{BTU}{hr}$$

$$Q_{loss.sg} := \frac{Q_{cool.sg} - Q_{steam.sg}}{Q_{cool.sg}}$$

$$Q_{loss.sg} = 0.067 \qquad\qquad \frac{BTU}{hr}$$

Campus steam generation design

$$Q_{need} = 38087040 \qquad\qquad \frac{BTU}{hr}$$

$$T_s := 500 \qquad\qquad \text{°F}$$

$$P_s := 100 \qquad\qquad \text{psi}$$

$$H_s := 1277.37 \qquad\qquad \frac{BTU}{lb}$$

$$T_{feed} := 80 \qquad\qquad \text{°F}$$

$$C_{pfeed} := 0.998 \qquad\qquad \frac{BTU}{lb \cdot \text{°F}}$$

$$T_{sat} := 338 \qquad\qquad \text{°F}$$

$$C_{p338} := 0.59 \qquad\qquad \frac{BTU}{lb \cdot \text{°F}}$$

$$C_{p500} := 0.51 \qquad\qquad \frac{BTU}{lb \cdot \text{°F}}$$

$$C_{ps} := \frac{C_{p500} + C_{p338}}{2}$$

$$C_{ps} = 0.55 \qquad\qquad \frac{BTU}{lb \cdot \text{°F}}$$

$$\lambda_s := 881.04 \qquad\qquad \frac{BTU}{lb}$$

$$m_s := \frac{Q_{need}}{H_s}$$

$$m_s = 2.982 \times 10^4 \qquad\qquad \frac{lb}{hr}$$

$$Q_w = m_s \left[C_{pfeed}\left(T_{sat} - T_{feed}\right) + \lambda_s + C_{ps}\cdot\left(T_s - T_{sat}\right)\right]$$

$$Q_w = 3.66 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$Q_{c.sg} := \frac{Q_w}{1 - Q_{loss.sg}}$$

$$Q_{c.sg} = 3.924 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$m_c := \frac{Q_{c.sg}}{C_{p.c}\cdot\left(T_{in.c.sg} - T_{out.c.sg}\right)}$$

$$m_c = 4.547 \times 10^5 \qquad\qquad \frac{lb}{hr}$$

$$Q_{c.r} := m_c\cdot C_{p.c}\cdot\left(T_{out.c.r} - T_{in.c.r}\right)$$

$$Q_{c.r} = 3.8 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$Q_r := \frac{Q_{c.r}}{1 - Q_{loss.r}}$$

$$Q_r = 4.281 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$Q_{r.MW} := \frac{Q_r}{Q_{BTU}}$$

$$Q_{r.MW} = 12.546 \qquad\qquad MW$$

A.4 MSR Steam Production and Specific Power Calculations

MSR Steam Generation

MSR steam generation system design

$$Q_{BTU} := 3412142 \qquad \frac{\frac{BTU}{hr}}{MW}$$

Fuel loop

$$C_{pf} := 0.47 \qquad \frac{BTU}{lb \cdot °F}$$

$$T_{in.fr} := 1175 \qquad °F$$

$$T_{out.fr} := 1225 \qquad °F$$

Primary Heat Exchanger

$$Q_h := \frac{0.03}{Q_{BTU}} \qquad \frac{BTU}{hr}$$

$$Q_{loss} = 0.0498$$

Fuel on shell side

$$T_{in.f.px} := 1225 \qquad °F$$

$$T_{out.f.px} := 1175 \qquad °F$$

Coolant on tube side

$$T_{in.c.px} := 1025 \qquad °F$$

$$T_{out.c.px} := 1100 \qquad °F$$

Coolant loop

$$C_{pc} := 0.53 \qquad \frac{BTU}{lb \cdot °F}$$

Steam Generator

$$T_{in.c.sg} := 1100 \qquad °F$$

$$T_{out.c.sg} := 1025 \qquad °F$$

$$T_{in.w} := 80 \qquad °F$$

$$T_{out.s} := 1000 \qquad °F$$

$T_{sat} := 338$ °F

$Q_{loss.sg} := 0.05$

$C_{p.w} := 0.998$ $\dfrac{BTU}{lb \cdot °F}$

$C_{p.s} := 0.555$ $\dfrac{BTU}{lb \cdot °F}$

$P_s := 100$ psi

$\lambda_s := 881.04$ $\dfrac{BTU}{lb}$

$H_{s.1000} := 1531.75$ $\dfrac{BTU}{lb}$

$Q_{need} := 32000 \cdot 1190.22$

$$Q_{need} = 3.809 \times 10^7 \qquad \frac{BTU}{hr}$$

Steam required for campus heating

$$m_s = \frac{Q_{need}}{H_{s.1000}}$$

$$m_s = 2.487 \times 10^4 \qquad \frac{lb}{hr}$$

Reactor output required

$$Q_w = m_s \left[C_{p.w} \left(T_{sat} - T_{in.w} \right) + \lambda_s + C_{p.s} \cdot \left(T_{out.s} - T_{sat} \right) \right]$$

$$Q_w = 3.745 \times 10^7 \qquad \frac{BTU}{hr}$$

$$Q_c = \frac{Q_w}{1 - Q_{loss.sg}}$$

$$Q_c = 3.942 \times 10^7 \qquad \frac{BTU}{hr}$$

$$m_c := \frac{Q_c}{C_{pc} \cdot \left(T_{in.c.sg} - T_{out.c.sg}\right)}$$

$$m_c = 9.916 \times 10^5 \qquad\qquad \frac{lb}{hr}$$

$$Q_c = 3.942 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$Q_f = \frac{Q_c}{1 - Q_{loss}} - Q_h$$

$$Q_f = 4.148 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$Q_f := \frac{Q_f}{Q_{BTU}}$$

$$Q_f = 12.157 \qquad\qquad MW$$

$$\eta := \frac{Q_{need}}{Q_f}$$

$$\eta = 0.918$$

MSRE Specific Power Calculation

$v_f := 73$ ft^3 Volume of fuel present in primary circulation system (per Design and Operations Report)

$$mm := \frac{25.94(0.65) + 47.01(.291) + 167.21(0.05) + 314.02(0.009)}{1000} = 0.042 \quad \frac{kg}{mol}$$

molar mass of fuel

$\rho_f := 134$ $\dfrac{lb}{ft^3}$ density of fuel

$m_f := v_f \cdot \rho_f = 9782$ lb

$9782 lb = 4437 kg$

$m = 4437$ mass of fuel in kg

$\dfrac{m}{mm} = 106333$ mol

$U_{mol} := 0.009 \left(\dfrac{m}{mm} \right) = 956.993$ mol U

$m_U := U_{mol} \dfrac{238.03}{1000} = 227.793$ kg U in MSRE

$\dfrac{10 \cdot 1000}{227.793} = 43.9$ $\dfrac{kW}{kg}$ Specific power of MSRE fuel

APPENDIX B: Aspen Input Files

B.1 Campus Energy Need

;Input Summary created by Aspen Plus Rel. 28.0 at 21:43:08 Wed Dec 17, 2014

;Directory   C:\ProgramData\AspenTech\Aspen   Plus   V8.2   Filename C:\Users\anhardin\AppData\Local\Temp\14\~ap835b.txt

;

IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

     INVERSE-PRES='1/bar'

DEF-STREAMS CONVEN ALL

DATABANKS 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' / &

     'APV82 INORGANIC' / NOASPENPCD

PROP-SOURCES 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' &

     / 'APV82 INORGANIC'

COMPONENTS

    WATER H2O

SOLVE

    RUN-MODE MODE=SIM

FLOWSHEET

    BLOCK B1 IN=1 OUT=2

PROPERTIES ELECNRTL

PROP-DATA HOCETA-1

    IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

        INVERSE-PRES='1/bar'

    PROP-LIST HOCETA

    BPVAL WATER WATER 1.700000000

STREAM 1

    SUBSTREAM MIXED TEMP=80. <F> PRES=100. <psig> &

        MASS-FLOW=32000. <lb/hr>

    MOLE-FRAC WATER 1.

BLOCK B1 HEATER

    PARAM PRES=100. <psig> VFRAC=1.

EO-CONV-OPTI

STREAM-REPOR MOLEFLOW

B.2 MSRE Steam Production

;Input Summary created by Aspen Plus Rel. 28.0 at 09:28:25 Mon Dec 15, 2014

;Directory   R:\WINDOWS\system\MQP\FIREHEATER   Filename C:\Users\anhardin\AppData\Local\Temp\6\~ape0d9.txt

IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

    INVERSE-PRES='1/bar'

DEF-STREAMS CONVEN ALL

DATABANKS 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' / &

    'APV82 INORGANIC' / NOASPENPCD

PROP-SOURCES 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' &

    / 'APV82 INORGANIC'

COMPONENTS

    WATER H2O /

    LITHI-01 LIF /

    BERYL-01 BEF2 /

    URANI-01 UF4

SOLVE

    RUN-MODE MODE=SIM

FLOWSHEET

    BLOCK PRIMARY IN=3 1 OUT=4 2

    BLOCK STEAMGEN IN=5 OUT=6

    BLOCK HEATER IN=4 OUT=9

PROPERTIES ELECNRTL

PROP-DATA REVIEW-1

    IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

        INVERSE-PRES='1/bar'

    PROP-LIST DHVLB / PC / TC / VC / ZC

    PVAL LITHI-01 32.5 / 689 / 3223 / 4220 / .5

    PVAL BERYL-01 32.5 / 689 / 3223 / 4220 / .5

PROP-DATA HOCETA-1

    IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

        INVERSE-PRES='1/bar'

    PROP-LIST HOCETA

    BPVAL WATER WATER 1.700000000

STREAM 1

    SUBSTREAM MIXED TEMP=1025. <F> PRES=47. <psig> &

        VOLUME-FLOW=850. <gal/min>

    MOLE-FRAC WATER 0. / LITHI-01 0.66 / BERYL-01 0.34 / &

        URANI-01 0.

STREAM 3

    SUBSTREAM MIXED TEMP=1225. <F> PRES=35. <psig> &

        VOLUME-FLOW=1200. <gal/min>

MOLE-FRAC WATER 0. / LITHI-01 0.7 / BERYL-01 0.291 / &

    URANI-01 0.009

STREAM 5

  SUBSTREAM MIXED TEMP=80. <F> PRES=100. <psig> &

    MASS-FLOW=27000. <lb/hr>

  MOLE-FRAC WATER 1. / LITHI-01 0. / BERYL-01 0. / &

    URANI-01 0.

BLOCK HEATER HEATER

  PARAM PRES=55. <psig> DUTY=30. <kW>

BLOCK STEAMGEN HEATER

  PARAM PRES=100. <psig> DEGSUP=662. <F>

BLOCK PRIMARY HEATX

  PARAM T-COLD=1100. <F> MIN-TAPP=1. <F>

  FEEDS HOT=3 COLD=1

  OUTLETS-HOT 4

  OUTLETS-COLD 2

EO-CONV-OPTI

SENSITIVITY S-1

  DEFINE SGDUTY BLOCK-VAR BLOCK=STEAMGEN VARIABLE=NET-DUTY &

SENTENCE=RESULTS

TABULATE 1 "SGDUTY"

VARY STREAM-VAR STREAM=5 SUBSTREAM=MIXED VARIABLE=MASS-FLOW

RANGE LOWER="8000" UPPER="10000" NPOINT="10"

STREAM-REPOR MOLEFLOW

PROPERTY-REP NOPARAM-PLUS

B.3 PWR Steam Production

;Input Summary created by Aspen Plus Rel. 28.0 at 09:50:17 Mon Dec 15, 2014

;Directory   R:\WINDOWS\system\MQP\FIREHEATER   Filename
C:\Users\anhardin\AppData\Local\Temp\6\~ape6a5.txt

;

IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

INVERSE-PRES='1/bar'

DEF-STREAMS CONVEN ALL

DATABANKS 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' / &

'APV82 INORGANIC' / NOASPENPCD

PROP-SOURCES 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' &

/ 'APV82 INORGANIC'

COMPONENTS

  WATER H2O /

  LITHI-01 LIF /

  BERYL-01 BEF2 /

  URANI-01 UF4

SOLVE

  RUN-MODE MODE=SIM

FLOWSHEET

  BLOCK PRIMARY IN=3 1 OUT=4 2

  BLOCK STEAMGEN IN=5 OUT=6

  BLOCK HEATER IN=4 OUT=9

PROPERTIES ELECNRTL

PROP-DATA REVIEW-1

  IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &

    INVERSE-PRES='1/bar'

  PROP-LIST DHVLB / PC / TC / VC / ZC

  PVAL LITHI-01 32.5 / 689 / 3223 / 4220 / .5

  PVAL BERYL-01 32.5 / 689 / 3223 / 4220 / .5

PROP-DATA HOCETA-1

IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &
    INVERSE-PRES='1/bar'
  PROP-LIST HOCETA
  BPVAL WATER WATER 1.700000000

STREAM 1
  SUBSTREAM MIXED TEMP=1025. <F> PRES=47. <psig> &
    VOLUME-FLOW=850. <gal/min>
  MOLE-FRAC WATER 0. / LITHI-01 0.66 / BERYL-01 0.34 / &
    URANI-01 0.

STREAM 3
  SUBSTREAM MIXED TEMP=1225. <F> PRES=35. <psig> &
    VOLUME-FLOW=1200. <gal/min>
  MOLE-FRAC WATER 0. / LITHI-01 0.7 / BERYL-01 0.291 / &
    URANI-01 0.009

STREAM 5
  SUBSTREAM MIXED TEMP=80. <F> PRES=100. <psig> &
    MASS-FLOW=27000. <lb/hr>
  MOLE-FRAC WATER 1. / LITHI-01 0. / BERYL-01 0. / &
    URANI-01 0.

BLOCK HEATER HEATER
  PARAM PRES=55. <psig> DUTY=30. <kW>

BLOCK STEAMGEN HEATER

PARAM PRES=100. <psig> VFRAC=1.

BLOCK PRIMARY HEATX

PARAM T-COLD=1100. <F> MIN-TAPP=1. <F>

FEEDS HOT=3 COLD=1

OUTLETS-HOT 4

OUTLETS-COLD 2

EO-CONV-OPTI

SENSITIVITY S-1

DEFINE SGDUTY BLOCK-VAR BLOCK=STEAMGEN VARIABLE=NET-DUTY &

SENTENCE=RESULTS

TABULATE 1 "SGDUTY"

VARY STREAM-VAR STREAM=5 SUBSTREAM=MIXED VARIABLE=MASS-FLOW

RANGE LOWER="12000" UPPER="18000" NPOINT="10"

STREAM-REPOR MOLEFLOW

PROPERTY-REP NOPARAM-PLUS

B.4 MSR Steam Production

;Input Summary created by Aspen Plus Rel. 28.0 at 10:07:22 Mon Dec 15, 2014

;Directory   R:\WINDOWS\system\MQP\FIREHEATER   Filename
C:\Users\anhardin\AppData\Local\Temp\6\~ap884b.txt

;

IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &
    INVERSE-PRES='1/bar'

DEF-STREAMS CONVEN ALL

DATABANKS 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' / &
    'APV82 INORGANIC' / NOASPENPCD

PROP-SOURCES 'APV82 PURE28' / 'APV82 AQUEOUS' / 'APV82 SOLIDS' &
    / 'APV82 INORGANIC'

COMPONENTS
    WATER H2O /
    LITHI-01 LIF /
    BERYL-01 BEF2 /
    URANI-01 UF4

SOLVE
    RUN-MODE MODE=SIM

FLOWSHEET

BLOCK PRIMARY IN=3 1 OUT=4 2

BLOCK STEAMGEN IN=5 OUT=6

BLOCK HEATER IN=4 OUT=9

PROPERTIES ELECNRTL

PROP-DATA REVIEW-1
    IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &
        INVERSE-PRES='1/bar'
    PROP-LIST DHVLB / PC / TC / VC / ZC
    PVAL LITHI-01 32.5 / 689 / 3223 / 4220 / .5
    PVAL BERYL-01 32.5 / 689 / 3223 / 4220 / .5

PROP-DATA HOCETA-1
    IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar &
        INVERSE-PRES='1/bar'
    PROP-LIST HOCETA
    BPVAL WATER WATER 1.700000000

STREAM 1
    SUBSTREAM MIXED TEMP=1025. <F> PRES=47. <psig> &
        VOLUME-FLOW=850. <gal/min>
    MOLE-FRAC WATER 0. / LITHI-01 0.66 / BERYL-01 0.34 / &
        URANI-01 0.

STREAM 3

    SUBSTREAM MIXED TEMP=1225. <F> PRES=35. <psig> &

       VOLUME-FLOW=1200. <gal/min>

    MOLE-FRAC WATER 0. / LITHI-01 0.7 / BERYL-01 0.291 / &

       URANI-01 0.009

STREAM 5

    SUBSTREAM MIXED TEMP=80. <F> PRES=100. <psig> &

       MASS-FLOW=27000. <lb/hr>

    MOLE-FRAC WATER 1. / LITHI-01 0. / BERYL-01 0. / &

       URANI-01 0.

BLOCK HEATER HEATER

    PARAM PRES=55. <psig> DUTY=30. <kW>

BLOCK STEAMGEN HEATER

    PARAM PRES=100. <psig> DEGSUP=662. <F>

BLOCK PRIMARY HEATX

    PARAM T-COLD=1100. <F> MIN-TAPP=1. <F>

    FEEDS HOT=3 COLD=1

    OUTLETS-HOT 4

    OUTLETS-COLD 2

EO-CONV-OPTI

SENSITIVITY S-1

   DEFINE SGDUTY BLOCK-VAR BLOCK=STEAMGEN VARIABLE=DUTY &

     SENTENCE=PARAM

   TABULATE 1 "SGDUTY"

   VARY STREAM-VAR STREAM=5 SUBSTREAM=MIXED VARIABLE=MASS-FLOW

   RANGE LOWER="10000" UPPER="14000" NPOINT="10"

STREAM-REPOR MOLEFLOW

PROPERTY-REP NOPARAM-PLUS

APPENDIX C: Equipment design calculations

C.1 Primary Heat Exchanger

MSR Steam Generation Primary Heat Exchanger Design Characteristics

$vol_{c.MSRE} := 850$ $\dfrac{Gal}{min}$

$V_{ft3.hr} := 8.021$ $\dfrac{\frac{ft^3}{hr}}{\left(\frac{Gal}{min}\right)}$

$vol_c := vol_{c.MSRE} \cdot V_{ft3.hr} = 6.818 \times 10^3$ $\dfrac{ft^3}{hr}$

$m_c := 9.916 \cdot 10^5$ $\dfrac{lb}{hr}$

$T_{in.c} := 1025$ °F

$T_{out.c} := 1100$ °F

$Q_{fuel} := 4.148 \cdot 10^7$ $\dfrac{BTU}{hr}$

$T_{in.f} := 1225$ °F

$T_{out.f} := 1175$ °F

$C_{p.f} := 0.47$ $\dfrac{BTU}{lb \cdot °F}$

$C_{p.c} := 0.53$ $\dfrac{BTU}{lb \cdot °F}$

$\rho_c := 120$ $\dfrac{lb}{hr}$

$\Delta T_{lm} := \dfrac{\left[\left(T_{in.f} - T_{out.c}\right) - \left(T_{out.f} - T_{in.c}\right)\right]}{\ln\left(\dfrac{T_{in.f} - T_{out.c}}{T_{out.f} - T_{in.c}}\right)} \cdot 0.97 = 133.007$ °F

$k_c := 3.5$ $\dfrac{BTU}{hr \cdot ft^2 \cdot °F}$

$\mu_c := 24$ $\dfrac{lb}{hr \cdot ft}$

$$t_p := \frac{0.042}{12} = 3.5 \times 10^{-3} \qquad\qquad\qquad \text{ft}$$

MSRE Primary heat exchanger overall heat transfer coefficient

$$Q_r := 10 \qquad \text{MW}$$

$$Q_{BTU} := 3412142 \qquad\qquad \frac{\frac{BTU}{hr}}{MW}$$

$$Q_R := Q_r \cdot Q_{BTU} = 3.412 \times 10^7$$

$$N_{MSRE} := 159 \qquad\qquad \text{tubes}$$

$$D_{o.MSRE} := \frac{0.5}{12} = 0.042 \qquad\qquad \text{ft}$$

$$L := 6 \qquad\qquad \text{ft}$$

$$A_o := 2 N_{MSRE} \cdot \pi \cdot L \cdot D_{o.MSRE}$$

$$A_o = 249.757 \qquad\qquad \text{ft}^2$$

$$U := \frac{Q_R}{A_o \cdot \Delta T_{lm}} = 1.027 \times 10^3 \qquad\qquad \frac{BTU}{lb \cdot hr \cdot °F}$$

Steam generation primary exchanger design

$$Q_{fuel} = 4.148 \times 10^7 \qquad\qquad \frac{BTU}{hr}$$

$$U = 1.027 \times 10^3 \qquad\qquad \frac{BTU}{lb \cdot hr \cdot °F}$$

$$\Delta T_{lm} = 133.007 \qquad\qquad °F$$

$$A_p := \frac{Q_{fuel}}{U \cdot (\Delta T_{lm})} = 303.619 \qquad\qquad \text{ft}^2$$

$$d_o := \frac{1}{12} = 0.083 \qquad\qquad \text{ft}$$

Guess

$$L := 10 \qquad \text{ft}$$

$$N_{design} := 100 \qquad \text{tubes}$$

Given

$$A_p = \pi \cdot d_o \cdot 2 N_{design} \cdot L$$

$$Find(N_{design}) = 58$$

To get triangular pitch of 1.25", 2-Pass U-tube exchanger, the next closest shell would be 12" shell diameter, which can fit 66 tubes. Also, design heuristic recommends 10% area safety factor

$$N_{steam.loop} := 58 \qquad \text{tubes}$$

$$A := 1.1 \cdot A_p = 333.981$$

Given

$$A = \pi \cdot d_o \cdot 2 N_{steam.loop} \cdot L$$

$$Find(L) = 11 \qquad \text{ft}$$

hi for steam generation heat exchanger design

$$d_i := D_{o.MSRE} - t_p = 0.038$$

$$Pr_c := \frac{C_{p.c} \cdot \mu_c}{k_c} = 3.634$$

$$v_{MSRE} := \frac{vol_c}{\frac{\pi}{4} \cdot (D_{o.MSRE} - t_p)^2 \cdot N_{MSRE}}$$

$$v_{MSRE} = 3.748 \times 10^4$$

$$Re_c := \frac{\rho_c \cdot d_i \cdot v_{MSRE}}{\mu_c} = 7.152 \times 10^3$$

$$h_i := \frac{k_c}{d_i} \cdot (0.023) \cdot Re_c^{0.8} \cdot Pr_c^{0.4} = 4.284 \times 10^3$$

C.2 Steam Generation Exchangers

$m_w := 24865$ $\dfrac{\text{lb}}{\text{hr}}$

$C_{pc} := 0.53$ $\dfrac{\text{BTU}}{\text{lb} \cdot \text{°F}}$

$C_{pw.80} := 0.998$ $\dfrac{\text{BTU}}{\text{lb} \cdot \text{°F}}$

$C_{pw.338} := 1.04$ $\dfrac{\text{BTU}}{\text{lb} \cdot \text{°F}}$

$C_{pw.338s} := 0.6$ $\dfrac{\text{BTU}}{\text{lb} \cdot \text{°F}}$

$C_{pw.1000} := 0.5$ $\dfrac{\text{BTU}}{\text{lb} \cdot \text{°F}}$

$\lambda_w := 881.04$ $\dfrac{\text{BTU}}{\text{lb}}$

$T_{c1} := 1100$ °F

$T_{c4} := 1025$ °F

$T_{w1} := 80$ °F

$T_{w2} := 337$ °F

$T_{w3} := 338$ °F

$T_{w5} := 1000$ °F

$Q_{cw} := m_w \cdot \lambda_w = 21907060$ $\dfrac{\text{BTU}}{\text{hr}}$

$Q_{cc} := \dfrac{Q_{cw}}{0.95} = 2.306 \times 10^7$ $\dfrac{\text{BTU}}{\text{hr}}$

$Q_{dw} := m_w \cdot C_{pw.80} \cdot (T_{w2} - T_{w1}) = 6377524$ $\dfrac{\text{BTU}}{\text{hr}}$

$Q_{dc} := \dfrac{Q_{dw}}{0.95} = 6.713 \times 10^6$ $\dfrac{\text{BTU}}{\text{hr}}$

Guess

$$m_c := 9.916 \cdot 10^5 \qquad \frac{\text{lb}}{\text{hr}}$$

$$Q_{ac} := 10000 \qquad \frac{\text{BTU}}{\text{hr}}$$

$$Q_{aw} := 0.95 \cdot Q_{ac} \qquad \frac{\text{BTU}}{\text{hr}}$$

$$Q_{bw} := Q_{aw} \qquad \frac{\text{BTU}}{\text{hr}}$$

$$Q_{bc} := \frac{Q_{bw}}{0.95} \qquad \frac{\text{BTU}}{\text{hr}}$$

$$T_{c2} := 1070 \qquad \text{°F}$$

$$T_{c3} := 1040 \qquad \text{°F}$$

$$T_{w4} := 600 \qquad \text{°F}$$

Given

$$Q_{cc} = m_c \cdot C_{pc} \cdot \left(T_{c2} - T_{c3} \right)$$

$$Q_{dc} = m_c \cdot C_{pc} \cdot \left(T_{c3} - T_{c4} \right)$$

$$Q_{bw} = m_w \cdot C_{pw.338s} \cdot \left(T_{w4} - T_{w3} \right)$$

$$Q_{ac} = 0.5 m_c \cdot C_{pc} \cdot \left(T_{c1} - T_{c2} \right)$$

$$Q_{aw} = m_w \cdot C_{pw.1000} \cdot \left(T_{w5} - T_{w4} \right)$$

$$Q_{ac} = \frac{Q_{aw}}{0.95}$$

$$Q_{bc} = Q_{ac}$$

$$Q_{bw} = Q_{aw}$$

$$\text{Find}(m_c, T_{c2}, T_{c3}, T_{w4}, Q_{aw}, Q_{ac}, Q_{bw}, Q_{bc}) = \begin{pmatrix} 986775 \\ 1082 \\ 1038 \\ 639 \\ 4489263 \\ 4725540 \\ 4489263 \\ 4725540 \end{pmatrix}$$

$m_c := 986775$ $\dfrac{\text{lb}}{\text{hr}}$

$T_{c2} := 1082$ °F

$T_{c3} := 1038$ °F

$T_{w4} := 639$ °F

$Q_{aw} := 4489263$ $\dfrac{\text{BTU}}{\text{hr}}$

$Q_{ac} := 4725540$ $\dfrac{\text{BTU}}{\text{hr}}$

$Q_{bw} := Q_{aw}$ $\dfrac{\text{BTU}}{\text{hr}}$

$Q_{bc} := Q_{ac}$ $\dfrac{\text{BTU}}{\text{hr}}$

$k_c := 3.5$ $\dfrac{\text{BTU}}{\text{hr} \cdot \text{ft} \cdot °\text{F}}$

$\mu_c := 24$ $\dfrac{\text{lb}}{\text{ft} \cdot \text{hr}}$

$Pr_c := \dfrac{C_{pc} \cdot \mu_c}{k_c} = 3.634$

$\rho_c := 120$ $\dfrac{\text{lb}}{\text{ft}^3}$

Exchanger A (first superheater) Design

$$\Delta T_{lm.a} := \frac{\left(T_{c1} - T_{w4}\right) - \left(T_{c2} - T_{w3}\right)}{\ln\left(\dfrac{T_{c1} - T_{w4}}{T_{c2} - T_{w3}}\right)} \cdot 0.97 = 573.517$$

$Q_{ac} = 4725540$

$\dfrac{BTU}{hr}$

$UA_a := \dfrac{Q_{ac}}{\Delta T_{lm.a}} = 2.114 \times 10^4$

$\dfrac{BTU}{hr \cdot °F}$

$h_i := 4284$

$\dfrac{BTU}{hr \cdot ft^2 \cdot °F}$

$T_{s.a} := \dfrac{T_{w4} + T_{w3} + T_{c1} + T_{c2}}{4} = 789.75$

°F

$T_{bulk.a} := \dfrac{T_{w4} + T_{w3}}{2} = 489$

°F

$t_p := \dfrac{0.042}{12} = 3.5 \times 10^{-3}$

ft

$k_p := 12.7$

$\dfrac{BTU}{hr \cdot ft \cdot °F}$

$g_{ft.sec2} := 32.17$

$\dfrac{ft}{s^2}$

$G_{ft.hr2} := g_{ft.sec2} \cdot (3600)^2 = 4.169 \times 10^8$

$\dfrac{ft}{hr^2}$

Water properties at 489 F

$\rho_{w.489} := 0.207$

$\dfrac{lb}{ft^3}$

$C_{pw.489} := 0.513$

$\dfrac{BTU}{lb \cdot °F}$

$\beta_{w.489} := 0.00118$

$\dfrac{1}{°F}$

$$\mu_{w.489} := \left(1.23 \cdot 10^{-5}\right) \cdot 3600 = 0.044 \qquad \frac{lb}{ft \cdot hr}$$

$$\nu_{w.489} := \frac{\mu_{w.489}}{\rho_{w.489}} = 0.214 \qquad \frac{ft^2}{s}$$

$$k_{w.489} := 0.0233 \qquad \frac{BTU}{hr \cdot ft \cdot °F}$$

$$Pr_{w.489} := \frac{C_{pw.489} \cdot \mu_{w.489}}{k_{w.489}} = 0.975$$

$$\alpha_{w.489} := \frac{k_{w.489}}{\rho_{w.489} \cdot C_{pw.489}} = 0.219$$

$$d_{o.a} := \frac{0.75}{12} = 0.063 \qquad ft$$

$$d_{i.a} := d_{o.a} - t_p = 0.059 \qquad ft$$

$$Ra_{D.a} := \frac{G_{ft.hr2} \cdot \beta_{w.489} \cdot \left(T_{s.a} - T_{bulk.a}\right) \cdot d_{o.a}^3}{\nu_{w.489} \cdot \alpha_{w.489}}$$

$$Ra_{D.a} = 7.709 \times 10^5$$

$$h_{o.a} := \left[0.60 + \frac{0.387 \cdot Ra_{D.a}^{\frac{1}{6}}}{\left(1 + \frac{0.559}{Pr_{w.489}^{\frac{9}{16}}}\right)^{\frac{8}{27}}}\right]^2 \cdot \frac{k_{w.489}}{d_{o.a}} = 5.509 \qquad \frac{BTU}{hr \cdot ft^2 \cdot °F}$$

$$x_a := \frac{1}{UA_a} = 4.73 \times 10^{-5} \qquad \frac{hr \cdot °F}{BTU}$$

Guess

$N_a := 50$

$L_a := 10$

$Re_{c.a} := 10000$

$A_{i.a} := 250$

$A_{o.a} := 275$

Given

$$x_a = \frac{1}{h_i \cdot A_{i.a}} + \frac{t_p}{k_p \cdot A_{ave.a}} + \frac{1}{h_{o.a} \cdot A_{o.a}}$$

$$A_{i.a} = \pi \cdot d_{i.a} \cdot L_a \cdot 2N_a$$

$$A_{o.a} = \pi \cdot d_{o.a} \cdot L_a \cdot 2 \cdot N_a$$

$$A_{ave.a} := \frac{A_{i.a} + A_{o.a}}{2}$$

$$Re_{c.a} = \frac{\rho_c \cdot d_{i.a} \left(\dfrac{0.5m_c}{\dfrac{\pi}{4} \cdot \rho_c \cdot d_{i.a}^2 \cdot N_a} \right)}{\mu_c}$$

$$h_i = \frac{k_c}{d_{i.a}} \cdot 0.023 \cdot Re_{c.a}^{0.8} \cdot Pr_c^{0.4}$$

$$A_{i.a} > 0$$

$$A_{o.a} > 0$$

$$14 > L_a > 0$$

$$\text{Find}(A_{i.a}, A_{o.a}, L_a, N_a, Re_{c.a}) = \begin{pmatrix} 187 \\ 198 \\ 14 \\ 36 \\ 12329 \end{pmatrix}$$

$A_{i.a} := 187$ ft^2

$A_{o.a} := 198$ ft^2

$L_a := 14$ ft

$N_a := 36$ tubes

For a heat exchanger needing 36 0.75" U-tubes (2 passes), the best shell size choice would be 8" in diameter at a triangular pitch of 1". Actual area should be ~10% larger than area required (as calculated above). This heuristic will be used to determine the appropriate straight section length.

*Only the straight sections of tubing are considered because of the less efficient heat transfer in the U-bend section.

ft^2

$A_{o.actual.a} := 1.1 \cdot A_{o.a} = 217.8$

$L_a := \dfrac{A_{o.actual.a}}{\pi \cdot d_{o.a} \cdot N_a \cdot 2} = 15.4$ ft

Exchanger B (second superheater) Design

$$\Delta T_{lm.b} := \frac{(T_{c1} - T_{w5}) - (T_{c2} - T_{w4})}{\ln\left(\dfrac{T_{c1} - T_{w5}}{T_{c2} - T_{w4}}\right)} = 230$$ $°F$

$Q_{bc} = 4725540$ $\dfrac{BTU}{hr}$

$UA_b := \dfrac{Q_{bc}}{\Delta T_{lm.b}} = 2.051 \times 10^4$ $\dfrac{BTU}{hr \cdot °F}$

$h_i := 4284$ $\dfrac{BTU}{hr \cdot ft^2 \cdot °F}$

$$T_{s.b} := \frac{T_{w4} + T_{w5} + T_{c1} + T_{c2}}{4} = 955.25 \qquad \text{°F}$$

$$T_{bulk.b} := \frac{T_{w4} + T_{w5}}{2} = 820 \qquad \text{°F}$$

$$t_p := \frac{0.042}{12} = 3.5 \times 10^{-3} \qquad \text{ft}$$

$$k_p := 12.7 \qquad \frac{\text{BTU}}{\text{hr·ft·°F}}$$

$$g_{ft.sec2} := 32.17 \qquad \frac{\text{ft}}{\text{s}^2}$$

$$G_{ft.hr2} := g_{ft.sec2} \cdot (3600)^2 = 4.169 \times 10^8 \qquad \frac{\text{ft}}{\text{hr}^2}$$

Water properties at 820 F

$$\rho_{w.820} := 0.151 \qquad \frac{\text{lb}}{\text{ft}^3}$$

$$C_{pw.820} := 0.509 \qquad \frac{\text{BTU}}{\text{lb·°F}}$$

$$\beta_{w.820} := 0.000807 \qquad \frac{1}{\text{°F}}$$

$$\mu_{w.820} := \left(1.75 \cdot 10^{-5}\right) \cdot 3600 = 0.063 \qquad \frac{\text{lb}}{\text{ft·hr}}$$

$$\nu_{w.820} := \frac{\mu_{w.820}}{\rho_{w.820}} = 0.417 \qquad \frac{\text{ft}^2}{\text{s}}$$

$$k_{w.820} := 0.0346 \qquad \frac{\text{BTU}}{\text{hr·ft·°F}}$$

$$Pr_{w.820} := \frac{C_{pw.820} \cdot \mu_{w.820}}{k_{w.820}} = 0.927$$

$$\alpha_{w.820} := \frac{k_{w.820}}{\rho_{w.820} \cdot C_{pw.820}} = 0.45$$

$d_{o.b} := \dfrac{0.75}{12} = 0.063$ ft

$d_{i.b} := d_{o.b} - t_p = 0.059$ ft

$Ra_{D.b} := \dfrac{G_{ft.hr2} \cdot \beta_{w.820} \cdot \left(T_{s.b} - T_{bulk.b}\right) \cdot d_{o.b}{}^3}{\nu_{w.820} \cdot \alpha_{w.820}}$

$Ra_{D.b} = 5.937 \times 10^4$

$h_{o.b} := \left[0.60 + \dfrac{0.387 \cdot Ra_{D.b}{}^{\frac{1}{6}}}{\left(1 + \dfrac{0.559}{Pr_{w.820}{}^{\frac{9}{16}}}\right)^{\frac{8}{27}}}\right]^2 \cdot \dfrac{k_{w.820}}{d_{o.b}} = 4.064$ $\dfrac{BTU}{hr \cdot ft^2 \cdot {}^\circ F}$

$x_b := \dfrac{1}{UA_b} = 4.877 \times 10^{-5}$ $\dfrac{hr \cdot {}^\circ F}{BTU}$

Guess

$N_b := 100$

$L_b := 10$

$Re_{c.b} := 5000$

$A_{i.b} := 100$

$A_{o.b} := 125$

Given

$A_{i.b} = \pi \cdot d_{i.b} \cdot L_b \cdot 4 \cdot N_b$

$$A_{o.b} = \pi \cdot d_{o.b} \cdot L_b \cdot 4 \cdot N_b$$

$$A_{ave.b} := \frac{A_{i.b} + A_{o.b}}{2}$$

$$x_b = \frac{1}{h_i \cdot A_{i.b}} + \frac{t_p}{k_p \cdot A_{ave.b}} + \frac{1}{h_{o.b} \cdot A_{o.b}}$$

$$Re_{c.b} = \frac{\rho_c \cdot d_{i.b} \left(\dfrac{0.5 m_c}{\dfrac{\pi}{4} \cdot \rho_c \cdot d_{i.b}^{2} \cdot N_b} \right)}{\mu_c}$$

$$h_i = \frac{k_c}{d_{i.b}} \cdot 0.023 \cdot Re_{c.b}^{0.8} \cdot Pr_c^{0.4}$$

$$A_{i.b} > 0$$

$$A_{o.b} > 0$$

$$10 > L_b > 0$$

$$\text{Find}\left(A_{i.b}, A_{o.b}, L_b, N_b, Re_{c.b}\right) = \begin{pmatrix} 267 \\ 283 \\ 10 \\ 36 \\ 12329 \end{pmatrix}$$

$A_{i.b} := 267$ ft^2

$A_{o.b} := 283$ ft^2

$L_b := 10$ ft

$N_b := 36$ tubes

For the secondary superheater, the exchanger will contain four passes instead of two. For an exchanger to have 36 four pass 0.75" tubes, the shell diameter chosen should be 8" at a triangular pitch of 17/18. Actual area should be ~10% larger than area required (as calculated above). This heuristic will be used to determine the appropriate straight section length.

*Only the straight sections of tubing are considered because of the less efficient heat transfer in the U-bend section.

$$A_{o.actual.b} := 1.1 \cdot A_{o.b} = 311.3 \qquad \text{ft}^2$$

$$L_{b} := \frac{A_{o.actual.b}}{\pi \cdot d_{o.b} \cdot N_{b} \cdot 4} = 11 \qquad \text{ft}$$

Exchanger C (Evaporator) Sizing Calculations

$$\Delta T_{lm.c} := \frac{(T_{c2} - T_{w3}) - (T_{c3} - T_{w2})}{\ln\left(\frac{T_{c2} - T_{w3}}{T_{c3} - T_{w2}}\right)} = 722 \qquad \text{°F}$$

$$Q_{cc} = 23060063 \qquad \frac{\text{BTU}}{\text{hr}}$$

$$UA_{c} := \frac{Q_{cc}}{\Delta T_{lm.c}} = 3.193 \times 10^4 \qquad \frac{\text{BTU}}{\text{hr} \cdot \text{°F}}$$

$$h_{i} := 4284 \qquad \frac{\text{BTU}}{\text{hr} \cdot \text{ft}^2 \cdot \text{°F}}$$

$$h_{o.c} := 360 \qquad \frac{\text{BTU}}{\text{hr} \cdot \text{ft}^2 \cdot \text{°F}}$$

$$t_{p} := \frac{0.042}{12} = 3.5 \times 10^{-3} \qquad \text{ft}$$

$$k_{p} := 12.7 \qquad \frac{\text{BTU}}{\text{hr} \cdot \text{ft} \cdot \text{°F}}$$

$$g_{ft.sec2} := 32.17 \qquad \frac{\text{ft}}{\text{s}^2}$$

$$G_{ft.hr2} := g_{ft.sec2} \cdot (3600)^2 = 4.169 \times 10^8 \qquad \frac{\text{ft}}{\text{hr}^2}$$

$$x_{c} := \frac{1}{UA_{c}} = 3.132 \times 10^{-5} \qquad \frac{\text{hr} \cdot \text{°F}}{\text{BTU}}$$

$$d_{o.c} := \frac{0.75}{12} = 0.063 \qquad \text{ft}$$

$$d_{i.c} := d_{o.c} - t_{p} = 0.059 \qquad \text{ft}$$

Guess

$$N_c := 100$$

$$L_c := 10$$

$$Re_{c.c} := 5000$$

$$A_{i.c} := 100$$

$$A_{o.c} := 125$$

Given

$$A_{i.c} = \pi \cdot d_{i.c} \cdot L_c \cdot 2 \cdot N_c$$

$$A_{o.c} = \pi \cdot d_{o.c} \cdot L_c \cdot 2 \cdot N_c$$

$$A_{ave.c} := \frac{A_{i.c} + A_{o.c}}{2}$$

$$x_c = \frac{1}{h_i \cdot A_{i.c}} + \frac{t_p}{k_p \cdot A_{ave.c}} + \frac{1}{h_{o.c} \cdot A_{o.c}}$$

$$Re_{c.c} = \frac{\rho_c \cdot d_{i.c} \left(\dfrac{0.5 m_c}{\dfrac{\pi}{4} \cdot \rho_c \cdot d_{i.c}^2 \cdot N_c} \right)}{\mu_c}$$

$$h_i = \frac{k_c}{d_{i.c}} \cdot 0.023 \cdot Re_{c.c}^{0.8} \cdot Pr_c^{0.4}$$

$$A_{i.c} > 0$$

$$A_{o.c} > 0$$

$$16 > L_c > 10$$

$$\text{Find}\left(A_{i.c}, A_{o.c}, L_c, N_c, Re_{c.c}\right) = \begin{pmatrix} 133 \\ 141 \\ 10 \\ 36 \\ 12329 \end{pmatrix}$$

$A_{i.c} := 133$ ft^2

$A_{o.c} := 141$ ft^2

$L_c := 10$ ft

$N_c := 36$

The ideal shell size to hold 36 two pass U-tubes with diameter 0.75" and pitch of 1" would be an 8" shell.

$A_{o.actual.c} := 1.1 \cdot A_{o.c} = 155.1$ ft^2

$L_c := \dfrac{A_{o.actual.c}}{\pi \cdot d_{o.c} \cdot N_c \cdot 2} = 11$ ft

Exchanger D (economizer) Design

$$\Delta T_{lm.d} := \frac{\left(T_{c3} - T_{w1}\right) - \left(T_{c4} - T_{w2}\right)}{\ln\left(\dfrac{T_{c3} - T_{w1}}{T_{c4} - T_{w2}}\right)} \cdot 0.97 = 791.098 \quad °F$$

$Q_{dc} = 6713184$ $\dfrac{BTU}{hr}$

$UA_d := \dfrac{Q_{dc}}{\Delta T_{lm.d}} = 8.486 \times 10^3$ $\dfrac{BTU}{hr \cdot °F}$

$h_i := 4284$ $\dfrac{BTU}{hr \cdot ft^2 \cdot °F}$

$T_{s.d} := \dfrac{T_{w1} + T_{w2} + T_{c3} + T_{c4}}{4} = 620$ °F

$T_{bulk.d} := \dfrac{T_{w1} + T_{w2}}{2} = 209$ °F

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$$t_p := \frac{0.042}{12} = 3.5 \times 10^{-3}$$ 　　　　　ft

$$k_p := 12.7$$ 　　　　　$\dfrac{BTU}{hr \cdot ft \cdot °F}$

$$g_{ft.sec2} := 32.17$$ 　　　　　$\dfrac{ft}{s^2}$

$$G_{ft.hr2} := g_{ft.sec2} \cdot (3600)^2 = 4.169 \times 10^8$$ 　　　　　$\dfrac{ft}{hr^2}$

Water properties at 209 F

$$\rho_{w.209} := 59.9$$ 　　　　　$\dfrac{lb}{ft^3}$

$$C_{pw.209} := 1.01$$ 　　　　　$\dfrac{BTU}{lb \cdot °F}$

$$\beta_{w.209} := 0.000411$$ 　　　　　$\dfrac{1}{°F}$

$$\mu_{w.209} := 0.000193 \cdot 3600 = 0.695$$ 　　　　　$\dfrac{lb}{ft \cdot hr}$

$$\nu_{w.209} := \frac{\mu_{w.209}}{\rho_{w.209}} = 0.012$$ 　　　　　$\dfrac{ft^2}{s}$

$$k_{w.209} := 0.392$$ 　　　　　$\dfrac{BTU}{hr \cdot ft \cdot °F}$

$$Pr_{w.209} := \frac{C_{pw.209} \cdot \mu_{w.209}}{k_{w.209}} = 1.79$$

$$\alpha_{w.209} := \frac{k_{w.209}}{\rho_{w.209} \cdot C_{pw.209}} = 6.479 \times 10^{-3}$$

$$d_{o.d} := \frac{1.25}{12} = 0.104$$ 　　　　　ft

$$d_{i.d} := d_{o.d} - t_p = 0.101$$ 　　　　　ft

$$Ra_{D.d} := \frac{G_{ft.hr2} \cdot \beta_{w.209} \cdot \left(T_{s.d} - T_{bulk.d}\right) \cdot d_{o.d}^{3}}{\nu_{w.209} \cdot \alpha_{w.209}}$$

$$Ra_{D.d} = 1.06 \times 10^{9}$$

$$h_{o.d} := \left[0.60 + \frac{0.387 \cdot Ra_{D.d}^{\frac{1}{6}}}{\left(1 + \frac{0.559}{Pr_{w.209}^{\frac{9}{16}}}\right)^{\frac{8}{27}}} \right]^{2} \cdot \frac{k_{w.209}}{d_{o.d}} = 522.113 \qquad \frac{BTU}{hr \cdot ft^{2} \cdot {}^{\circ}F}$$

$$x_d := \frac{1}{UA_d} = 1.178 \times 10^{-4} \qquad \frac{hr \cdot {}^{\circ}F}{BTU}$$

Guess

$$N_d := 50$$

$$L_d := 10$$

$$Re_{c.d} := 10000$$

$$A_{i.d} := 250$$

$$A_{o.d} := 275$$

Given

$$A_{i.d} = \pi \cdot d_{i.d} \cdot L_d \cdot 2 \cdot N_d$$

$$A_{o.d} = \pi \cdot d_{o.d} \cdot L_d \cdot 2 \cdot N_d$$

$$A_{ave.d} := \frac{A_{i.d} + A_{o.d}}{2}$$

$$x_d = \frac{1}{h_i \cdot A_{i.d}} + \frac{t_p}{k_p \cdot A_{ave.d}} + \frac{1}{h_{o.d} \cdot A_{o.d}}$$

$$Re_{c.d} = \frac{\rho_c \cdot d_{i.d} \left(\dfrac{m_c}{\dfrac{\pi}{4} \cdot \rho_c \cdot d_{i.d}^2 \cdot N_d} \right)}{\mu_c}$$

$$h_i = \frac{k_c}{d_{i.d}} \cdot 0.023 \cdot Re_{c.d}^{0.8} \cdot Pr_c^{0.4}$$

$$A_{i.d} > 0$$

$$A_{o.d} > 0$$

$$16 > L_d > 10$$

$$Find(A_{i.d}, A_{o.d}, L_d, N_d, Re_{c.d}) = \begin{pmatrix} 137 \\ 142 \\ 10 \\ 22 \\ 24042 \end{pmatrix}$$

$A_{i.d} := 137$ ft^2

$A_{o.d} := 142$ ft^2

$L_d := 10$ ft

$N_d := 22$ tubes

For a heat exchanger with 22 1.25" U-tubes (2 passes), the best shell size choice would be 10" in diameter at a triangular pitch of 1 5/8". Actual area should be ~10% larger than area required (as calculated above). This heuristic will be used to determine the appropriate straight section length.

*Only the straight sections of tubing are considered because of the less efficient heat transfer in the U-bend section.

$$A_{o.actual.d} := 1.1 \cdot A_{o.d} = 156.2$$ ft^2

$$L_d := \frac{A_{o.actual.d}}{\pi \cdot d_{o.d} \cdot N_d \cdot 2} = 10.8$$ ft

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APPENDIX D: Heat exchanger shell diameter charts

From (Starr, 2014)

NUMBER OF TUBES IN SHELL

½" O.D. Tubes on ⅝" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	33	30	24	31	26	16	24	20	16
6"	55	48	48	42	40	36	38	36	28
8"	96	99	80	68	62	72	85	76	66
10"	159	150	140	151	138	124	131	128	116
12"	241	236	228	232	196	180	212	196	180
14"	297	280	268	253	242	224	268	254	236
16"	392	384	364	345	330	304	361	346	328
18"	514	498	476	448	432	408	475	458	436
20"	642	622	596	554	538	504	592	570	548
22"	788	776	736	692	672	636	728	716	638
24"	942	922	884	821	812	776	860	828	804
26"	1304	1248	1220	1148	1120	1064	1196	1188	1132
32"	1742	1696	1656	1550	1536	1464	1622	1600	1548
36"	2226	2184	2132	2025	1976	1940	2188	2054	2012

'1-P = 1 Pass, 2-P = 2 Pass, 4-P = 4 Pass.

EXTRAPOLATE TO LARGER DIAMETERS IF NEEDED

⅝" O.D. Tubes on 13/16" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	22	20	16	19	18	12	19	14	12
6"	37	23	28	31	26	24	31	26	16
8"	68	66	56	61	62	48	56	52	44
10"	110	106	96	104	98	84	96	90	76
12"	170	164	150	151	142	128	151	138	128
14"	212	196	138	178	172	156	187	184	160
16"	263	270	253	241	239	230	258	242	224
18"	364	348	332	315	298	292	336	326	304
20"	451	440	420	396	388	352	406	412	392
22"	562	551	525	490	434	456	526	502	480
24"	668	646	612	588	570	618	608	598	55
28"	922	902	858	812	808	761	860	836	80
32"	1230	1212	1172	1106	1092	1040	1152	1124	1088
36"	1590	1560	1516	1438	1430	1336	1496	1468	1424

'1-P = 1 Pass, 2-P = 2 Pass, 4-P = 4 Pass.

¾" O.D. Tubes on ⅞" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	22	18	16	19	14	12	14	14	12
6"	31	30	24	26	26	16	22	20	16
8"	61	52	48	55	48	44	51	48	40
10"	96	94	76	88	82	76	85	76	72
12"	151	138	132	130	124	112	130	120	112
14"	187	176	168	151	148	132	163	152	144
16"	241	232	224	206	196	184	216	214	196
18"	333	302	292	268	270	252	288	282	264
20"	396	384	352	336	334	312	358	350	340
22"	482	472	456	418	416	396	450	436	416
24"	568	554	536	506	492	472	526	505	484
28"	792	780	752	700	700	660	724	720	696
32"	1062	1030	1008	946	930	896	994	978	948
36"	1356	1346	1304	1234	1220	1180	1288	1252	1220

'1-P = 1 Pass, 2-P = 2 Pass, 4-P = 4 Pass.

¾" O.D. Tubes on 1" Square Pitch

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	21	16	16	13	12	12	12	12	12
6"	26	26	24	22	22	16	21	16	16
8"	49	52	52	45	44	44	45	38	32
10"	84	82	80	74	76	76	74	70	68
12"	128	124	120	109	112	112	109	112	112
14"	158	158	148	137	138	120	133	140	128
16"	213	208	208	177	176	164	188	183	174
18"	277	266	264	241	236	230	246	248	240
20"	344	332	336	293	384	284	316	308	304
22"	428	404	404	366	368	360	394	388	384
24"	502	476	488	436	432	432	456	448	445
28"	694	668	684	612	608	603	640	636	623
32"	922	900	908	828	812	812	862	848	846
36"	1174	1160	1164	1070	1066	1048	1122	1112	1100

'1-P = 1 Pass, 2-P = 2 Pass, 4-P = 4 Pass.

¾" O.D. Tubes on 15/16" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	19	14	12	14	14	8	10	10	4
6"	27	26	16	22	18	16	19	18	12
8"	55	48	40	42	40	36	42	40	32
10"	85	76	72	74	72	60	73	66	60
12"	126	118	112	109	106	96	109	106	92
14"	151	146	140	158	124	112	140	138	124
16"	206	196	180	174	168	156	187	184	168
18"	268	266	240	241	258	216	253	242	224
20"	340	330	320	288	282	264	320	294	280
22"	414	408	392	361	318	322	400	380	352
24"	486	484	456	438	420	408	454	436	416
28"	684	656	640	608	588	572	642	622	604
32"	910	902	868	824	808	772	860	842	812
36"	1175	1152	1120	1056	1044	1012	1112	1104	1068

'1-P = 1 Pass, 2-P = 2 Pass, 4-P = 4 Pass.

¾" O.D. Tubes on 1" Triangular Pitch H

Shell Size			Inside Floating Head Apex Horizontal		
			1-P	2-P	4-P
5"				4	
6"				16	
8"				34	
10"				61	
12"				102	
14"				124	
16"				178	
18"				232	
20"				294	
22"				368	
24"				424	
28"				618	
32"				850	
36"				1070	

'1-P = 1 Pass, 2-P = 2 Pass, 4-P = 4 Pass.

¾" O.D. Tubes on 1" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	14	14	12	10	10	8	10	10	4
6"	22	20	16	19	18	16	19	14	12
8"	42	44	36	39	36	32	37	32	28
10"	73	72	64	64	66	60	61	60	48
12"	109	86	96	96	94	84	96	94	80
14"	139	134	134	121	116	108	121	118	108
16"	187	184	168	151	146	140	163	164	148
18"	241	232	220	204	196	188	212	211	196
20"	296	280	280	258	242	242	268	274	260
22"	372	354	344	326	316	306	336	338	324
24"	434	429	404	380	372	364	396	398	376
28"	604	594	568	530	526	508	568	554	536
32"	808	804	772	724	696	688	756	714	716
36"	1035	1026	1000	946	922	904	980	978	944

*1-P = 1 Pass. 2-P = 2 Pass. 4-P = 4 Pass.

¾" O.D. Tubes on 1" Triangular Pitch H

Shell Size			Inside Sheet's Hd. Agns Horizontal		
			1-P	2-P	4-P
5"				6	
6"				16	
8"				32	
10"				56	
12"				86	
14"				118	
16"				156	
18"				208	
20"				256	
22"				330	
24"				372	
28"				554	
32"				732	
36"				940	

*1-P = 1 Pass. 2-P = 2 Pass. 4-P = 4 Pass.

⅝" O.D. Tubes on 1" Square Pitch

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	12	12	12	9	12	4	9	8	4
6"	21	16	16	16	16	12	16	16	12
8"	38	38	32	27	32	32	30	32	32
10"	61	56	52	57	56	52	56	52	52
12"	97	90	88	89	82	76	89	82	80
14"	117	114	112	97	94	88	104	104	96
16"	158	150	148	137	128	120	143	140	140
18"	206	208	188	177	176	164	188	184	180
20"	254	256	254	224	216	216	238	236	232
22"	316	316	308	274	276	268	304	292	284
24"	370	372	368	304	332	316	341	332	332
28"	522	524	500	464	456	448	484	472	468
32"	693	692	688	620	620	612	650	648	640
36"	894	892	880	816	812	804	810	828	824

*1-P = 1 Pass. 2-P = 2 Pass. 4-P = 4 Pass.

1" O.D. Tubes on 1¼" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	8	6	4	7	6	4	7	6	4
6"	53	14	12	18	16	8	16	10	8
8"	31	26	24	22	22	16	22	20	16
10"	42	44	36	38	40	36	38	36	38
12"	64	66	56	61	52	48	56	52	48
14"	86	82	72	70	68	64	74	72	68
16"	110	110	100	96	94	80	100	98	92
18"	151	146	136	130	124	116	130	132	120
20"	187	180	172	163	150	144	170	160	160
22"	230	228	212	202	192	180	212	200	196
24"	266	270	252	238	232	212	238	236	232
28"	380	368	352	336	334	308	346	346	324
32"	506	494	480	456	448	432	472	464	440
36"	646	642	624	596	582	572	618	610	584

*1-P = 1 Pass. 2-P = 2 Pass. 4-P = 4 Pass.

1" O.D. Tubes on 1¼" Square Pitch

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	9	6	4	6	4	4	6	6	4
6"	12	12	12	4	8	8	9	6	4
8"	22	24	16	21	16	16	21	16	16
10"	38	36	28	37	34	32	37	37	32
12"	61	56	52	48	52	52	49	52	32
14"	74	74	68	61	60	52	69	60	60
16"	97	94	88	89	82	84	89	88	84
18"	128	124	124	109	113	112	116	112	112
20"	158	160	156	130	136	132	150	138	148
22"	196	196	192	177	168	164	188	180	180
24"	234	232	224	213	208	208	216	208	208
28"	324	321	316	334	280	280	305	300	300
32"	440	436	432	384	392	392	410	400	392
36"	562	556	552	510	508	508	534	536	532

*1-P = 1 Pass. 2-P = 2 Pass. 4-P = 4 Pass.

1¼" O.D. Tubes on 1¼" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	7	4	4	5	4	4	4	4	4
6"	8	6	4	8	6	4	7	6	4
8"	19	18	12	15	14	12	14	14	12
10"	31	30	24	31	26	24	24	24	20
12"	43	44	40	30	40	36	30	40	32
14"	56	52	48	40	48	40	55	48	44
16"	76	76	68	61	66	60	68	68	60
18"	97	98	92	88	82	76	86		80
20"	126	118	112	108	106	100	115	116	104
22"	131	150	140	136	134	121	144	142	128
24"	186	184	172	162	152	141	170	164	156
28"	262	250	240	230	224	216	238	232	220
32"	341	356	336	308	295	288	324	316	301
36"	450	392	420	904	401	386	418	412	400

*1-P = 1 Pass. 2-P = 2 Pass. 4-P = 4 Pass.

3/4" O.D. Tubes on 15/16" Triangular Pitch V

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	7	4	4	4	4	4	4	4	4
6"	8	6	4	7	6	4	7	4	4
8"	14	14	12	11	14	12	13	14	12
10"	24	26	20	22	22	16	22	20	16
12"	38	40	36	31	30	28	33	30	28
14"	46	48	44	42	40	36	42	64	36
16"	64	66	60	53	52	48	64	52	48
18"	82	82	76	74	72	68	81	78	72
20"	108	106	100	92	86	88	96	94	92
22"	130	134	124	114	110	104	126	118	112
	155	150	144	148	134	128	144	142	160
	220	220	212	196	192	180	206	200	188
32"	292	290	280	268	262	252	276	274	268
36"	360	372	352	348	346	324	384	354	336

*1-P = 1 Pass.   2-P = 2 Pass.   4-P = 4 Pass.

3/4" O.D. Tubes on 1" Square Pitch

Shell Size	Fixed Tube Sheet			Outside Packed Floating Head			Inside Floating Head		
	1-P	2-P	4-P	1-P	2-P	4-P	1-P	2-P	4-P
5"	5	4	4	4	4	1	4	4	4
6"	6	6	4	6	4	4	6	6	4
8"	16	12	12	12	12	12	12	12	12
10"	22	24	24	22	16	16	21	16	16
12"	37	34	32	30	32	32	30	32	32
14"	45	44	41	38	36	32	40	36	32
16"	61	60	60	48	52	52	57	56	52
18"	78	78	76	70	68	68	71	74	68
20"	100	96	96	82	88	80	94	68	88
22"	128	130	120	104	112	112	116	112	112
24"	150	148	148	180	120	184	134	124	132
28"	204	208	208	184	180	176	192	188	188
32"	274	276	276	246	248	248	262	256	256
36"	355	350	348	324	316	316	340	332	332

*1-P = 1 Pass.   2-P = 2 Pass.   4-P = 4 Pass.