Final Report

Team 16: The Nuclear Family

Meredy Brichford
Christina Headley
Joel Smith
Thane Symens

Engineering 340
Senior Design Project
Executive Summary

The purpose of this report is to summarize the design developed by Team 16 for Calvin College’s Engineering Senior Design Project class. The team’s focus was a nuclear fission power plant using the thorium fuel cycle. The objective was to mitigate problems with current power production methods, including environmental implications, cost, human health and safety, efficiency, and fuel availability. Alternatives were evaluated by these criteria. Of the reactor alternatives compatible with the fuel cycle, the molten salt breeder reactor was selected. The design of the reactor system was scaled from research done by Oak Ridge National Laboratory, resulting in a 5000-ft$^3$ reactor costing $93 million annually for capital and operating costs. Because of the fluid nature of the fuel, a reprocessing system was also designed, resulting in a $3 million process. The power cycle was a supercritical CO$_2$ recompression Brayton cycle, which cost $140 million annually. Upon economic analysis, it was determined that the selling cost of electricity for such a plant would be 16 cents/kWh, which was not competitive on the current market. For further study, the use of a different fuel salt and a different power output should be investigated to increase the profitability of the plant.
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<tr>
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</tr>
<tr>
<td>ADSR</td>
<td>b</td>
<td>outer diameter</td>
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<tr>
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<td>c</td>
<td>speed of light ((3.0 \times 10^8 \text{ m/s})), specific cost</td>
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<td>N</td>
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<td>resonance escape probability</td>
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<td>P_{TNL}</td>
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<td>IEEE</td>
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<td>LFR</td>
<td>Lead-Cooled Fast Reactor</td>
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<td>NRC</td>
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<td>$T_{h,i}$</td>
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<td>Oak Ridge National Laboratory</td>
<td>$T_{h,o}$</td>
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<td>$\sigma_f$</td>
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<tr>
<td>$\sigma_t$</td>
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<tr>
<td>$\psi$</td>
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1. Introduction

This report is a detailed summary of the work done by Team 16 as part of Calvin College’s Engineering Senior Design Project. Team 16 set out to design a nuclear power plant using the thorium fuel cycle. This section details the progression of the project definition, the team members and advisors, and an overview of the Calvin engineering program.

1.1. Project Description

Throughout the course of the design process, the team focused on the problem, solution, and requirements defined at the outset of the project. The details of these definitions are included in their respective sections. The scope was continually adjusted to ensure feasibility and is also detailed below. The overall objective, which summarizes all of these aspects, is included at the end of this section.

1.1.1. Problem

As the world’s population grows and technological advancements necessitate more electricity, electrical power generation has become a worldwide issue. Current power generation technologies include fossil fuel combustion, harnessing of renewable energy, and nuclear fission in pressurized water reactors (PWRs). These methods present issues in terms of environmental implications, cost, human health and safety, efficiency, and fuel availability. The details of these issues are discussed below, in order of importance, and are summarized in Table 1.
Environmental Implications

Currently, the world is highly dependent on fossil fuels; see Figure 1.

Figure 1. Distribution of U.S. energy consumption by source, November 2014 [1].

The burning of fossil fuels results in greenhouse gas emissions, which are linked to climate change. Carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases are the primary offenders. Eighty-two percent of emissions are CO₂ [2]. Coal, petroleum, and natural gas combustion release 2.1, 1.8, and 1.2 pounds of CO₂ per kWh, respectively [3]. Impurities in the fuel also contribute to NOₓ and SOₓ production, which are air pollutants. In the United States, the electrical power generation sector produces the largest amount of greenhouse gases; see Figure 2. Therefore, the greatest potential decrease in greenhouse gas emission is rooted in the improvement of this area.
The Environmental Protection Agency’s (EPA) Clean Power Plan proposes a thirty percent decrease in carbon pollution from 2005 by 2030. This can be achieved through switching to cleaner power sources, such as renewables and nuclear. However, while renewables seem to present carbon-free or –neutral alternatives, some renewable sources have other negative impacts. At this point, it is important to note that all power plants require land and greenhouse gas emissions to construct. These factors will be treated as equal for all types of plants.

The production of photovoltaic panels involves the creation of silicon dust and uses solvents such as nitric and hydrofluoric acids and sodium hydroxide. The solvents are often recycled, reducing the waste produced. Water in geothermal reservoirs is contaminated with hydrogen sulfide, which oxidizes to sulfur dioxide in the present of air. As previously mentioned, SO$_x$s are air pollutants and may contribute to acid rain. Impurities in biofuels also result in NO$_x$ and SO$_x$ production when combusted. The scale of these emissions is often orders of magnitude smaller than those of fossil fuel plants.

Nuclear fission presents different challenges regarding environmental impact. Its waste products are not climate-altering but are radioactive and often long-lived. PWR fuel pellets are comprised of enriched uranium, which is 3% fissile. The rest is uranium which is not fissile and leaves the reactor as long-lived waste with half life of 4 billion years. This uranium accounts for 95% of the spent fuel; the remaining 5% consists of unused fissile uranium (7 billion years), plutonium (24 thousand years), and smaller elements, which are the results of the fission reactions. The disposal of waste is heavily regulated in the United States; this will be discussed in Section 2.1.3.
Cost

The per-kWh cost of the major current sources of electrical power are shown in Figure 3 and Figure 4. As of 2013, coal, gas, and nuclear power nearly converged at the lowest cost. Renewables, given low thermal efficiencies, have are less cost effective as well; see Section 1.1.1.

Figure 3. Cost of electricity from fossil fuel combustion and nuclear fission in PWRs [5].

Figure 4. Cost of electricity from renewable energy sources [6].
While the overall cost of these sources are comparable, the capital cost of PWRs is high due to enhanced materials and safety system requirements; see Figure 5. The continually rising capital cost coupled with the stigma of nuclear power may deter energy companies from investing in the construction of new nuclear plants. The PWRs constructed in and after the 1970s were designed for a lifetime of 30 to 40 years. However, in the interest of avoiding decommissioning and reconstruction, many reactors will be maintained for 40 to 60 years [7]. While postponing cost issues, this practice may present safety issues, as older reactors are more prone to failure.

![Figure 5. Construction costs for U.S. nuclear power plants completed 1960-2000 [8].](image)

**Human Health and Safety**

Personal health and safety is of particular concern for people living near power production facilities. These concerns are of smaller scale than environmental health and safety issues. However, they must also be considered. Long-term health concerns include exposure to particulate matter and incident radiation and safety concerns are specified as plant disasters.

Toxic species such as nickel sulfides, chromium, and arsenic are present in ash produced from the combustion of fossil fuels [9]. Being airborne, these substances cannot be contained within the power plant. They are carried downwind before settling to the ground and affecting nearby humans. Also,
surprisingly, coal power plants release three times more ionizing radiation to the surrounding environment than do nuclear power plants [10]. This is because of the radon mined with the coal. Living within fifty miles of a nuclear plant results in exposure to only 0.0009 mrem of radiation per year [11]. For context, the average human is exposed to 310 mrem of natural radiation annually (i.e. soil, space, other humans), an instantaneous dose of 50,000 mrem is correlated to increased cancer risk, and between 80,000 and 1,600,000 mrem were released in Chernobyl, causing acute radiation sickness and 28 radiation-linked deaths [12].

In addition to health effects, the public is rightly concerned about explosions. While fossil fuel plant and mining disasters are more frequent, nuclear disasters get more publicity. Chernobyl, Three Mile Island, and Fukushima are household names. Because of the lack of transparency, the perceived safety of nuclear plants is often less than the actual safety. Still, in order to achieve higher thermal efficiency, LWRs operate at high temperatures, which require high pressures. Special materials and safety systems are in place to account for this risk, but it is not as inherently safe as a low-pressure system.

Beyond nuclear plant explosions, nuclear reactions are also associated with nuclear weapons. The United States’s nuclear power industry turned to uranium because bombs could be made from the spent fuel. Ever since, it has been difficult to shake the association between the controlled reactors and the uncontrolled weapons. Even though the use of technology is drastically different in these two applications, spent fuel can still be used to create bombs. The prevention of the spread of nuclear weapons is known as non-proliferation and is codified by the Non-Proliferation Treaty, which has been signed by 191 countries to date.

**Efficiency**

Thermal efficiency is dependent on the highest and lowest temperatures in a system. Steam power cycles are currently used in most fossil fuel and nuclear plants. The greatest efficiency achieved in current steam cycles is 45% [13]. This is limited by temperature and pressure constraints. Steam cycle temperatures typically reach 600 °C and drop to 30 °C, but require pressures near 280 bar at the higher temperature [14]. Increasing temperature would increase thermal efficiency but would require even higher pressures.

As of 2014, the average capacity factor, or fraction of a plant’s actual output over its available output, of American coal plants was 60.9% [15]. This means that the plant is operating at less than its designed output, which may be caused by plant down time or overproduction for the grid. Current renewable technologies also offer lower capacity factors; solar and wind power, the primary constituents of renewable sources, both depend on weather conditions. Because of their variable outputs, providing
constant base load power would require vast overproduction at most times. In Arizona, the average capacity factor for solar power is 22%, but in less-sunny places, it drops below 10% [16]. Wind turbines offer slightly better capacity factors, with optimistic speculations approaching 40% as offshore sites become more prevalent [17]. It is predicted that, in combination with geothermal energy and hydropower, and clean-burning materials, renewables may be capable of supplying eighty percent of the U.S.’s power by 2050 [18].

Nuclear technology today has among the highest capacity factors with some plants pushing 98%, even for high power ratings [19]. While they consistently generate base load power, their fuel conversion low. Only 0.7% of natural uranium can be burned in current reactors. Uranium is enriched to 3% fuel, but 30% of the fuel is lost in that process. Once in the reactor, 25% of the fuel goes unused and is discarded with the waste.

**Fuel Availability**

Although it may seem like natural gas is booming, fossil fuel reserves are not unlimited. In 1956, Marion King Hubbert developed his peak theory, predicting that the production of power from any source fits a Gaussian curve. While his prediction that U.S. oil production would peak in 1971 was accurate (see Figure 6), his world oil curve predicted a steep decline near 2000, which has yet to be realized. More recent studies by The Association for the Study of Peak Oil and Gas predict a peak for both between 2010 and 2040 [20]. Peak coal predictions range from 1 to 200 years in the future [21]. Even nuclear energy is not failsafe, as uranium reserves are expected to peak by 2100 [22].

![Figure 6. Hubbert’s peak oil predictions for the U.S. vs. historical data [23].](image)
Also, while the name “renewables” suggests that the resources will never dwindle, the materials used in renewable energy-harnessing devices are not unlimited. One of the biggest obstacles to implementing large-scale solar power is the limited reserves of indium and neodymium, which are used for solar panel and wind turbine gearbox construction, respectively [24]. While these shortages may not seem like immediate issues, it is important to prepare for the future.

**Summary**

Table 1. Problems with current methods of power production.

<table>
<thead>
<tr>
<th>Environmental Implications</th>
<th>Fossil Fuels</th>
<th>Renewables</th>
<th>PWRs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental Implications</strong></td>
<td>Production of greenhouse gases and air pollutants</td>
<td>Use of hazardous chemicals</td>
<td>Production of radioactive waste</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>---</td>
<td>---</td>
<td>High capital cost of special materials and safety features</td>
</tr>
<tr>
<td><strong>Human Health and Safety</strong></td>
<td>Release of radiation (Rn) from coal plants</td>
<td>---</td>
<td>High pressures of operation</td>
</tr>
<tr>
<td></td>
<td>High particulate production</td>
<td></td>
<td>Nonproliferation issues</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Inefficient thermal cycle</td>
<td>Low efficiency (20%)</td>
<td>Low-temperature heat production (300 °C)</td>
</tr>
<tr>
<td></td>
<td>Low specific energy of fuel</td>
<td></td>
<td>Low neutron economy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low fuel burnup</td>
</tr>
<tr>
<td><strong>Long-Term Fuel Availability</strong></td>
<td>Predicted fuel shortages</td>
<td>Intermittent fuel supply</td>
<td>Requirement of U-235 enrichment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inability to provide base load power</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not enough materials to make renewables on scale necessary</td>
<td></td>
</tr>
</tbody>
</table>
1.1.2. Solution

All of the methods of power production mentioned in Table 1 have issues. None are perfect, nor will be any other alternative. In the transition to cleaner, safer, and cheaper energy, the diversification of fuel sources is desired; depending on too few resources is risky. The solution should be an “energy mix,” including nuclear power as well as other sources.

In addition to technical analysis, the team must emphasize the safety and environmental benefits of their design. This will promote caring, stewardship, and trust in the team’s design and the power industry as a whole. Through the transparency of the design, it is hoped that the public will understand the benefits of including nuclear in the energy mix, as well as recognizing that nuclear reactors are a safe and feasible option for clean energy production.

In the interest of mitigating the aforementioned issues, solutions to each problem were developed; see Table 2. These solutions include both the initial project objectives (nuclear fission reactor, thorium fuel cycle) as well as other design components compatible with those objectives.

<table>
<thead>
<tr>
<th>Environmental Implications</th>
<th>Thorium fuel cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Consider small modular reactors</td>
</tr>
</tbody>
</table>
| **Human Health and Safety**| Consider Generation IV reactors  
  Consider coolants other than water (low pressure) |
| **Efficiency**             | Thorium fuel cycle  
  Consider other power cycle working fluids |
| **Long-Term Fuel Availability** | Thorium fuel cycle |

The considerations listed in Table 2 will reappear as alternatives in the design decision.
1.1.3. Requirements

Project requirements give structure to the completion of the design. Within the design, interface, functional, performance, and environmental requirements must be met. As this project was completed as part of Calvin College’s Engineering Senior Design class, scholastic requirements are also included in this section.

Design Requirements

Essentially, the requirements of the design are to address the issues laid out in the problem statement. To further structure this requirement, a hypothetical customer was created. The goal of the project was to create a design which would satisfy the intended customer’s requirements. For this project, the final product was a nuclear power plant design, so the direct customers were electric power companies. The company operating the team’s design would sell electricity to consumers, making those consumers the team’s indirect customers.

The team also considered catering to other indirect customers: spent fuel processors and excess heat users. The most valuable products from Th-232 reactions are plutonium (Pu)-238 and molybdenum (Mo)-99. Pu-238 is used for deep space exploration [25] and Mo-99 is a parent isotope of technetium (Tc)-99, which is used in nuclear medicine [26]. Excess heat may be used for desalination or hydrogen generation. While these potential customers were recognized, they were not considered actively during the design process, as their inclusion broadened the scope of the project.

In keeping with the direct customer alone, the requirements were set such that the designed power plant would be environmentally friendly, cost effective, safe, efficient, and supplied by an abundant fuel source. The qualitative aspects of the design are discussed in the following sections.

Interface Requirements

Interface should be taken into consideration when taking into account workplace simplicity. However, the aim of this project is to meet consumer energy needs rather than to design a tangible product for a consumer base. Therefore, the interface requirements should meet the operating standards of a typical reactor power plant. The design should be in such a way that employees can be trained in an appropriate amount of time and that outside sources and companies can be integrated into the design and working processes.
**Functional Requirements**

The design should be such that the power output of the reactor varies depending on the needs of the local grid system dependent on it. A modular design will be the focus of the reactor design as it allows for such a variance as it produces smaller amounts of energy than a standard size reactor, but can also be linked in series with additionally added modular reactor systems for additional power if need be. The functionality of the reactor should be such that the working conditions are safe for employees and simplistic while meeting standards of reactor safety regulations.

**Performance Requirements**

Due to the modular focus of the reactor, the reactor power plant will be designed in such a way that the amount of power output is approximately 200 MWe. A typical reactor power plant outputs significantly more energy, around several thousand megawatts of power, which is impractical for certain grid systems, such as in rural or geographically isolated areas with small populations. Using a modular design can meet the needs of any grid system without overpowered the grid system and lowering the economic impact. Furthermore, modular designs can be built to operate underground, making the design significantly less impactful on aesthetics of the area of implementation. Being respectful of the area that the reactor is implemented is one of the goal design norms of this project, that being stewardship.

Additionally, the reactor is expected to use the thorium fuel cycle. For this reason, it is expected that the reactor will produce the desired amount of energy meanwhile lessening waste production, as mentioned in the environmental requirements section.

**Environmental Requirements**

The main concerns of reactor safety pertain to the handling and storage of useful and useless waste. With uranium-235, approximately 90% of waste is useless and must be stored for about 10,000 years, give or take, before it is considered stable. In contrast, thorium produces several different types of useful waste, such as Pu-238 and Mo-99, as well as several others. Overall, thorium waste production is 95% useful and 5% useless. This is not only beneficial for production of useful byproducts, but also for the significant decrease in waste. Moreover, thorium waste does not need to be stored as long waste from uranium.

**Class Requirements**

As part of the Engineering Senior Design Project class at Calvin College, teams of students select a design project to study for two semesters. The final product of the first semester was the Project Proposal and Feasibility Study, in which the team defined a realistic scope for a project which would be designed
in the subsequent semester. This report is the final project for the second semester. Throughout both terms, status reports were given to the team’s advisors, presentations were given to the entire class, posters were made to advertise to prospective students, and a team website was cultivated to continually report on the status of the project. The final presentation at Calvin was an open house poster session followed by dinner and formal presentations to the public. While this was the end for many teams, Team 16 will be presenting at the Thorium Energy Alliance Conference (TEAC) in June of 2015.

1.1.4. Scope

The scope of this project was purely design-based, as legal restrictions prevent the construction and operation of a nuclear power plant or even a prototype. The final deliverables were theoretical models. Research on the particular reactor was done by other institutes and included computer models for optimization and laboratory reactors. To perform bench studies on radioactive materials or to develop code for modeling calculations was beyond the scope of this project. Therefore, reactor systems designs were scaled from other universities’ research. As none of the advanced reactors are currently used in industry, the data available on their physical operation is limited to laboratory applications. The power cycle design was taken from other institutions’ research as well but was optimized by the team. However, the vessels of the The details of the control systems necessary to operate and maintain these systems were considered outside of the scope of this project and, while important to the design, were not addressed in this report. The team’s final design includes speculation on industrial implementation and operation, but this was not able to be compared to industrial data.

1.1.5. Objective

The team’s proposal was to design the reactor, containment, and safety systems for a small modular MSR plant. The heat transfer fluid for the power cycle was to be chosen and the components and stream specifications optimized. The thorium fuel cycle was to be studied with the intent of determining the fuel required to produce 200 MWe of power. The plant location was to be determined and waste containment and disposal to be considered. The methods of excess heat use were to be evaluated. Finally, a cost analysis of all aspects of the plant was to be performed to determine the ultimate feasibility of the hypothetical implementation of the plant.

Upon revision of the scope (see Section 1.1.4), the plant location, excess heat usage analysis, and detailed plan for waste containment and disposal were eliminated from the objective. The overall objective was to evaluate alternatives for the reactor and power cycle systems, with the end goal of producing an economic analysis of the final design.
1.2. Personnel

The Nuclear Family consists of four Calvin College engineering students, two in the chemical concentration and two in the mechanical concentrations. They are guided by a faculty advisor and industrial consultant. Other contributors are acknowledged at the end of this report.

1.2.1. Team Members

![Nuclear Family portrait](image)

Figure 7. Nuclear Family portrait.

**Meredy Brichford**

Meredy Brichford, a Farmington Hills native, is a senior at Calvin College studying chemical engineering and flute performance. She has held engineering internships at MacDermid (New Hudson, MI) and Vertellus Specialties (Zeeland, MI). At Calvin, she plays principal flute in the Wind Ensemble and Orchestra and is a member of the Renewable Energy Organization. She will be pursuing a Ph.D. in nuclear engineering at the University of Wisconsin after graduation. When she is not doing homework or practicing, Meredy enjoys reading, watching *Jeopardy!* and riding her unicycle.
Christina Headley

Christina Headley grew up in Chesterland, Ohio where she graduated from Cornerstone Christian Academy. She is a senior at Calvin College studying chemical engineering and chemistry. While at Calvin, she participated in the student martial arts club. During the summers of 2013 and 2014, she interned at Sherwin-Williams (Cleveland, OH) and Lubrizol (Wickliffe, OH), respectively. After graduating from Calvin, Christina would like to work in the food processing industry.

Joel Smith

Joel Smith is from Port Huron, MI and will graduate with a degree in engineering in the mechanical concentration as well as with a degree in French and a minor in Physics. He enjoys playing the trumpet with the Salvation Army as well as with the Calvin College Wind Ensemble and Orchestra, time permitting. He held an internship position at Dunn Paper (Port Huron, MI) during the summers of 2012 and 2013. After finishing his engineering degree, he plans on participating in a study abroad program through Calvin College in Grenoble, France, where he will finish his bachelor’s degree for French. Then after, Joel intends to pursue a master’s degree in the renewable energy field.

Thane Symens

Thane Symens hails from Maple Grove, MN and will be graduating from Calvin College in May of 2015 with Bachelor of Science in Engineering with a mechanical concentration and a minor in mathematics. Thane enjoys camping and being outdoors in general. He has a passion for anything that flies and is especially excited by space. After graduation, Thane will be seeking full-time employment and ultimately hopes to enter the aerospace industry.

1.2.2. Advisors

Team 16 was advised both by Calvin faculty and by industrial experts. Professor Jeremy VanAntwerp, the team’s faculty advisor, provided guidance on the progress of the project. Sigval Berg, the team’s industrial consultant, provided technical information and support on the project details.

Jeremy VanAntwerp

Jeremy VanAntwerp is a chemical engineering professor at Calvin College and is Team 16’s faculty advisor. He received his undergraduate degree in Chemical Engineering from Michigan State University and his doctorate in Chemical Engineering from the University of Illinois Urbana-Champaign. Currently, he is an assistant editor for IEEE Control Systems Magazine.
Sigval Berg

Sigval Berg is the industrial consultant for Team 16. He attended the United States Naval Academy and has experience in the U.S. Navy Nuclear Program, World Association of Nuclear Operators, Institute of Nuclear Power Operators, and Severn Leadership Group. In addition, he has taught informational and certification classes on the basics and operation of boiling water reactors.

1.3. Calvin College Engineering Department

The Calvin College Engineering Program is accredited by the Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology (ABET). Students who complete the program graduate with a Bachelor of Science in Engineering with concentrations in chemical, civil and environmental, electrical and computer, or mechanical engineering. Beyond achieving mastery of technical curriculum, “the engineering program equips students to glorify God by meeting the needs of the world with responsible and caring engineering” [27]. The engineering senior design project course sequence, Engineering 339/340, spans two semesters. It encompasses many aspects of Christian engineering education: extensive research on a technical subject, application of design procedure, collaboration with a team of student engineers and professional leaders, presentation of a final project to the public, and Christian service through designs and interactions.
2. Background

The background section details the research done by the team. Background knowledge in both nuclear reactor and power cycle systems was required for further design work.

2.1. Nuclear Reactor Theory

The design of nuclear reactors includes the reaction physics and thermodynamics, which occur within the reactor core. The vessel specifications, including material of construction, pressure and temperature rating, and geometry must also be considered for the reactor design. However, the design is not limited to the reactor core; it requires safety considerations, shielding, waste containment, and cooling systems. These components are required for the safe operation of a nuclear reactor.

2.1.1. Nuclear Physics

Nuclear physics is the basis on which nuclear reaction technology is built. This section reviews the notation and basic principles of radiation science, nuclear fission reactions, and reactor physics.

Notation

The composition of an atom’s nucleus is notated $^A_Z^S$, where $A$ is the mass number, $Z$ is the atomic number, and $S$ is the chemical symbol. Each of these identifiers can be found on the periodic table of elements; see Figure 8. A list of chemical symbols is given in Appendix A: Index of chemical symbols. $A$ is the total number of nucleons (protons and neutrons) in the nucleus. $Z$ is the total number of protons in the nucleus. $S$ corresponds to the $Z$, as each $Z$ is unique to a single element. Each element, however, can have multiple $A$s. These species are called isotopes. Isotopes of an element are identical except for having a different number of neutrons, $N$. From the above nomenclature, $N$ can be calculated:

$$N = A - Z \quad (1)$$

As $Z$ and $S$ are synonymous, a shorthand notation is often used to avoid redundancy: the chemical symbol followed by its mass number alone. For example, $^{235}_{92}U$ is equivalent to U-235 and $^{232}_{90}Th$ is equivalent to Th-232.
Nuclear Reactions

Nuclear reactions are divided into two categories: radioactive decay and collision reactions. Radioactive decay is a natural decomposition reaction, whereas collision reactions require interaction between a nucleus and a neutron.

Data on nuclear reactions was collected and is available in the Evaluated Nuclear Data File (ENDF) library, which is located at https://www-nds.iaea.org/exfor/endf.htm. These data are organized and updated by the International Atomic Energy Agency (IAEA). The libraries are extensive, including decay data as well as all possible collision reaction responses for many isotopes of each element.

Radioactive Decay

Radioactive decay is the process by which unstable nuclei transform into stable ones. Nuclear instability is characterized by the tension between strong nuclear attraction and electromagnetic repulsion. As the nucleus increases in size, stability requires more neutrons than protons to maintain the balance between these two forces. However, regardless of the number of neutrons, there is a threshold number of protons after which stability cannot be achieved: Bi-209 is the largest stable isotope. Smaller nuclei may also be unstable if they contain a disproportionate number of neutrons. For example, the decay of C-14 is
exploited in the dating of organic material. The size of unstable isotopes, or radioisotopes, follows a trend known as the band of stability; see Figure 9.

![Figure 9. Trend of nuclear stability [29].](image)

To fix the imbalance, unstable nuclei release energy in the form of radiation. There are three mechanisms of radioactive decay: emission of alpha particles, beta particles, or gamma rays. Alpha particles, $^4_2\alpha$, are identical to helium nuclei. Beta particles, $^0_{-1}\beta$ or $^0_{+1}\beta$, are electrons or positrons, respectively; beta decay is linked to the conversion of a nuclear neutron to a proton. Gamma rays, $^0_0\gamma$, are high-energy radiation with wavelengths below $10^{-12}$ m, which result in the transition of a nucleus from an excited state to a lower excitation or ground state; see Figure 10.
Decay by alpha and beta emission changes the identity of the atom. Chemical equations can be written for the decay reactions. To balance the equations, the number of protons and neutrons must be conserved. Examples are given in Table 3. Gamma decay does not result in a different element but, rather, a lower-energy atom. Alpha and beta decay are often accompanied by gamma emission as well.

Table 3. Examples of alpha and beta decay reactions.

<table>
<thead>
<tr>
<th>Particle Emitted</th>
<th>Balanced Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alpha</strong></td>
<td>$^{239}<em>{94}\text{Pu} \rightarrow ^{235}</em>{92}\text{U} + \frac{4}{2}\alpha$ (2)</td>
</tr>
<tr>
<td><strong>Beta</strong></td>
<td>$^{233}<em>{91}\text{Pa} \rightarrow ^{233}</em>{92}\text{U} + 0_0^0\beta$ (3) or $^{233}<em>{91}\text{Pa} \rightarrow ^{233}</em>{90}\text{Th} + 0_1^1\beta$ (4)</td>
</tr>
</tbody>
</table>

Positrons, in Equation (4), do not exist independently for long. They pair almost immediately with electrons. Each combination produces two gamma rays; see Figure 11.
Radioactive decay continues until a stable element is reached. The series of elements through which the isotope progresses is known as a decay chain; see Figure 12.
Nuclear reactors have a negative connotation because of the radioactive waste they produce. There are indeed hazards associated with radioactive decay. However, the different decay products present different issues; see Table 4.

Table 4. Penetration abilities of radioactive decay products [33].

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Distance Traveled in Air (m)</th>
<th>Shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>0.02-0.04</td>
<td>paper or clothing</td>
</tr>
<tr>
<td>Beta</td>
<td>2-3</td>
<td>heavy clothing</td>
</tr>
<tr>
<td>Gamma</td>
<td>500</td>
<td>lead or concrete</td>
</tr>
</tbody>
</table>

Alpha particles present the highest health hazard. In human bones, nuclei emit alpha particles, which exit the bones and leave a network of porous tunnels behind. Because alpha particles have a low penetration capacity, they must be inhaled, ingested, or taken in through an open wound to cause damage. This was an issue in World War II with women working in watch factories, painting glowing numbers on soldiers’ watches with radium, sharpening the tip of the paintbrush with their teeth, and thus ingesting the radium. Beta particles, or electrons, can cause skin damage on prolonged contact [34]. Protection from gamma rays is similar to that from the slightly less energetic x-rays. Exposure to gamma rays does not produce any lasting effects in non-fictional humans.

The rate at which a radioisotope decays is quantified by its half life. The half life is the amount of time it takes for half of the initial mass of the nuclei in a sample to decay. The longer an element’s half-life, the closer it is to being stable. A half-life of 14 billion years is considered stable [35].

Radioactive decay is a first-order chemical reaction, meaning that for a given element at a given temperature, the half-life is constant. The integrated rate law for radioactive decay is

\[ N = N_0 \left( \frac{1}{2} \right)^{t/t_H}, \]  

where \( N_0 \) is the initial number of nuclei present, \( N \) is the current number of nuclei present, \( t \) is the time elapsed between initial and current conditions, and \( t_H \) is the half life of the isotope.
**Neutron Collision Reactions**

Nuclear reactions are divided into two categories: scattering and absorption. The probability a specific reaction will occur is called the activation cross section. Cross sections are typically measured in barns; 1 barn is equivalent to $10^{-28}$ m$^2$. The origin of this term stemmed from the Manhattan project [36]:

The “Oppenheimer” was discarded because of its length… The “Bethe” was thought to lend itself to confusion because of the widespread use of the Greek letter $\beta$… Manley was thought to be too long. The “John” was considered, but was discarded because of the use of the term for purposes other than as the name of a person. The rural background of one of the authors then led to the bridging of the gap between the “John” and the “barn.” This immediately seemed good, and further it was pointed out that a cross section of $10^{-24}$ cm$^2$ for nuclear processes was really as big as a barn. Such was the birth of the barn.

Cross sections can also be measured in sheds, $10^{-48}$ cm$^2$, but this is less common.

Cross sections can be either macroscopic or microscopic:

$$\Sigma_t = N\sigma_t,$$

where $\Sigma_t$ is the macroscopic total cross section, $N$ is the atomic number density, and $\sigma_t$ is the microscopic total cross section. Macroscopic cross sections apply to specific samples of material, while microscopic cross sections are properties of certain materials.

Cross sections vary with neutron energy; see Figure 13. A resonance effect occurs when the energy of the neutron is approximately equal to the lowest energy state of the A+1 nucleus. This is because the supposed mechanism for neutron reactions is the compound nucleus model. In this model, the neutron is first absorbed, creating the A+1 nucleus. The nucleus then either undergoes scattering, emitting the neutron, capture, keeping the neutron, or fission, splitting the atom and emitting the neutron.
Figure 13. Effect of neutron energy on neutron capture cross section for the F-19 nucleus.

**Fission**

Fission is the reaction that takes place in typical nuclear reactors and provides the heat for power generation. In the fission process, a neutron is fired at a nucleus, splitting the nucleus into two fragments known as fission products. The general form of a fission reaction is

\[
^{235}_{92}U + {}^1_0n \rightarrow ^{A_1}_{Z_1}F_1 + ^{A_2}_{Z_2}F_2 + v_0n + \text{energy},
\]

where \( F_1 \) and \( F_2 \) represent fission products, \( v \) is the number of neutrons produced in the reaction, and energy is another required product to satisfy the mass-energy balance. At this level of detail, mass and energy balances must be combined by the mass-energy equivalency:

\[
E = mc^2,
\]

where \( E \) is energy, \( m \) is mass, and \( c \) is the speed of light.

Nuclear reactors require the maintenance of chain reactions. The nuclear fission chain reaction occurs because the rate of neutron production is greater than that of neutron consumption. However, fission reactions are not the only consumers of neutrons.
**Scattering**

Neutron scattering is a phenomenon in which a neutron is absorbed and then re-emitted. A change of direction or energy results from this interaction. These collisions can be elastic or inelastic, but they do not result in a production of more neutrons.

**Capture**

Neutrons can also be absorbed and kept by the nucleus. This changes the isotopic identity of the nucleus. Capture of neutrons is the main inhibitor of also inhibits the production of new neutrons.

**Breeding**

Some reactors produce enough neutrons not only to sustain a fission chain reaction, but to produce more fuel as well. These reactors are called “breeders.” This is only possible for fertile, not fissile, materials such as Th-232. Th-232 cannot sustain a nuclear chain reaction; it requires neutron capture to be transmuted into U-233. U-233 is fissile, which means that it can sustain nuclear chain reactions. In a breeder reactor, enough neutrons are emitted as fission products to supply both fission and capture requirements. The breeding ratio quantifies this process and is defined as the average rate of fission atom production over the average rate of fission atom consumption. For a reactor to be a breeder, this ratio must be greater than one.

**Criticality**

Critical mass is the amount of fuel required to sustain a nuclear fission chain reaction in the reactor. Critical mass varies for different isotopes, geometries, and surrounding systems. Nuclear cross sections must be considered, as neutrons and energy lost to scattering and absorption detract from the fissibility of the fuel. Depending on the fuel, different critical masses may be required. Figure 14 shows a comparison of the critical masses for fissile materials.
The geometry also affects the criticality of a system because it defines the mass transport properties of the neutrons. Surrounding materials with different cross sections also affect neutron behavior.

Criticality can be calculated using empirical data. It is defined by the reactor multiplication factor $k$:

$$k \equiv \frac{P(t)}{L(t)}, \quad (9)$$

where $P(t)$ is neutron production rate and $L(t)$ is neutron loss rate. It is used to predict the sustainability of nuclear fission chain reactions in the reactor core; see Table 5.

Table 5. Effect of reactor multiplication factor on criticality.

<table>
<thead>
<tr>
<th>$k$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k &lt; 1$</td>
<td>subcritical</td>
</tr>
<tr>
<td>$k = 1$</td>
<td>critical</td>
</tr>
<tr>
<td>$k &gt; 1$</td>
<td>supercritical</td>
</tr>
</tbody>
</table>

The reactor multiplication factor is calculated by the six factor formula [38]:

$$k = \eta fpe P_{FNL} p_{INL}, \quad (10)$$
where the six factors are the thermal fission factor ($\eta$), thermal utilization factor ($f$), resonance escape probability ($p$), fast fission factor ($\epsilon$), fast non-leakage probability ($P_{FNL}$), and thermal non-leakage probability ($P_{TNL}$).

The thermal fission factor is, qualitatively, the average number of neutrons produced per neutron absorbed:

$$\eta = \frac{\nu \sigma^F_t}{\sigma^a_F},$$

(11)

where $\nu$ is the average number neutrons produced per fission, $\sigma^F_t$ is the microscopic fission cross-section for the fuel, and $\sigma^a_F$ is the microscopic absorption cross-section of the fuel.

The thermal utilization factor is the probability that, if a neutron is absorbed, it is absorbed in the fuel:

$$f = \frac{\Sigma^F_a}{\Sigma_A},$$

(12)

where $\Sigma^F_a$ is the macroscopic absorption cross-section of the fuel and $\Sigma_A$ is the macroscopic absorption of the entire system.

The resonance escape probability is the fraction of neutrons which slow from fast to thermal without being absorbed:

$$p = \exp \left[ \frac{\Sigma_{i=1}^N N_i I_{rA,i}}{(\bar{\xi} \Sigma_p)_{mod}} \right],$$

(13)

where $N_i$ is the concentration of atoms per unit volume of a given nuclide, $\bar{\xi}$ is the average energy lost per scattering event, and $I_{rA,i}$ is the resonance integral for absorption,

$$I_{rA,i} = \int_{E_{th}}^{E_0} \frac{\Sigma_p^{mod} \sigma^i_a(E')}{\Sigma_t(E')} \frac{dE'}{E'}. $$

(14)

The fast fission factor is the total number of neutrons from fast and thermal fissions over the number of neutrons from thermal fissions alone:

$$\epsilon = 1 + \frac{1 - p}{p} \frac{u_t \nu_p P_{FAF}}{f_t P_{TAF} P_{TNL}}.$$

(15)
where $u_f$ is the probability that a fast neutron will be absorbed by the fuel, $P_{FAF}$ is the probability that a fast neutron absorption causes fission, $\nu_f$ is the average number of neutrons produced per fission from fast neutrons, $\nu_t$ is the average number of neutrons produced per fission from thermal neutrons.

The thermal non-leakage factor is the probability that a thermal neutron will not leak before it is absorbed:

$$P_{TNL} = \frac{1}{1 + \frac{L_{th}^2}{B_g^2}}$$  \hspace{1cm} (16)

where $B_g^2$ is the geometric buckling and $L_{th}^2$ is the diffusion length of thermal neutrons.

$$L_{th}^2 = \frac{D}{\Sigma_{a,th}}.$$  \hspace{1cm} (17)

The fast non-leakage factor is the probability that a fast neutron will not leak before it is absorbed:

$$P_{FNL} = \exp(-B_g^2 \tau_{th}),$$  \hspace{1cm} (18)

where $\tau_{th}$ is

$$\tau_{th} = \int_{E_{th}}^{E'} \frac{1}{E''} \frac{D(E'')}{\xi[D(E'')B_g^2 + \Sigma_t(E')]} dE''.$$  \hspace{1cm} (19)

Management of $k$ is important, as supercritical systems produce runaway reactions, or bombs. Subcritical systems cannot support fission chain reactions, and the reactor ceases to function. $k$ is kept at a value of one by controlling the geometry of the system. This is achieved by manipulating the position of control rods, which are discussed in Section 28.

**Neutron Spectra**

The incident energy of a neutron is characterized by the terms “fast” and “thermal.” Fast neutrons have energies above 100 MeV and thermal neutrons have energies less than $10^{-3}$ MeV. The region in between these constraints is called the “epithermal” region. Nuclear reactors can operate at any neutron energy. Neutrons produced by fission reactions are inherently fast. Nuclei which undergo fission by fast neutrons are considered “fissionable.” Th-232 and U-238 are both fissionable nuclei; they do not undergo fission when bombarded with thermal neutrons. Nuclei which undergo fission by neutrons of any energy are called “fissile.” U-235 is the only naturally-occurring fissile isotope. To slow fast neutrons coming from
fission reactions, a substance called a “moderator” must be used; see Section 28. Moderators are not present in fast reactors.

2.1.2. Nuclear Fuel Cycles

A nuclear fuel cycle is defined as the processes undergone by a nuclear fuel from its mining to its retirement in a waste containment facility. After mining the ore, the fuel cycle typically begins with fuel fabrication. This includes purification processes such as centrifugation and oxidation of the he elemental fuel. In solid fuel reactors, fabrication also includes the formation of fuel pellets. The processed fuel is loaded into the reactor fuel array. During the operation of the reactor, fission, capture, and decay reactions occur, transmuting the fuel into new elements. After its lifetime in the reactor, the fuel is removed as spent fuel. At this point, it is placed in storage; see Section 2.1.3. Another potential fate for spent fuel is reprocessing, or removal of fuel poisons generated during operation so that the fissile material remaining in the spent fuel may be used again.

2.1.3. Nuclear Waste Disposal

Proliferation and radiation poisoning are the main concerns with nuclear waste disposal. For proliferation, the fear is that hostile countries will gain access to nuclear weapons fueled by the byproducts of the nuclear reactors. The fissile isotopes produced in nuclear reactors are generally the result of neutron capture, such as Pu-239 formed from U-238. Products of fission reactions are the primary concerns with respect to radiation exposures.

Contents of Nuclear Waste

Transmutation of elements in a reactor typically results from fission, neutron capture, or radioactive decay.

Fission

Fission reactions split target nuclei into two smaller fragments, known as “daughters” or “fission products.” The sizes of these fragments are dictated by mass and energy balances. However, the exact size of the fragments cannot be predicted. Instead, the frequencies of occurrence of each daughter nucleus can be measured from experimental data. These data are used to calculate the probability of formation of each nucleus, which can be used to predict the composition of a sample of spent nuclear fuel. For example, the primary daughter nuclei of U-235 fission are krypton and barium isotopes. Histograms are used to map the probable distribution of fission products; see Figure 15.
Figure 15. Distribution of fission product atomic numbers from thermal fission of different fissile isotopes [39].

**Neutron Capture**

As described in Section 2.1.1, the absorption of a neutron into a nucleus without re-emission or fission is termed “capture.” In capture reactions, smaller nuclei are transmuted into larger ones. Neutrons are typically captured by fuel particles, producing members of the actinide series on the periodic table. This process becomes a problem when the new nuclei are fissile, resulting in non-proliferation issues, or when the nuclei become unstable, resulting in radioactive decay and particle emission.

**Radioactive Decay**

Although the fuels used in nuclear reactors are almost stable, with half lives on the order of billions of years, transmutation of these isotopes can create unstable nuclei. Fission products, while smaller than the target nucleus, can still be radioactive. The half lives of these species vary significantly. Radiative capture also produces unstable nuclei. These species are typically actinides, which, like nuclear fuels, which are also actinides, remain unstable for long periods of time.
Current Containment Technology

The waste disposal process includes the transportation of spent fuel, classification as high-level or low-level waste, and its ultimate decommissioning.

Transportation

Transportation of nuclear waste is unavoidable and must be approached with safety being most important. There are three fundamental principles that guide nuclear waste transportation: packaging is to provide protection; the greater the hazard is, the greater the package must be; and design must assure safety [40]. The federal Department of Transportation and the Nuclear Regulatory Commission (NRC) regulate how radioactive material is transported [41]. The transportation vessels are designed to protect the contents from dangers both within and without the package, including excessive internal heating, criticality, free fall from 30-ft onto solid ground, and fire exposure at 1475 °F for 30 min [42]. Efforts have also been made to keep local emergency response teams familiar with how to handle an accident involving the transportation of radioactive waste [43]. All of this is to say that transportation of the nuclear waste is a well-established technology with safety always at the forefront of design. Transportation of spent fuel isn’t a huge consideration for nuclear facilities because most are designed with storage ponds that can hold the spent fuel generated over the lifetime of the reactor. Thus, location need not be a consideration when considering transportation. However, more land is necessary to build the ponds.

High-Level Waste Disposal

High-level waste (HLW) is defined as waste from reactors that still has high levels of radioactivity. Often times, spent fuel is disposed of the same way as HLW despite having recoverable fuel in it [44]. Before HLW is stored permanently somewhere, it has the possibility of going through reprocessing which removes some components of the waste to be used in reactors in the future (e.g. unspent U-235). However, this does not always occur as it is not always financially feasible. A popular way of storing nuclear waste is to melt glass and the waste together then pour the mixture into a canister to be stored away somewhere. The only place to legally store HLW in the U.S. is in Yucca Mountain, NV [45].

Low-Level Waste Disposal

Low-level waste (LLW) is waste that is not classified as HLW and does not contain plutonium or other heavier artificial isotopes. It has large amounts inert material with smaller amounts of radioactive material within it. LLW includes isotopes not associated with the nuclear reaction (e.g. C-14, Ni-63) or contaminated dry materials due to maintenance or leakage of coolant (e.g. paper, metal, wood). However,
the level of radioactivity can be comparable to that of HLW. Given the generally lower radioactivity LLW, it can sometimes be disposed of in near-surface containment facilities rather than deep-storage like Yucca Mountain. The material can also be burned with the ashes then being collected or the waste is shredded then stored in concrete blocks [46].

Decommissioning

After the useful life of a plant is reached, the plant must be shut down and taken care of accordingly. The four options provided by the NRC are SAFSTOR, ENTOMB, DECON, and delayed dismantlement. SAFSTOR is when the plant becomes an abandoned building that is subsequently monitored until a future date. ENTOMB is when all the contaminated materials are encased in concrete or are surrounded by protective barriers. The facility is still under surveillance. DECON is when the plant is immediately dismantled and all contaminated material is sent to an LLW disposal site. Delayed dismantlement is the same as DECON but with a waiting period before the plant is taken apart.

2.1.4. Reactor Loop Components

Typical nuclear plants employ at least two loops: the reactor loop and the power loop. The reactor loop consists of the components which generate the heat necessary to run the power loop. The power loop converts thermal power from the reactor to electricity. This section discusses the components of the reactor loop. The power loop components are detailed in Section 2.2.1.

Reactor systems consist of a containment facility, in which is housed the reactor vessel. The containment facility provides shielding from radiation as well as from potential disasters or attacks. The reactor vessel houses the reactor core, which includes the fuel, moderator, coolant, and control rods. The core is where the fission reactions take place. A diagram of a typical reactor system is shown in Figure 16.
Figure 16. Basic design of nuclear reactor system [47].

Fuel

The fuel is the material burned in the fission reaction. In most current reactors, solid fuel pellets are stacked in a fuel assembly. However, fluid fuel may also be used; fluid fuel circulates through the fuel rods. The type of fuel, whether fissile, fertile, or fissionable, depends on the fuel cycle and the energy of the incident neutrons. The most common fuel used in current commercial reactors is U-235. As the fuel region is where the heat is produced, fuel assemblies must be able to handle the greatest temperatures in the reactor system.

Containment

The containment structure is usually a thick concrete and-steel-wall, which protects outsiders from disasters within the reactor as well as protecting the reactor from outside damage. With walls between three and five feet thick, this wall is designed to be the last front against interaction between the reactor system and the outside environment.
Shield

The shield is a secondary containment structure located inside the primary containment. It surrounds the reactor primarily to prevent radiation from the reactor contents from leaking outside the containment.

Reactor Vessel

The reactor vessel is designed to handle the high pressures and temperatures of reactor operation as well as radiation damage. These walls contain the reactor contents within itself.

Reactor Core

The reactor core is the component where the fission reactions occur. The elements of the core sustain the most radiation damage because of the proximity to these reactions. Therefore, it is important that the materials and structures not be susceptible to failure. Because of its need to be so robust, most engineering challenges are concentrated in the core design. Core design varies based on the fuel, moderator, and coolant properties.

Moderator

The moderator is only present in thermal spectrum reactors. The function of the moderator is to slow or “thermalize” the neutrons that are present in the reactor core. Neutron thermalization occurs when neutrons collide with moderator particles, transferring their energy to the moderator. The most effective moderation occurs when the moderator particle is approximately equivalent in size to the neutron. For this reason, water is often used as a moderator, as hydrogen ions are protons, which have identical mass to neutrons. Other materials such as heavy water or graphite are also commonly used as moderators. However, due to particle size difference, they are less effective at slowing neutrons.

Coolant

The coolant is the material which transfers heat from the fuel to the power cycle. It flows through the reactor core and through a heat exchanger, where it connects to the power cycle. In LWRs, the coolant is water. To circulate continuously, LWRs must be situated near a large supply of water. Use of other coolants requires expulsion of heat to the environment through other methods.
Control Rods

Control rods determine the criticality of the reactor core. Control systems for the control rods determine the adjustments required to keep $k$ at a value of one. Control rods are typically made of the same material as the moderator, so criticality adjustment is dictated by the speed of the neutrons. Reactors are also equipped with absorption rods. These rods are intended to stop the reaction. They are constructed from materials with high neutron capture cross sections, such as silver or cadmium; their insertion removes neutrons from the system. Absorption rods are used only for reactor shutdown purposes, whether planned or emergency.

2.1.5. Reactor Safety Features

Although safety is important in all processes, it is paramount in nuclear power plants, as any breach in safe practice causes terrible, long-range disasters. For this reason, advanced reactor designs place a strong emphasis on safety features. Specifically, the Generation IV International Forum (GIF-IV) included passive safety features in all supported reactor designs. These safety features are “walk-away safe,” i.e. they rely on laws of nature and physics rather than on human action.

A thermal reactor design must take into careful consideration the fuel to moderator volume ratio. A concern would be the compaction of the core, which would lead to subcriticality due to lack of moderation, given an inappropriate ratio [48]. The geometry of the reactor is important for both fast and thermal reactors. Arranging the reactor fuel into a more compact shape could possibly increase the reactivity of a fast reactor, but not for a thermal reactor [49].

There are two major concerns that must be addressed when looking at fast reactor safety: a possible increase of fission power caused by a reactivity insertion into the reactor and any situation in which the fission chain reaction is stopped but there is not an adequate coolant flow to transfer heat from radioactive decay out of the core [50].

The coolant itself has safety consideration. One issue is the maintenance of the coolant density. A decrease of the density could cause competing reactivity effects including spectral hardening caused by a reduction of moderation by the coolant; reduced absorption by the coolant, reduction of scattering by the coolant which would lead to a higher leakage of neutrons; and higher temperatures due to the absence of coolant which could lead to larger absorption through the Doppler effect [51].

Finally, radiation from the radioactive materials must also be considered when looking at the safety aspects of a reactor design. While there is slight risk in damage from radioactivity of the fuel elements, all
current reactor designs are made in such a way that several barriers and fuel cladding are put in place so to not cause a breach of harmful radiation. The possibility of the release of this material has been made in such a way that the likeliness of release of some radioactive material from the containment building would not occur more than once in a thousand years for most all reactor power plants [52].

In addition, may regulatory bodies, such as the American National Standards Institute (ANSI), American Nuclear Society (ANS), the Health Physics Society (HPS), the Institute of Electrical and Electronics Engineers (IEEE), and the American Society for Testing and Materials (ASTM) have set regulations to maintain the safety and operation of all current and future nuclear reactor sites [53].

2.1.6. Cooling Technology

It is important, when looking at the overall reactor design, to account for the proper removal of excess heat from the system to prevent overheating of the system. Several possibilities will be considered when taking into account the need for removal of excess heat. The applications of this practice is primarily for water reactors, which require high flows of water from a specified reservoir to be returned to the environment at high temperatures. However, removal of heat from all coolant types is required.

Desalination provides a desirable service to those without access to clean water. To effectively incorporate a desalination process with a nuclear system, the process must be specified and accounted for in the transfer of heat. This process can be done with distillation process, such as a multistage flash process or multi-effect distillation process shown in Figure 17, or using reverse osmosis such as in Figure 18 [54].

![Figure 17. Schematic diagram for desalination using distillation system powered by excess heat from nuclear reactor [55].](image-url)
Figure 18. Schematic diagram for desalination using reverse osmosis system powered by excess heat from nuclear reactor [56].

Hydrogen generation is another feasible alternative to useful applications of excess heat. The heat from the reactor is used in a thermochemical or electrochemical process which produces the hydrogen; see Figure 19. The main advantage to hydrogen generation using reactor heat is that it provides heat for the thermochemical processes which require less heat to produce hydrogen in the same way than a process like electrolysis alone does, which requires a much higher minimum temperature of 2500 °C for operation [57].

Figure 19. Block flow diagram for hydrogen generation from excess heat from nuclear reactor [58].
Depending on the process chosen for hydrogen generation, different reactors must be considered; see Figure 20.

![Diagram](image)

Figure 20. Options for excess heat use for different reactor types [59].

Further application for using excess heat from the reactor would be to burn garbage or provide heating for reactor facilities. If no useful application is feasible for removal of excess heat, heat removal through use of a cold body, such as a cooling tower, lake, or canal is a viable option. Several possible applications and necessary operating temperatures for said applications are shown in Figure 21.
2.1.7. Cost Models

The cost of reactor system cost components can be calculated in two ways. First, data can be scaled from previously-run reactors. Second, the chemical process cost models may be employed. These models are called Guthrie cost estimation. These equations take into account a key design variable for each component. For example, reactor vessels are defined by volume and heat exchangers are defined by heat exchange area. The models also consider material of construction and pressure rating. The result of the estimation process is an itemized cost for the purchase of each component. Installation costs are scaled from the purchased costs. The Guthrie cost estimation spreadsheet is linked in Appendix B: Cost models.

Capital costs must also be scaled for the fluctuation of the chemical industrial market. This change is taken into account by the Chemical Engineering Plant Cost Index (CEPCI). Costs are scaled linearly between the year for which data are available and the year for which data are desired to be available. The CEPCI is published annually at http://www.chemengonline.com/pci-home.
2.2. **Thermal Systems**

Thermal systems are designed to take the heat generated by the reactor and turn it into usable electricity to be sold. Thermal cycles that keep their working fluid in the supercritical state are naturally more efficient. The supercritical state is when the temperature and pressure are high enough that the fluid gains properties of both gas and liquid at the same time. It has the thermal transfer properties and the compressibility of liquid without needing to remove energy to make it a liquid. This eliminates the need to worry about phase changes in the components it passes through.

2.2.1. **Thermal Loop Components**

In order to accomplish the electricity generation that this design intends, the thermal system used is a Brayton cycle using a gas as a working fluid and is composed of the respective Brayton cycle components, those being turbines, compressors, and heat exchangers. This section will cover background information relevant to each component. In addition, the applications of each component in the cycle will be discussed.

**History**

The concept of the turbine is not a relatively new idea. Early turbine theory can be traced back to 150 B.C. in Alexandria, Egypt by a man named Hero who was believed to have invented a steam powered “Whirligig” toy that worked in the same way as a turbine, was used more for amusement [61]. Further concepts, principles, and designs had been developed through the ages by notable scientists such as Leonardo Da Vinci, Giovanni Branca, and Sir Isaac Newton [62].

However, the first patent for the turbine was made by John Barber in 1791 and was described as being useful with other fluids beyond steam such as gas. From this, it can be noted that the similarities between steam and gas turbines are no coincidence. His concept for the turbine was that gas would be produced from heated coal, then mixed with air and compressed. It would then be burnt which would produce a high speed jet that, when directed at the blade of the turbine, would cause a rotation which would produce power [63].

Further development preceded from Barber’s patent. These developments come through centuries of study and conceptualization. Examples of this include the multi-stage turbine thought up by John Dumball in 1808, the idea from M. Bresson in 1837 to use a fan to drive pressurized air into a combustion chamber, the suggestion for a mixed stream turbine from Fernimough in 1850, and eventually the design of the first axial compressor driven by an axial turbine developed by Dr. Franz Stolze in 1872 through the works of
Barber and Dumball [64]. These concepts and ideas form the foundation for the basis of research and development of turbine technology. The culmination of this knowledge through centuries of work up to today, as well as advances in metallurgy for high temperature operations, and the utilization of computer technology in design and simulation for turbine airfoils and combustor and turbine blade cooling configurations, have led to modern day turbine technology.

The idea for the compressor, or reverse turbine as it was known, was conceived as early at 1884 by Sir Charles Parsons who received a patent for the concept [65]. Parsons, an English mechanical engineer, originally invented the steam turbine engine in 1884 and was intended for use in high-speed ocean liners [66]. His design worked by placing multiple blades on a single shaft and successfully drove high-velocity steam through a fixed casing and vanes. The rotor was able to reach speeds up to 15,000 revolutions per minute. His designs eventually led to 200 combined sets of steam turbine and turboelectric generators in use by 1895 [67].

The third and final component, the heat exchanger, was patented in the early part of the 1900s. During this period, the first commercially successful design for a plate heat exchanger was created by Dr. Richard Seligman, founder of the Aluminum Plant and Vessel Company Ltd. now known worldwide as APV, in 1923. This original design consisted of cast gun metal plates which were enclosed in a filter press-like frame [68]. Since this model, various other types of heat exchangers have been successfully developed and implemented in varying applications from radiators in vehicles to air conditioning systems for climate control.

**Turbine Applications and Theory**

Turbines prove to be useful in many facets of today’s infrastructure. A very common application is the jet engine turbine, in which hot gases are expanded either through a turbine for shaft power generation or through a nozzle for thrust. Different types of jet engine turbines, such as turbojets, turbofans, or turboprops, all work in different ways but all serve the same purpose, which is to provide work that is used by a jet for movement [69].

Mechanical drive gas turbines are another type of turbine in which a shaft is used for shaft work for mechanical drive operations, electricity generation, combined cycle power plants, and marine propulsion systems. They include the steam derived heavy industrial gas turbines, aero-derivative gas turbines, and the hybrid industrial gas turbines. There are three types of mechanical drive configurations, those being single spool-integral output shaft, single spool-split output shaft, and dual spool-split output shaft [70].
Depending on where the output shaft extends from, the shaft is either a Hot End Drive, where the output shaft is an extension of the turbine component shaft, or a Cold End Drive, where the output drive shaft is an extension of the compressor component shaft. With each configuration comes certain disadvantages. With a hot end drive configuration, operating temperatures are high, ranging from 800°F to 1000°F. Under these conditions, the life and bearing operation of the shaft are affected. What is more, designing the assembly for hot end drive configurations are difficult due to the placement of the assembly through the exhaust duct. This assembly constraint causes the designer of the assembly to account for aspects such as the output shaft length, exhaust duct turbulence, pressure drop, and maintenance accessibility in addition to the high temperatures. The cold end drive configuration differs from the hot end because of the output shaft which extends out of the front of the compressor. This configuration makes servicing of the system much easier. A major concern for this configuration is the need to accommodate the output shaft and driven equipment. In addition, turbulence at the inlet duct is a major concern, which can result in induced surge in the gas turbine compressor, causing complete destruction of the configuration. Examples of both configurations can be seen in Figure 19 and Figure 20 [71].

![Hot End Drive Configuration](image1)

Figure 22. Single spool gas turbine with hot end drive [72].

![Cold End Drive Configuration](image2)

Figure 23. Single spool gas turbine with cold end drive [73].
As for this project, a simple turbine will be used which strictly consists of a shaft and connect blades that rotate the shaft under the force of the moving gas. The work output of this type of turbine is governed by

\[ \dot{W} = \dot{m}(h_{in} - h_{out}), \]  

(20)

where \( W \) is work, \( m \) is mass flow rate, and \( h \) is enthalpy. In other words, the work out of the turbine is equal to the mass flow rate of the gas multiplied by the change of energy of the mass across the turbine.

**Compressor Applications and Theory**

The intentions behind the design of compressors are to compress a gas to a higher pressure used typically in expansion or combustion of a gas through a turbine. Through this, the compressor provides the static thrust that is needed by the turbine to produce shaft work [74]. Examples of compressors are everything that acts as a fan or blower. The compressor itself is made up of a moving part, the impeller or rotor, and a part that remains stationary, known as the diffuser and both are responsible for increasing the pressure [75]. As can be seen by Figure 21, compressors can be divide into two different categories: positive displacement and continuous flow. These categories expand into more specific types of compressors which are used in various situations applicable to the type of pressures each is capable of producing.

![Diagram of compressor types](image)

*Figure 24. Types of compressors [76].*
Positive displacement compressors, otherwise known as centrifugal or annular compressors, accelerates the gas outward away from the center shaft which increases the speed and pressure. The pressure is then further increased by the diffuser which slows the speed of flow out of the compressor. This type of compressor is advantageous because of its simplicity and efficient enough to increase the gas to the desired pressure with only one stage. However, these types of compressors produce lower airflow, causing a lower pressure ratio which makes it overall less capable of producing thrust. For this reason, it is typically seen in smaller engines rather than larger systems [77].

Continuous flow, the most common of which is axial flow, compressors work under the same properties as positive displacement compressors but with more airflow at the same size and provides a greater pressure ratio. This overall provides higher thrust of mass and better fuel efficiency. Unfortunately, this type of compressor does not provide enough compression for most applications, so it is common for running a system with multistage devices when implementing axial flow compressors [78].

Similar to the turbine, a the energy balance for a compressor is

\[ \dot{W} = m(h_{out} - h_{in}) \]  \hspace{1cm} (21)

It should be noted that the state point enthalpy terms are reversed for the compressor from the turbine equation. This is due to the fact that the compressor is putting energy into the mass flow while the turbine is in turn extracting that energy.

**Heat Exchanger Applications and Theory**

As can be applied by the component name, the heat exchangers main purpose is to exchange heat from one medium to another. This is done through the use of gases or fluids, one if which is heated and transfers heat, and the other which is cool and absorbs heat. During the heat transfer process, heat transfer occurs between three different mediums, those being the convective heat transfer from the hot fluid to the inner wall of the tube, conductive heat transfer through the tube wall, and convective heat transfer again from the outer tube wall to the outside cooler fluid.
Figure 25. Representation of heat transfer from a hot fluid to a cold fluid between a pipe wall [79], where T is temperature and r is radius.

A mathematical representation of simple heat transfer is similar to that of an electric circuit in which temperature acts as the potential difference for which energy can be transferred and the properties of the materials acts as the resistance:

\[ \dot{Q} = \frac{\Delta T}{R_m} \]

(22)

where \( \dot{Q} \) is the heat transferred, \( \Delta T \) represents the temperature difference, and \( R \) is the resistance of the material to heat transfer. Give the geometry of the heat exchanger pipe, this equation can be derived to account for the three types of heat transfer occurring in a heat exchanger:

\[ \dot{Q} = \frac{2\pi k(T_A - T_B)}{r_1 h_1} + \frac{k}{r_2 h_2} + \ln \left( \frac{r_2}{r_1} \right) \]

(23)

where \( k \) is the thermal conductivity of the pipe material and \( h \) is the heat transfer coefficient of the inside and outside fluids of the pipe. This values account for the overall heat resistance of the system.

Classification of heat exchangers is done according to the arrangement of the flow of mass and the type of construction. The two most common and simple types can be seen in Figure 22, showing examples of parallel flow and counter flow heat exchangers.
In parallel flow, both fluids enter and exit the heat exchanger in the same direction, while the counter flow heat exchanger does the opposite. Both types of systems are represented graphically in Figure 24 and show how the resulting temperatures can vary. It can be noted that more heat transfer occurs in a counter flow heat exchanger because of its ability to heat the exit cool fluid to a temperature above the exit hot fluid, but is not the case with the parallel heat exchanger [81]. For this reason, counter flow heat exchangers are a more desirable setup, especially for large systems such as the one addressed in this project.

Figure 26. Examples of parallel flow and counter flow heat exchangers [80].

Figure 27. Graphical representation of heat transfer in counter flow and parallel heat exchangers [82], where subscript c indicates the cold stream, h indicates the hot stream, i is in and o is out.
2.2.2. Brayton Cycle

The Brayton cycle is a thermodynamic power cycle that uses gas as the working fluid. The cycle starts compressing the fluid. Next the fluid is heated, then the pressurized, heated fluid goes through a turbine to produce power. If the Brayton cycle is closed, then the heated gas is cooled and sent back to the beginning of the cycle. If the Brayton cycle is open, then the gas is simply expelled to the surroundings. This is the cycle that would be used in a very high temperature gas-cooled reactor with the possibility of attaching a Rankine power cycle powered by the exit gas from the Brayton cycle.

2.2.3. Rankine Cycle

The Rankine cycle accurately describes steam-powered heat engines. The cycle starts with saturated water then increases the pressure. The pressurized water is then super-heated, typically in a combustion chamber, then the super-heated steam is sent through a turbine to produce power. Then heat is removed from the working fluid and the cycle starts over again.

2.2.4. Cost Models

The system was analyzed using exergoeconomic techniques. Exergy is defined as the ability for a fluid to do work and is defined mathematically as

$$\psi_i = (h_i - h_0) - T_0(s_i - s_0)$$

and

$$\Psi_i = \dot{m}_i \psi_i,$$

where $\psi_i$, $h_i$ and $s_i$ are the specific exergy, enthalpy, and entropy, respectively, of stream $i$. $h_0$, $s_0$ and $T_0$ are the enthalpy, entropy, and temperature of the dead state, otherwise thought of as the surrounding conditions. The dollar value of a stream was calculated:

$$\dot{C}_i = \Psi_i c_i,$$

where $\dot{C}_i$ is the dollar value of the stream and $c_i$ is the specific cost of stream $i$. The cost of each stream takes into account the cost of running and maintaining each component. Using exergoeconomics allows the system to be optimized for things besides cost, like cost of destroyed exergy. The individual component costs were based inlet and outlet conditions and flow rates through the given component. Specific equations governing the cost are included in Appendix B: Cost models.
3. Design

As this project was completed for the engineering senior design course, developing the design was the primary objective. Alternatives were researched, decision criteria were chosen and ranked, and a decision will ultimately be made. Analysis of that design decision was performed both on a technical and economic basis and the elements of the design were integrated together. Testing and implementation, while not specifically suited to the team’s paper power plant, were also considered.

3.1. Design Criteria

The primary design considerations were the five core problems with current power production facilities identified in the problem definition: cleanliness, cheapness, safety, efficiency, and fuel availability.

Being a group focused on Christian values, the design norms were also an integral part of the overall design and presentation of this project. Stewardship was an important aspect of the project, as the team hoped to present an alternative which uses God’s resources more reverently. Transparency was also an integral aspect of this project. Although the design was complex, clear communication of its benefits was imperative to its positive receipt.

3.2. Design Alternatives

Before any decisions could be made, the design alternatives were identified. The project was divided into four categories. The reactor types were researched in the fall and, therefore, were selected first. The reactor, fuel reprocessing, and power cycle systems were investigated in parallel during the spring semester.

3.2.1. Reactor Types

The reactor type alternatives were selected such that each was compatible with Th-232. All of the potential reactors are considered either Generation III or IV reactors by the World Nuclear Association. The nuclear reactor generation system classifies the following generations seen in Table 6:
Table 6. Timeline of nuclear reactor generations [83].

<table>
<thead>
<tr>
<th>Generation</th>
<th>Time Frame</th>
<th>Design Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1950s-60s</td>
<td>• natural uranium fuel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• graphite moderator</td>
</tr>
<tr>
<td>II</td>
<td>present</td>
<td>• enriched uranium fuel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• light water moderator and coolant</td>
</tr>
<tr>
<td>III</td>
<td>present (Japan) or under construction</td>
<td>• “Advanced Reactors”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• no one general design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• some modifications of Gen-II reactors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• some new designs</td>
</tr>
<tr>
<td>IV</td>
<td>operational by 2020 at the earliest</td>
<td>• closed fuel cycles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• burn actinides; produce only fission products as waste</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• operate at high temperature (gas-cooled), low pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• (liquid metal- or salt-cooled)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• emphasis on passive safety features</td>
</tr>
</tbody>
</table>

Both thermal and fast reactors were considered. The following section includes a brief description of the researched reactor types.

**Thermal Reactors**

As described in Section 2.1.1, thermal fission reactions take place when the neutrons are in thermal equilibrium with the fuel. Four primary types of thermal reactors were considered for this project: light water reactors, heavy water reactors, supercritical water-cooled reactors, very high temperature gas reactors, and molten salt reactors.

**Light Water Reactors (LWR)**

LWRs use light water as both the reactor moderator and coolant. Two types are in existence today: boiling and pressurized water reactors.

**Boiling Water Reactors (BWR)**

BWRs are the second most common reactor currently in use. BWRs operate at a pressure of 75 atm and a temperature of 285 °C [84]. They are classified as Generation II reactors, which means they are in the
category of reactors that are currently being used. They are used currently in commercial plants and in large naval vessels.

BWRs have a very simple design compared to Generation III and IV reactor designs. A BWR has only one coolant loop. Water is used as both the moderator and the cooling fuel. Water enters the reactor and flows around the reactor core. The water then boils and leaves the reactor as steam. This steam is used to turn the blades of a turbine which in turn creates electricity.

![A Typical Boiling Water Reactor (BWR)](image)

Figure 28. Block flow diagram of BWR [85].

Since the same water flows through the reactor core and passes through the turbine, the turbine has to be shielded from radionuclides contaminating the water [86]. In addition, the workers must wear protective clothing when performing maintenance on the turbine or any part of the reactor water cycle. However,
BWRs have a much simpler design than most reactors, thus there is an inherent cost savings due to the simple design which offsets some of the cost of the additional shielding [87].

*Pressurized Water Reactors (PWR)*

PWRs are very similar to BWRs. Like a BWR, a PWR is very common and there are 230 currently in use in the United States [88]. Both types of LWRs are used in naval vessels and electricity production plants.

![A Typical Pressurized Water Reactor (PWR)](image)

The design of a PWR is more intricate than a BWR. It involves two cooling circuits. In the first cooling circuit, the water flows in the vessel containing the control rods, around the cooling rods, out the vessel containing the cooling rods, through a heat exchanger, and then back into the vessel containing the control rods. This water is kept at a temperature of 325 °C and a pressure of 150 atm [90]. In the second circuit, water flows through a heat exchanger where it is vaporized. The water vapor then flows through a turbine which creates electricity and finally is condensed back to liquid water.
**Heavy Water Reactors (HWR)**

Heavy water (D₂O) is a substance in which the hydrogen atoms (¹H) of normal (light) water are replaced with deuterium atoms (²D). ²D is an isotope of hydrogen containing two protons instead of the typical one proton. A sample of water contains 130-160 ppm D₂O [91]. D₂O can simply be from H₂O, but this distillation is difficult and demands a high energy input. To remedy this, light water is subjected to single replacement reactions with other deuterated compounds such as hydrogen sulfide (HDS), ammonia (NDH₂), or aminomethane (CH₃NDH) [92]:

$$HX + DY \leftrightarrow DX + HY \quad (27)$$

The resulting compounds are easier to separate from D₂O. Because the kinetics of the latter two options are slow and require catalysis, the Girdler-Sulfide (G-S) method is preferred. Using this process, a concentration of 99.75% D₂O can be achieved [93]. Before their shutdown in 1997, four Canadian G-S plants produced over 2000 tonnes of D₂O per year [94].

The most basic heavy water reactors (HWRs) use D₂O as both the moderator and coolant. Using D₂O as a moderator presents costs and benefits. Neutrons produced by fission are moderated most efficiently when collided with particles of identical size; a larger volume of ²D is required to slow the neutrons. However, ¹H atoms also have a higher absorption cross-section than ²D atoms, reducing the total number of working neutrons.

By preserving more of the neutrons from the fission reaction, fewer fissions must occur in the first place. Less U-235 is required, and natural (unenriched) uranium can be used. As D₂O is cheaper to obtain than enriched uranium, HWRs are more feasible on a lower budget. For this reason, HWRs are attractive to countries interested in obtaining fissionable plutonium for nuclear weapons. Therefore, the trade of heavy water is strictly regulated.

The systems involved in heavy water reactors (HWRs) are similar to those in pressurized LWRs. They each contain two loops: a reactor loop and a steam loop. The most common HWR is the Canadian Deuterium Uranium (CANDU) design; see Figure 30.
The CANDU HWRs operates at a low moderator pressure, reducing leakage potential. Coolant temperatures can reach 290 °C, requiring high pressures to maintain liquid phase [96]. The moderator resides in the calandria, a large tank where fast neutrons produced by fission reactions are returned to thermal equilibrium with the moderator. Fuel elements are encased in pressure tubes, which are inserted horizontally. These tubes are all independent; they can be refueled one-at-a-time without taking the reactor off line. The control rods are vertical.

The Advanced CANDU Reactor (ACR) improved on the original CANDU reactor. It featured a compact, more efficient core. Light water replaced heavy water in the coolant cycle and uranium fuel was slightly enriched. The reactor was run at higher temperature and pressure, yielding higher thermal efficiency and burn-up [97]. Unfortunately, all projects were aborted before they were licensed.
The Indians also proposed improvements to the CANDU design; see Figure 18. The Advanced Heavy Water Reactor (AHWR) uses Th-232 fuel and the pressure tubes are rotated to a vertical orientation, eliminating sagging at elevated temperatures. Several passive safety features were also included [98].

- negative void coefficient
- gravity driven water pool (heat sink)
- natural circulation used to remove head from core
- increased fuel poisoning at higher temperatures

Additional safety control systems such as emergency core cooling and backup shutdown were also implemented.

Figure 31. Schematic of AHWR [99].

*Supercritical Water-Cooled Reactors (SCWR)*

SCWRs use water as the working fluid with the pressure above the critical point (22.1 MPa, 647 K). SCWRs are already a proven technology and have been used in coal-fired plants with good success. However, the addition of radiation adds engineering challenges.
One of the advantages of SCWRs is that there is only one loop of working fluid. The simplicity of the design decreases overall cost and maintenance of the plant. Because the water is super-critical, the heat transfer properties throughout the process remain relatively constant, which allows for more efficient heat transfer. This, together with higher temperatures, greatly increases the overall efficiency. Typical PWR efficiencies are around 33% while it is predicted that SCWRs would be closer to 44%. Increased efficiency means more energy for a given amount of fuel and thus higher profit related to fuel costs during the life of the plant. The overall plant can be smaller because the high enthalpies of the water means that less water is needed to supply the same power output. A smaller plant means a lower initial capital investment. Since boiling does not occur, there is no possibility for voiding to occur.

The simplicity of the system is also a drawback. Because there is only one loop, all of the equipment is irradiated and requires special training for the workers and special shielding for everything at the plant. The high pressures inside the reactor mean increased material strength requirements and thus higher costs. In the event of power loss, there have not been any passive safety features that have been developed. The core has the possibility of dealing with the actinides depending on its design.
Figure 32. Block flow diagram of SCWR [100].

Very High Temperature Gas-Cooled Reactors (VHTR)

When considering the need for higher power energy density, the need for higher operating temperatures to increase thermal efficiency becomes increasingly important. For this reason, gas coolant becomes increasingly desirable as it can operate at very high temperatures with reduced risk of boiling effects because there is no phase change of the gas in the reactor core. When considering types of gases to use, CO$_2$ was first; however, CO$_2$ at high temperatures corrodes graphite moderators in thermal reactors. This gave cause to using helium instead, which is chemically inert, has a high specific heat, and is neutronically transparent [101].

Gas-cooled reactors (GCRs) were first developed in the United Kingdom and France; they were designed with natural uranium fuel cladded in a type of magnesium alloy. This design was known as the Magnox reactor. Soon after, advanced GCRs were developed which used 2% to 4% enriched uranium oxide fuel.
This type of reactor had a higher power density and burn-up rate and are 10% more efficient than the Magnox reactor [102].

Next in development was the high temperature gas-cooled reactor (HTGR), which used graphite as a moderator and introduced helium as a coolant. During the 1960s several experimental prismatic reactors were built in places like the U.S. and France. However, in 1961, Germany began development of the HTGR using the pebble bed reactor design. Soon after, Germany built a second HTGR called the Thorium High-Temperature Reactor (THTR-300). This reactor went critical in 1983. Most recently, two other HTGRs, one in Japan and one in China, have been built which have designed outlet temperatures of up to 950°C, much higher than most other designs [103].

VHTGRs are GIF-IV thermal reactors. The main characteristics of these reactors are the use of helium as a coolant and graphite as a moderator. What is more, it is expected that a VHTGR have a coolant exit temperature of above 1000°C from the reactor [104]. There are two types of reactor designs for the VHTGR: pebble bed and prismatic. This difference is discussed in the following sections.

![Diagram of VHTR](image)

Figure 33. Block flow diagram of VHTR [105].
**Pebble Bed**

Pebble Bed reactors were developed in Germany during the early 1990s at the Juelich Research Center. The technology developed for this research reactor ran for 22 years, thus proving the feasibility of the technology. Since this first reactor, work on its advancement in design has been done at the Institute of Nuclear Energy of the Tsinghua University in Beijing, China and at the Petten Research Institute in the Netherlands [106].

Reactors using a pebble bed system use “pebbles” about 6 cm in diameter. These pebbles have within them microspheres approximately 0.9 mm in diameter, which are made of layers of a porous buffer, silicon carbide, and a pyrocarbon outer shell. At the center of the microsphere is the fuel kernel which is typically UO$_2$. The pebble itself is made of graphite, serving as a moderator for the heat of the reactions [107].

For energy generation, approximately 360,000 pebbles are placed inside of the reactor core where they produce heat upon contact with each other [108]. Helium as the working fluid is then passed through the reactor core where heat is transferred out at high temperatures which can then be used to power a Brayton cycle. Further research in the design of this system have produced a new reactor concepts of this type, such as using direct or indirect cycle helium gas turbines as opposed to steam cycles [109]. When considering safety, the pebbles only produce enough heat to reach critical mass when in contact with each other, so when they are emptied out of the core or separated, there is no risk of overheating [110].
Prismatic

Prismatic gas-cooled reactors use a prismatic design for the fuel rods which house the fuel. As is with the pebble bed design, a fuel kernel, typically uranium, is covered in layers of carbon and silicon carbide. These small particles are then pressed into compacts, which being the prismatic fuel rod, analogous to the one seen in the figure. The geometry of the prismatic block which houses the fuel is important for moderating and slowing down the energy level of the neutrons created by the fission process. This allows for them to be absorbed by other fuel molecules in the core, which in turn allows for even more fission to occur.
Molten Salt Reactors (MSR)

MSRs are reactors that use molten salt as working fluid. They allow the fuel to be dissolved in solution. In solid-fuel reactors, the fuel rods inside the reactor eventually need to be replaced because they are not structurally safe anymore due to the high-heat, radioactive environment. Having the fuel dissolved in solution also allows the actinides and fission products to be removed while the process is still running, allowing the reaction to be more efficient and less likely for the reaction to slow down. Some of these actinides decay into fuel that can be put back into the reactor, while other parts of the waste can be sold. Since the working fluid is always in the liquid state, this stops the need for high pressures inside of the reactor and piping. Decreased pressure means that the system does not need to be as strong, decreasing
costs and increasing safety in the event of a system failure. On a cost basis, MSRs look very promising. The median of five separate cost estimates put the cost of an MSR at $1.98/watt for initial capital investment, compared to $2.30/watt for coal-fired plants or $4/watt for an LWR [113].

Safety is paramount with everything nuclear. An advantage of MSRs is that in the event of a power failure or a runaway reaction, the system can drain into an underground container that is designed to dissipate all the latent heat and stop the reaction. At the base of the reactor there would be a salt plug that would be cooled from the outside to keep the reaction in the reactor. But in the event of a power outage, the cooling system would turn off and the salt plug would break and release the contents of the reactor to the underground container. There are no components that need to be kept powered to keep the facility safe.

Corrosion within the piping has not been completely solved. However, when Oak Ridge National Laboratory (ORNL) tested their MSR using FLiBe salt, corrosion was within acceptable limits to still perform safely after over 3000 hours of successful operation [114]. FLiBe salt is a controlled substance because of the beryllium in it. So either the MSR will use FLiBe, which is difficult to obtain, or it will use a more common salt which will be more corrosive. When the salt becomes radiated, the resulting salt reacts much more violently with air than their non-radiated isotope. As a result, there needs to be an additional fuel loop to further remove the radiated salt from the possibility of reacting with air. This added loop increases costs and complexity of the overall system.
Fast Reactors

Unlike thermal reactors, fast reactors do not require moderators. The neutrons are at a higher energy level than the fuel with which they interact. More information on fast reactors can be found in Section 3.1. Gas-cooled fast reactors (GCFRs), MSRs, liquid metal-cooled reactors (LMCRs), and accelerator-driven subcritical reactors (ADSRs) were researched and considered for this project.

Gas-Cooled Fast Reactors (GFR)

During the 1950s, much work was done with thermal gas cooled reactors. This led to the advancement of gas cooled fast reactors starting in 1962. These reactors were all based on liquid metal fast breeder reactor
(LMFBR) designs, at the same time making changes for gas coolant requirements. The difference between LMFBR and GCFR fuel is that the fuel pins are roughened with small ridges perpendicular to the direction of coolant flow. This induces turbulence of the coolant and increases heat exchange between the fuel and coolant [116].

Just like VHTGRs, GCFRs are GIF-IV reactors. The main design aspects of the GCFR is for having a fast reactor core without fertile blankets, meaning all new fissile fuel is bred in the core, having the breeding gain equal to zero, and creating a low fuel specific power allowing for the addition of a Brayton cycle powered by the exhaust heat of the core. These reactors operate under a closed loop system and can have one or two loop systems. Improved technology for the core of the reactor comes in the form of matrix or particle fuel designs instead of pin fuel designs to reduce release of radioactive materials into the environment [117].

After construction of the first fast reactors, gas-cooling for fast reactor systems was considered due to several advantages, one being the reduced risk of reactivity induced transients due to coolant voiding or a decrease in coolant density. Additionally, gas coolants in fast reactors reduce parasitic absorption by the coolant which causes better neutron economy and improved breeding gain [118].

A possible concern for fast gas cooled reactors is excess decay heat after shutdown. With metal cooled fast reactors, its high thermal conductivity and use of natural convection prove useful with Decay Heat Removal (DHR). With gas-cooled fast reactors, the removal of decay heat needs to be very efficient and stable without depressurization of the system [119].
Liquid Metal-Cooled Reactors

LMCRs use liquid metal as the coolant and moderator for the reactor system. Lead and sodium are the metals most commonly used in LMCRs.

Lead Cooled Fast Reactors (LFR)

While LFRs are still in the development phase, there are plans to construct several by 2020. Belgium plans to build an LFR which they call MYRRHA [121].
The working fluid for LFRs is lead. Lead has a boiling point of 1,740 °C [123]. Thus, unlike PWRs, LFRs do not have to operate under high pressures, which eliminates the safety risk of flashing if pressure is suddenly reduced. In addition, unlike sodium, lead does not readily react with water vapor in the air. LFRs can be used as a burner to consume actinides from spent LWR fuel [124]. In addition, LFRs produce electricity and hydrogen. On the down side, lead becomes increasingly corrosive with higher operating temperatures.

*Sodium-Cooled Fast Reactors (SFR)*

SFRs are almost identical to LFRs. They use liquid sodium as the working fluid instead of lead. Concerns with the use of sodium instead of lead include possible contact with water due to leakage into the wet air.

*Molten Salt Fast Reactor (MSFR)*

The MSR described in the Thermal Reactors section may also be operated in the absence of a moderator.
3.2.2. Reactor Design

Of the reactor type alternatives, the MSBR was selected. Details of the reactor type selection process are given in Section 3.2.1. For the MSBR, the primary components of the design were the materials required for construction and operation, core geometry, and safety system specifications.

Materials

The materials involved in the operation of an MSBR include the fuel and fuel solvent, which are generated and consumed, respectively, in the reactor. The moderator, which dictates the neutron energy spectrum, and the piping and vessel construction materials are non-consumable structures.

Fuel

Fission reactions require both a target nucleus and a neutron. The combination of target identity and neutron source is termed the “fuel cycle;” see Section 2.1.1.

Target

The MSBR designed for this project operates using the thermal neutron spectrum. Therefore, the potential nuclear fuels are all fissile materials: U-233, U-235, and Pu-239. U-233 is produced from Th-232, U-235 is mined directly, and Pu-239 is produced from U-238. The thorium fuel cycle was selected from the outset as the focus of this project; see Section 3.3.2. However, the other target options were studied as well to determine if further study of the alternatives would be recommended.

▸ U-233

In the thorium fuel cycle, the target nucleus is U-233; see Figure 39. Th-232 is charged to the reactor and is transmuted to U-233, which can then be fissioned. This process occurs by neutron capture of a fission neutron and the subsequent radioactive decay of Th-233 and Pa-233. The half lives of Th-233 and Pa-233 are 22 minutes and 27 days, respectively. In a breeder reactor, enough neutrons are produced by fission both to sustain a chain reaction and produce more U-233 than is consumed in the reaction. As Th-232 is not fissile, its presence alone is not sufficient for reactor startup. The fuel must be spiked with a critical mass of a fissile isotope, such as U-235, to initiate the chain reaction.
Figure 39. Thorium fuel cycle [125].

► U-235

U-235 is the most common fissile isotope used in current commercial nuclear reactors. The U-235 itself is the charge to the reactor; it is not produced in the reactor. The part of the U-235 fuel cycle which takes place in the reactor is simply the fission reaction; see Figure 40.

Figure 40. Fission of U-235 nucleus [126].

► Pu-239

In the uranium-plutonium fuel cycle, the target nucleus is Pu-239; see Figure 41Figure 39. U-238 is charged to the reactor and is transmuted to Pu-239, which can then be fissioned. This process occurs by
neutron capture of a fission neutron and the subsequent radioactive decay of U-239 and Np-239. The half lives of U-239 and Pa-239 are 23.5 minutes and 2.3 days, respectively. Like U-233, Pu-239 can also be bred in a nuclear reactor. Also, like the thorium fuel cycle, an initial charge of a fissile material must be present at the startup of the reactor.

Figure 41. Uranium-plutonium fuel cycle [127].

Neutron Source

Once running, a nuclear reactor is designed to sustain a controlled chain reaction. However, startup of a reactor requires the presence of an energetic neutron as well as a critical mass of target nuclei. The most common neutron sources are small devices, including alpha emitter-light element matrices and nuclei which undergo spontaneous fission. Research is also being done on the use of particle accelerators to supply neutrons to reactor assemblies with subcritical masses of fuels.

► Alpha Emitter-Light Element Matrices

In alpha emitter-light element matrices, an element which decays by alpha emission is paired with an element with a small nucleus. Common pairings include Po-Be and Ra-Be. The mechanism by which Be produces neutrons is

\[ ^7\text{Be} + ^4\alpha \rightarrow ^{12}\text{C} + ^1\text{n}. \] (28)

67
Spontaneous Fission

Elements which fission spontaneously produce fission neutrons as do forced fission reactions. Californium (Cf)-252 is the most common isotope to spontaneously fission. It is produced in the United States at ORNL. It has a half life of 2.6 years, and 3% of Cf decay reactions are spontaneous fission reactions.

Accelerator Driven Subcritical Reactors

ADSRs, also known as energy amplifiers, are attractive due to their inherent safety features and ability to incinerate hazardous radioactive waste. By design, they are supplied with less than the critical mass of fuel. Therefore, it is impossible for a meltdown to occur. For instance, in the event of a power outage, the particle accelerator would lose power and stop supplying the neutrons necessary to sustain fission in the reactor.

Particle accelerators can be used with many reactor designs. They act as the neutron source alone; the rest of the system can be modified separately. Most often, ADSRs are paired with LFRs, as in Belgium, but HWRs are also being developed in India [128]. Neutrons are produced in a process called spallation. High-energy protons bombard a heavy metal target and emit a stream of fast neutrons, which is sent to the reactor core; see Figure 27. The heavy metals are often of the actinide family, the long-lived waste products of nuclear fission reactions. These radioactive materials are incinerated in the spallation process, reducing waste reserves and producing fast neutrons simultaneously.
ORNL has been at the forefront of the development of spallation neutron source (SNS) technology; Figure 43. They use a 1.4-MW linear accelerator to produce neutrons. However, most current ADSR designs require 3- to 4-MW accelerators; the current holdback is not the ADSR itself but accelerator technology. Earlier in 2014, the Swedish Nuclear Regulator (SSM) presented a proposal for the European Spallation Source (ESS), which would provide neutron beams thirty times brighter than SNS. This program is to be launched in 2025 [130].
Additionally, the large size of particle accelerators may break containment barrier requirements. Reactor down time may also increase due to both accelerator and reactor system maintenance. While ADSRs present safety and environmental benefits, their logistical drawbacks make them reactors of the future, not the present.

**Salt**

In the MSBR, an ionic salt is used as the coolant as well as the solvent for the fuel. Salt alternatives included variations in the anions, cations, and composition of the salt. The potential anions considered were carbonates, nitrates, fluorides, and chlorides. The potential cations were lithium, beryllium, sodium, potassium, rubidium, and zirconium. Once the constituent salts were selected, the composition of the salt was studied. The balance of the selected salts was varied, but the concentration of fuel in the salt was fixed by criticality calculations.
**Moderator**

As the MSBR selected was a thermal reactor, a moderator was necessary. Moderator alternatives include both solid and fluid species: light water, heavy water, and graphite. All three are currently used in commercial nuclear power plants. However, graphite is employed in different reactor types than is water, as the state of the moderator must be compatible with the state of the coolant and fuel.

**Piping and Vessel Construction**

The metals used for the piping and vessel structures was Hastelloy N, a nickel-molybdenum alloy; see Table 7.

Table 7. Composition of Hastelloy N used in MSBR construction [132].

<table>
<thead>
<tr>
<th>Metal</th>
<th>Concentration (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>71</td>
</tr>
<tr>
<td>Cr</td>
<td>7</td>
</tr>
<tr>
<td>Mo</td>
<td>16</td>
</tr>
<tr>
<td>Fe</td>
<td>5</td>
</tr>
<tr>
<td>Si</td>
<td>1</td>
</tr>
<tr>
<td>Mn</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>0.08</td>
</tr>
<tr>
<td>Co</td>
<td>0.2*</td>
</tr>
<tr>
<td>Cu</td>
<td>0.35*</td>
</tr>
<tr>
<td>W</td>
<td>0.5*</td>
</tr>
<tr>
<td>Al+Ti</td>
<td>0.35*</td>
</tr>
</tbody>
</table>

*maximum

**Core Design**

The basis for the design of the entire power plant was the electrical power output. For nuclear plants, there are two major alternatives: greater or less than 300 MWe. Typical commercial plants operate near 1000 MWe; plants smaller than 300 MWe are termed “small.” Small reactors may also be modular, or able to be combined with other reactors to scale the power output to the required capacity. The required power output is directly related to the power cycle, which produces electrical power for the grid, and
indirectly related to the reactor cycle, which produces thermal power for the power cycle. However, the sizing of the reactor core is dependent upon the sizing of the entire plant.

The reactor volume is a function of the uranium-to-thorium ratio as well as the graphite-to-salt ratio. Two reactor concepts were studied: the single-fluid and the two-fluid designs. These two designs varied the uranium-to-thorium ratio. In the single-fluid design, the U-233 and Th-232 were dissolved in the same salt, and both fission and breeding occurred in the same (center) region of the reactor; see Figure 44. In the two-fluid design, fission occurs in the central zone of the reactor, and the central zone is surrounded by a blanket zone, where breeding occurs; see Figure 45. These zones are separated by a graphite sheath.

In both concepts, the fuel salt flows through channels in moderator elements. The graphite-to-salt ratio is fixed such that the proper thermal power will be produced. However, the geometry may be varied to alter the overall volume of the reactor. The moderator elements are long vertical rods with a circular annulus in the center, through which the fuel salt flows. The geometries studied in this report were square and hexagon.

![Horizontal cross-section of single-fluid MSBR core](image)

Figure 44. Horizontal cross-section of single-fluid MSBR core [133].
Safety Systems

The two main safety systems in the reactor design were the control rods and the salt plug. Neither of these systems was dispensable: control rods are present in all reactor types and the salt plug is a feature specifically designed for the MSBR, so no alternatives were considered. However, the geometry of the control rods was dependent on the geometry of the moderator elements; squares and hexagons were considered. The design of the salt plug system required the specification of drainage time.

3.2.3. Reprocessing System Design

The alternatives of the fuel reprocessing system align with the two reactor core design concepts: single-fluid and two-fluid. In the single-fluid design, the entirety of the fuel salt is sent through the same reprocessing system; see Figure 46. In the two-fluid design, the core and the blanket are reprocessed in separate systems; see Figure 47.
Figure 46. Block flow diagram of single-fluid MSBR fuel reprocessing cycle [135].
3.2.4. Thermal Cycle Design

The team considered power cycles using water, helium, and CO$_2$ as the working fluid. Each system posed different advantages and disadvantages.

Helium

As many helium power cycles are currently employed in industry, the technology needed to implement such systems is already in place. Another advantage of helium is the fact that it is a noble gas meaning chemical corrosion is basically a non-issue. Since helium is going to be a gas during the entire power cycle, the temperatures can be pushed much higher when compared to water or other fluids which are liquids at room temperature. One of the biggest disadvantages of using helium is that there is not much left that can be used. Helium is not a very abundant material on earth and a large portion of it has been used up, leaving the amount of helium available for power cycles, and other applications, limited. Helium also requires higher temperatures (~850°C) to achieve high thermal efficiencies (~45%).
Water

Water has been used as the working fluid in power plants for ages. This is also a tried and true working fluid. Water is also unreactive with the piping system meaning chemical corrosion is a non-issue with this fluid as well. High density is a desirable property with any working fluid because that means there does not need to be as much fluid in the system, and water has the highest density of the working fluids researched. It is also the most readily available of the researched fluids. However, because of the phase change that occurs, it requires that the water be saturated liquid when it enters the pump. Otherwise, the pump will be destroyed. So either the turbine needs to have a large pressure drop across it, which increases cost, or a lot of heat has to be taken out of the water before it becomes saturated liquid, which decreases performance. Typical steam cycles operate near 35% thermal efficiency, but can get as high as 45% with current technology. The higher thermal efficiencies are attained by making the water supercritical, which requires significantly higher temperatures and pressures; the critical point is at 22 MPa and 374°C. This starts pushing the limits of the material, requiring either more or stronger materials.

Carbon Dioxide

CO₂ has recently surfaced as a viable working fluid in high-temperature cycles. A unique and helpful property of CO₂ is that its critical point is less stressful on the materials and easier to achieve than either helium or water; the critical point is at 7.4 MPa and 31.1°C. This allows for modest temperatures and pressures while still maintaining supercriticality. Thermodynamically, this means that as the pressure increases near its critical temperature it behaves more and more like a liquid meaning decreased energy requirements for compression. An advantage that is not immediately thought of, but comes out in the cost, is the relative size of the turbines used to extract the power, which can be seen in Figure 56. The CO₂ turbine can extract more work in significantly less space. A large reason for lack of use so far is material issues. At high temperatures, the range that this plant would be working at, there are significant corrosion issues when using iron alloys. Fortunately, nickel alloys tend to mitigate this problem.

3.3. Decisions

In the decision-making process, the reactor type was selected first. This allowed for the reactor design, fuel reprocessing, and thermal loop design to proceed in compatibility with the selected reactor type. The latter three tasks were performed in parallel.
3.3.1. Reactor Type

The reactor type alternatives described in Section 3.2.1 were studied first to determine if their scope aligned with the scope of the project. Of primary concern was the availability of data and models from which to develop a process design for the power plant. LWRs and HWRs are the most common current industrial reactors. Therefore, operational data are readily available for these types. For the advanced reactor types, the GIF-IV Roadmap was consulted; see Figure 48.

![GIF roadmap 2002 and 2013](image)

Figure 48. GIF-IV reactor system development timelines [137].

The SCWR, MSR, and GFR were not scheduled to reach the performance stage until after 2015, rendering research data on said reactors sparse. Therefore, these reactor types were deemed too complex for the scope of this project. However, as a test MSR was run at ORNL in the past, data existed for this alternative, so it was reinstated.

After eliminating the unreasonable reactors, the remaining contenders were rated based on the issues identified in the problem statement; see Section 1.1.1. The environmental impact and fuel availability were normalized for all of the alternatives considered, as they all employed the thorium fuel cycle. Therefore, the remaining factors of cost, safety, and efficiency were quantified in a decision matrix; see Table 8.

<table>
<thead>
<tr>
<th>Availability of Coolant</th>
<th>Corrosion</th>
<th>Safety</th>
<th>Thermal Efficiency</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>25</td>
<td>25</td>
<td>30</td>
<td>20</td>
</tr>
</tbody>
</table>
The weights were scaled based on the priorities established in the problem statement. The cost category was affected by both the coolant availability and the materials required to prevent corrosion. Safety considered the robustness of the passive safety features of each design. Efficiency dealt with the temperatures achieved in each reactor, as higher temperature heat is more valuable. Despite issues with procuring of coolant and avoiding corrosion, its inherent safety and high temperature rendered the MSR the best option in terms of the established requirements.

### 3.3.2. Reactor

The major design components of the reactor were the fuel cycle and materials selection, core design, and safety systems. The thorium fuel cycle was selected as part of the initial project objective. The remaining components were adapted from the ORNL studies on MSBRs. As the scope of this project did not include the design of the reactor itself but, rather, the integration of the plant systems and the economic analysis, decisions on these components was influenced on the availability of information on the alternatives.

#### Materials

The reactor materials were selected based on their nuclear, thermal, and chemical properties as well as their cost.

#### Fuel

The decision-making process began with choosing a fuel. The team exhibited a shared interest in the budding technologies associated with Th-232. Originally, the plan was to research reactor-fuel pairs together to find the absolute optimum reactor design in terms of safety, environmental impact, thermal efficiency, and economics. However, this broadened the scope of the project significantly. To maintain feasibility, a fuel was selected first. Still, the thorium fuel cycle was compared to other fuel cycles to create groundwork for further studies.
The energy released per fission is comparable between the three potential nuclear fission fuels; see Table 9.

Table 9. Energy released from fission of U-233, U-235, and Pu-239 [138].

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>U-233</th>
<th>U-235</th>
<th>Pu-239</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneously-released energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinetic energy of fission fragments</td>
<td>168.2</td>
<td>169.1</td>
<td>175.8</td>
</tr>
<tr>
<td>Kinetic energy of prompt neutrons</td>
<td>4.9</td>
<td>4.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Energy carried by prompt ( \gamma ) (^-) rays</td>
<td>7.7</td>
<td>7.0</td>
<td>7.8</td>
</tr>
<tr>
<td>Energy from decaying fission products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy of ( \beta ) (^-) particles</td>
<td>5.2</td>
<td>6.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Energy of anti-neutrinos*</td>
<td>6.9</td>
<td>8.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Energy of delayed ( \gamma ) (^-) rays</td>
<td>5.0</td>
<td>6.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Binding energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy of captured delayed neutrons</td>
<td>9.1</td>
<td>8.8</td>
<td>11.5</td>
</tr>
<tr>
<td>TOTAL HEAT PRODUCED</td>
<td>200.1</td>
<td>202.5</td>
<td>211.5</td>
</tr>
</tbody>
</table>

\*does not contribute to heat production

The fission of Pu-239 produces more energy than does U-235 or U-233. In fact, U-233 produces the lowest amount of energy, requiring more reactions to produce the same amount of energy as either of the other fuels.

However, based on the neutronics of each system, the required critical mass of U-233 is less than that of U-235; see Table 10.

Table 10. Critical masses for unreflected spheres of fissile materials [139].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Critical Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-233</td>
<td>16</td>
</tr>
<tr>
<td>U-235</td>
<td>52</td>
</tr>
<tr>
<td>Pu-239</td>
<td>10</td>
</tr>
</tbody>
</table>
As the critical mass of a system depends not only on the fuel but also on the geometry and moderation of the system, the data in Table 10 do not apply in every instance. However, the numbers are diverse enough that, for most reactor configurations, the same trend will be seen: a higher mass of U-235 is needed than U-233, of which more is needed than Pu-239.

Also of importance is the fission cross section within each neutron spectrum; see Figure 49.

![Figure 49](image)

Figure 49. Fission cross sections for U-233, U-235, and U-239 at varying neutron energies [140].

As seen in the cross section graph, the fission cross sections are comparable for all three potential fuels in the thermal region. Pu-239 enters the resonance stage earlier than do U-233 or U-235, rendering it more unpredictable. In the fast region, U-233 exhibits the highest fission cross section. As the MSBR studied in this report was a thermal reactor, where the fission cross sections are approximately equal, the data are inconsequential.

However, the radiative capture cross section must also be studied; see Figure 50. Not only are fission reactions desired, but loss of neutrons due to capture is undesired.
The differences between the nuclei are more distinct for the capture cross sections than for the fission cross sections. In the thermal spectrum, U-233 clearly exhibits the lowest capture cross section, followed by U-235 and Pu-239. In the fast spectrum, however, Pu-239 dips below both uranium isotopes, indicating that the uranium-plutonium fuel cycle is better suited to fast reactors.

The thorium fuel cycle offers benefits over U-235 in terms of critical mass and over both U-235 and Pu-239 in terms of neutron capture. However, it exhibits the lowest energy per fission reaction and the lowest fission cross section in the thermal region.

In addition to its nuclear properties, though, the thorium fuel cycle offers other benefits. Thorium is three times as abundant as uranium on earth. 99.3% of natural uranium is U-238, which is used for the uranium-plutonium fuel cycle; 0.7% is U-235, which is used for the uranium fuel cycle. Thorium is concentrated highest in India and Australia, but the United States also has significant reserves. Thorium is often a byproduct of mining. It is extracted from the desired ore and discarded.

Furthermore, thorium presents less of a proliferation risk. Use of fertile material instead of fissile material, as in the thorium or uranium-plutonium fuel cycle, means that the materials being transported cannot be directly made into weapons. Nonproliferation issues also exist at the other end of the reactor. Remaining fissile material, either from the initial charge or from neutron capture, is of interest in the making of weapons. The thorium fuel cycle, however, produces waste which is denatured by U-232. U-232 is a strong gamma emitter with a half life of 69 years. Waste from the thorium fuel cycle undergoes the same process as current disposal methods, resting in an on-site containment pool before potentially...

Figure 50. Capture cross sections for U-233, U-235, and U-239 at varying neutron energies [141].
being stored in an off-site facility. However, theft of radioactive waste from a holding facility is extremely hazardous due to high amounts of gamma radiation.

**Salt**

The salt selected for this design was 71.7 mol% LiF, 16 mol% BeF$_2$, 12 mol% $^{232}$ThF$_4$, and 0.3% $^{233}$UF$_4$, as was used in the ORNL conceptual design. Its thermal properties were comparable or better than those of water, which is used in most current commercial nuclear plants.

Of the potential anions, oxygenates such as nitrates were eliminated because of chemical instability; they readily transition from NO$_2^-$ to NO$_3^-$. Carbonates were also eliminated due to inability to dissolve high enough quantities of the fuel salts. Fluoride anions were selected over chloride anions because of their lower thermal neutron capture cross sections; see Figure 51.

![Figure 51. Neutron capture cross sections for potential salt anions.](image)

Cations were selected in a similar fashion, using nuclear properties as the deciding factor. Beryllium had the lowest capture cross section, followed by lithium. Therefore, these two constituents were used to make up the salt; see Figure 52. Selecting the eutectic point would yield the lowest-melting mixture. However, the composition selected by ORNL was used so as to retain the same fluid dynamics and neutronics characteristics.
Figure 52. Binary eutectic diagram for lithium fluoride and beryllium fluoride [142].

The addition of thorium fluoride to the mixture yields a new phase diagram; see Figure 53.
Figure 53. Ternary solid-liquid equilibrium diagram for lithium fluoride-beryllium fluoride-thorium fluoride system [143].

The composition selected by the ORNL study was 71.7 mol% LiF-16 mol% BeF₂-12 mol% ThF₄-0.3 mol% UF₄. While this mixture was suitable in 1971, the LiF poses cost issues today. Natural lithium is 92.4% Li-7 and the balance Li-6. However, it must be enriched to 99.99% Li-7 to avoid the production of tritium:

\[
\frac{6}{3}Li + \frac{1}{3}n \rightarrow \frac{4}{2}He + \frac{3}{1}T(+\frac{1}{6}n)
\]  

(29)

The lithium enrichment process is currently not allowed in the United States, as the method of choice uses copious amounts of mercury. There are lithium enrichment plants in Siberia and China, but they sell enriched lithium for $10,000/kg [144], much more than the $15/lb in 1971 [145]. For this reason, given a larger project scope, the team would look into use of different salts.
**Moderator**

It was decided that this reactor will employ graphite as its moderator due to the benefits outlined in the background section: high density, low absorption cross-section, and cost. The infrastructure to produce graphite with the necessary specifications already exists meaning it is readily available now. However, graphite is not the perfect moderator and only has useful life of four years for this reactor [146]. The useful life is determined by the volumetric shrinkage and growth. The useful life of graphite is when the net volume change goes back to zero as can be seen in Figure 54. Another problem with graphite is that it is porous and can absorb $^{135}\text{Xe}$ which has a thermal absorption cross-section of $2.72 \times 10^6$ b. There are techniques that can be used to limit porosity of the graphite to keep $^{135}\text{Xe}$ from leaking into it via metallic or carbide coating, pyrolytic carbon coating, pyrolytic carbon impregnation, or liquid or solid salt impregnation [147]. The coating techniques are less desirable due to the possibility of surface chipping during transportation or manufacturing. Despite the lifetime of four years, additional costs are relatively low, approximately $850,000 per year with OM costs already being nearly $15 million [148].

![Figure 54. Irradiation-induced volumetric changes in graphite at reactor temperatures [149].](image)

**Piping and Vessel Construction**

Hastelloy N, an exotic nickel-based metal was selected to account for high reactor temperatures and chemical compatibility with FLiBe. Other alloys, such as stainless steel were considered qualitatively, but
metallurgy was deemed outside the scope of the project. Stainless steel is less expensive than are nickel alloys. However, its lifetime is lower, due to its lower heat tolerance. Some current small modular MSR startup companies, such as Terrestrial Energy, are considering the use of stainless steel. The low capital cost of a small reactor paired with the short lifetime of the stainless steel and graphite suggest that it may be profitable to replace the entire reactor every eight years.

Core Design

The selection of the size of the reactor was first divided into small modular or not. While economies of scale suggest that larger reactors would be more cost-effective, small modular reactors also present several benefits. First of all, the capital cost of a SMR is smaller than that of a large reactor. Therefore, an investor would take less risk in installing a SMR than a large reactor. Moreover, SMRs are small enough physically as well as power-wise that they can be manufactured off-site and transported, fully intact, to the installation site. Current reactors must be built on-site, requiring higher labor costs. Lastly, the modular nature of SMRs allows them to be matched better to the grid requirements or for use in distributed power. However, the neutronics, which were outside the scope of this project, must be considered in the reactor sizing as well, as smaller reactors exhibit lower fuel efficiency.

An electrical power output of 200 MWe was selected for this project’s plant. This was selected early to eliminate a degree of freedom and allow for advancement of the power cycle design. The reactor design is scalable by power output. The reactor fuel salt volume requirements are then fed to the reprocessing design, which can also be scaled accordingly. The scaling of the power cycle requires more work, however, as the optimization was performed by the team and not taken from previous data.

Although the use of hexagonal moderator elements would result in a smaller reactor volume, it was decided that the graphite could not sustain such intricate structure. Because of the irradiation of graphite, interstitial spaces were designed into the elements; see Figure 55.
Figure 55. Shapes of moderator elements used in fission zone in MSBR [150].

Different diameters are used to ensure the same temperature changes throughout the fission zone. The channels were orificed accordingly to regulate the flow.

**Safety Systems**

The safety systems of the MSBR include passive and active systems. The passive or “walk-away safe” feature is the salt plug. It is located at the bottom of the reactor, above the drain tank. It is cooled by air blowers. In the event of a power outage, the blowers cease to function and the plug melts. The fuel salt is drained into the drain tank, where no moderator is present to thermalize the neutrons. The plug will also melt if the criticality of the reactor rises too much. The reactivity coefficient of U-233 is positive, meaning that, as the temperature increases, it becomes more reactive. The plug is designed to drain by gravity alone, emptying the reactor in under seven minutes.

The active safety features are the same as in any nuclear reactor: control rods. Four rods are positioned at the center of the reactor. Two are composed of graphite and have a positive gain: as they are inserted, the reactivity increases, as more neutrons are thermalized. The other two are neutron absorbers. Possible materials include silver and cadmium. These are inserted in the event of a shutdown, emergency or planned. Their gain is negative, as the insertion of the rods decreases the reactivity by removing neutrons from the fuel salt.
3.3.3. Fuel Reprocessing

The objectives of fuel reprocessing are to remove the fission poisons from the fuel inside the reactor, to recover the U-233, which was bred, and to restore the fertile material to the fuel salt. Fission poisons are those materials produced from the fission reaction which absorb neutrons. The absorbance of neutrons without subsequent fission slows the chain reaction and decrease performance. Removal of poisons allows for continuous operation while maintaining performance.

Single-fluid and two-fluid reprocessing schematics were considered. The team chose single fluid reprocessing over two fluid reprocessing due to the following advantages. First, reductive extraction techniques were developed which showed protactinium and other fission products could be extracted from the salt into a bismuth stream [151]. Second, unlike a two fuel, single fuel system achieves a conversion ratio greater than 1. Third, single-fluid design allows for easy access to replace core graphite. Lastly, single-fluid is not dependent on the graphite in the reactor vessel to keep separate fuel and fertile salt streams [152].

The team is using the single-fluid fuel processing model designed by ORNL; however, the team has scaled the system from servicing a 1000 MWe reactor to a 200 MWe. The overall schematic of the fuel reprocessing system in shown in Figure 46.
3.3.4. Power cycle

The team decided to use a supercritical CO$_2$ recompression cycle (S-CO$_2$) due to its high efficiency at modest operating conditions and low cost. This specific design was developed at Sandia National Laboratories and the block flow diagram of the system is shown in Figure 56. The CO$_2$ is supercritical for most of the cycle, only not being supercritical on the hot sides of the heat exchangers. The recompression designation of the cycle comes from the fact that there are two compressors, a hot and a cold one, that are eventually recombined. For a given compression ratio, compressing a hot fluid will increase its temperature more than compressing a cold fluid. This is helpful because the streams are later recombined increasing the enthalpy of the stream without adding heat from an additional source.

One of the challenges with using a supercritical cycle is that the compressors need to be designed to allow for the rapid change in density. There are supercritical water cycles so the technology is available, but that complexity is not accounted for in the cost model used.

It was decided to not use other power cycles typically associated with nuclear power plants due primarily to cost but efficiency was also considered. A typical Rankine cycle with water as the working fluid requires large capital costs, 30% increase [154], and has lower typical thermal efficiencies, ~30% compared to ~40%. A helium power cycle was found to have an increased capital cost of 15% but had
comparable efficiency [155]. The biggest problem with a helium power cycle is that there is a limited amount of helium available. Some systems that use helium are attempting to switch off of helium due to the shortage.

As previously mentioned, there are chemical corrosion issues to deal with when using the S-CO₂ cycle. To get around this problem, the nickel alloy Incoloy 800H was selected; it offered superior corrosion resistance compared to 316SS and 310SS [156]. Incoloy 800H formed a protective chromium layer, among other layers, that kept the CO₂ from corroding too deeply into the metal [157]. The tests conducted were only done for 1500 hrs.

The material needed for the power cycle and the material needed for construction of the reactor coolant loop are different. This means the construction of the main heat exchanger that delivers heat to the power cycle will be difficult. Corrosion tests were done on various alloys, including Incoloy 800H, using FLiNaK and found that Incoloy 800H had poor corrosion resistance. While the salts tested were not the same as the salts to be used in this design, the mode of corrosion is still similar. Unfortunately, there does not appear to be any data on corrosion of Hastelloy N by CO₂.
3.4. Details

3.4.1. System Architecture

Figure 57. Block flow diagram of reactor system.
Figure 46. Block flow diagram of single-fluid MSBR fuel reprocessing cycle.

Figure 47. Block flow diagram for power cycle.
3.4.2. Integration

For the total design to work, the reactor must produce enough heat energy in order to provide the thermal system with enough energy to output the desired 200 MWe of power. To find this desired heat energy production, the thermal system was solved initially in EES for the necessary heat required from the connecting heat exchanger by setting the required power out and solving the system backwards. Using Flownex software, additional losses were accounted for which provided a more realistic estimate for the system. This analysis calculated a needed heat input from the reactor at 550 MWt. With this value known, the reactor system could be scaled down from the ORNL design to match the system demands. Furthermore, the required fuel reprocessing can be determined through finding the require flow rate through the heat exchanger at the given heat transfer rate.

3.4.3. System Details

Reactor

The overall reactor volume was calculated at 5000 ft³; see Figure 58.
<table>
<thead>
<tr>
<th>Label</th>
<th>Zone</th>
<th>Volume $^3$ (ft $^3$)</th>
<th>Composition (mol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Control Rods</td>
<td>6</td>
<td>100% Graphite (2) 100% Absorber (2)</td>
</tr>
<tr>
<td>B</td>
<td>Fission</td>
<td>443</td>
<td>13% Fuel salt 87% Graphite</td>
</tr>
<tr>
<td>C</td>
<td>Undermoderated</td>
<td>1018</td>
<td>37% Fuel salt 63% Graphite</td>
</tr>
<tr>
<td>D</td>
<td>Annulus</td>
<td>383</td>
<td>100% Fuel salt</td>
</tr>
<tr>
<td>E</td>
<td>Reflector</td>
<td>2491</td>
<td>100% Graphite</td>
</tr>
<tr>
<td>F</td>
<td>Vessel Wall</td>
<td>-</td>
<td>100% Hastelloy N</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>5000</strong></td>
<td><strong>150 m$^3$</strong></td>
</tr>
</tbody>
</table>

Figure 58. Reactor zone volume specifications.
The cost of the reactor was calculated for the construction and operation of the plant; see Table 11.

Table 11. Cost of reactor system for MSBR.

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital Cost (million USD)</th>
<th>Capital Cost (million USD/yr)</th>
<th>Operating Cost (million USD/yr)</th>
<th>Total Cost (million USD/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Vessel</td>
<td>37</td>
<td>5</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Reactor Graphite</td>
<td>28</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Control Rods</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Salt</td>
<td>108</td>
<td>13</td>
<td>42</td>
<td>55</td>
</tr>
<tr>
<td>Startup U-235</td>
<td>13</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Pump</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>14</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Plug Blower</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>15</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Buildings</td>
<td>70</td>
<td>9</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>240</strong></td>
<td><strong>30</strong></td>
<td><strong>54</strong></td>
<td><strong>93</strong></td>
</tr>
</tbody>
</table>

Reprocessing

*Separating Uranium Hexafluoride*

The reactor effluent flows at 1 m$^3$/day and will be detained in a storage tank for approximately 30 minutes to allow the decay heat generation rate to decrease approximately four fold. The salt is cooled to 500-600°C and 1 atm.
The salt stream then passes though the fluorinator where approximately 95% of the uranium content is volatilized as UF₆. The fluorinator bubbles fluorine gas through the salt stream and reacts with uranium via the reactions shown in the following equations.

\[
2UF_4 + F_2 \rightarrow 2UF_5
\]

\[
2UF_5 + F_2 \rightarrow 2UF_6
\]

The salt stream leaves the fluorinator enters the bottom of the main extractor where is contacted countercurrently with bismuth. The main extractor is a packed column. The protactinium and uranium in the salt stream are reduced by lithium and are extracted into the bismuth stream via the following reactions.

\[
UF_4(salt) + 4Li(Bi) \rightarrow 4LiF(salt) + U(Bi)
\]

\[
PaF_4(salt) + 4Li(Bi) \rightarrow 4LiF(salt) + Pa(Bi)
\]

This bismuth stream enters the hydrofluorinator where the dissolved elements are oxidized to fluorides by HF gas. The oxidized materials transfer from the bismuth to the salt. The bismuth stream leaving the hydrofluorinator is essentially pure and is mixed with Li before introduction to the rare earth removal system. The salt leaving the hydrofluorinator passes through fluorinator where uranium is removed as UF₆. The Pa is allowed to accumulate in the Pa decay tank. Once each day, the contents of the Pa decay tank are fluorinated and UF₆ is removed.

**Separating Fission Products**

The raffinate from the main extraction column which contains the salt without uranium or Pa is sent to the bottom of extractor 1. The raffinate from extractor 1 is recombined with the reduced uranium and returned to the reactor. The extract from extractor 1 which contains Bi and fission products is feed to the top of extractor 2. Extractor 2 is a packed column which has approximately 5 stages. LiCl is contacted with the Bi salt mixture. LiCl extracts the fission products and trace amount of thorium from the bismuth mixture. This LiCl is passed through two more extractors Extractor 3 and Extractor 4. Extractor 3 has approximately 3 stages and uses BiLi with a 0.5 mole fraction Li to remove the divalent rare earth elements. Extractor 4 which uses only one stage uses BiLi with a 0.05 mole fraction Li to extract trivalent rare earths. The LiCl which is circulated through these extractors will slowly buildup in pollutants and will in approximately 15 years need to be replaced with fresh LiCl.
All of the extractors in the fuel reprocessing system have a thin layer of frozen salt which acts as a corrosion barrier between the liquid salt and extraction wall. It takes 10 days to completely reprocess the reactor volume. A gas purge is taken from the fuel salt stream inside the storage tank. The off gases are stored in a drain tank for approximately 2 hours to allow for radioactive decay and cooling. The gases are then filtered through particle traps and then absorbed using charcoal beds. The main gases removed are xenon, krypton, and tritium.

*Equipment Sizing and Cost*

The equipment was sized based on the required flow rate coming out of the reactor to recycle the reactor salt volume in 10 days. The cost estimation was based on the cost report from the ORNL MSBR experiment. The cost was scaled using the chemical plant indexes.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Heat Transfer Area (ft²)</th>
<th>Capital Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main extractor</td>
<td>14.2</td>
<td>123,625</td>
</tr>
<tr>
<td>Extractor 1</td>
<td>13.7</td>
<td>115,618</td>
</tr>
<tr>
<td>Extractor 2</td>
<td>217.9</td>
<td>493,625</td>
</tr>
<tr>
<td>Extractor 3</td>
<td>219.8</td>
<td>365,802</td>
</tr>
<tr>
<td>Extractor 4</td>
<td>4.2</td>
<td>25,471</td>
</tr>
<tr>
<td>Hydrofluorinator</td>
<td>19.1</td>
<td>173,289</td>
</tr>
<tr>
<td>Fluorinator</td>
<td>18.1</td>
<td>22,537</td>
</tr>
<tr>
<td>Pa Decay Tank</td>
<td>4070.7</td>
<td>687,960</td>
</tr>
<tr>
<td>Pa Decay Fluorinator</td>
<td>53.5</td>
<td>43,103</td>
</tr>
<tr>
<td>Main Fluorinator</td>
<td>28.4</td>
<td>34,466</td>
</tr>
<tr>
<td>Reduction Column</td>
<td>35.4</td>
<td>33,420</td>
</tr>
<tr>
<td>Salt Purification</td>
<td>3.0</td>
<td>29,479</td>
</tr>
<tr>
<td>UF6 Collection</td>
<td>5.8</td>
<td>6,812</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>2,155,207</strong></td>
</tr>
</tbody>
</table>

The annual cost for fuel reprocessing is shown in Table 13. These values were scaled from the 1000 MWe MSBR run by ORNL.

Table 13. Annual materials costs for fuel reprocessing.
<table>
<thead>
<tr>
<th>Materials</th>
<th>Consumption (kg/y)</th>
<th>Annual Plant Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorine, F₂</td>
<td>23385</td>
<td>257,780</td>
</tr>
<tr>
<td>Hydrogen Fluoride, HF</td>
<td>891</td>
<td>810</td>
</tr>
<tr>
<td>Bismuth, Bi</td>
<td>15415</td>
<td>203,911</td>
</tr>
<tr>
<td>Lithium Chloride, LiCl</td>
<td>984</td>
<td>32,538</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>495,025</strong></td>
</tr>
</tbody>
</table>

**Power Cycle**

To meet a goal of designing a 200 MWe nuclear reactor using the thermal loop seen in Figure 47, a mathematical model was developed using Engineering Equation Software (EES) to understand what temperatures, pressures, and exergy losses should be expected within the thermal loop. Moreover, this analysis would provide a basis for the necessary heat from the reactor which will create the desired power out. The model gave an initial estimate of required heat transfer of approximately 200 MWth and calculated an overall thermal efficiency of 44% for the system.

After the initial optimization was finished, a more in-depth analysis was performed on the thermal loop using a software package called Flownex. Using this software allowed for component sizing, pipe diameter estimates, and simulation of startup and shutdown of the reactor and the stresses on each component. The following sections will provide a brief description of the results of this analysis.
Figure 48. Flownex model used to size components and calculate losses.

**Turbines**

As was stated in the turbine theory section, the main equation governing the work out of the turbine is

\[
W = \dot{m}(h_{in} - h_{out}),
\]

where \(\dot{m}\) is the mass flow rate and \(h_{in}\) and \(h_{out}\) are the enthalpies in and out of the turbine.

Anticipating increased losses in the system, the required work for each turbine was set higher, the values for which can be seen in Table. In order to further optimize and size the turbines, Flownex takes into account the diameters turbines in order to provide a more realistic estimate for mass flow rate given an appropriate pipe diameter. Using the designer tool in Flownex, the work out of the system could be solved for by setting a diameter and solving for the work out:

\[
\dot{m} = \rho V \left(\frac{\pi}{4} d^2\right),
\]
Flownex models the pressure drop across each vessel by

\[ \Delta p_0 = C_k \rho^\beta Q^\alpha, \]  

where \( \alpha \) and \( \beta \) are pressure loss constants set to values of 2 and 1 for this design, \( \rho \) represents the mean density of the CO\(_2\) based on the mean temperature and pressure, and \( Q \) is the volumetric flow rate through the turbine. \( C_k \) is defined as

\[ C_k = \frac{1}{2\hat{A}^2}, \]  

where \( \hat{A} \) is the effective cross section area of the pipe of the turbine. To find this effective cross section area,

\[ \hat{A} = C_d A, \]  

where \( C_d \) is the discharge coefficient, a value which can be altered in optimization, and \( A \) is the physical area of the turbine pipe. The diameter, in combination with the discharge coefficient, are used to size and optimize both turbines. The optimized values for the small and large turbines are summarized in Table 14.

**Compressors**

In the Flownex modeling software, the CO\(_2\) flowing through the system must be modeled as a two-phase fluid, adding to the complexity of the calculations performed in the program. In order to compensate for this complexity, a combination of a centrifugal pump component to find the work and a flow restrictor to simulate the pressure drop were used in combination for the compressors. An example of this assembly can be seen in Figure 59.
The governing equation for the centrifugal pump is

\[ \dot{W} = \dot{m}(h_{out} - h_{in}). \tag{34} \]

The centrifugal pump component simulates the flow of fluid mass through a compressor through the use of work put into the fluid. In order to find the work consumed by the compressor system, the total head is calculated by

\[ \Delta H_T = S \left[ k_1 d_2^2 \omega^2 - k_2 \frac{\omega Q}{d_2} - k_3 \frac{\omega Q^2}{d_2^4} \right], \tag{35} \]

where \( \Delta H_T \) is the total fluid head, \( \omega \) is the angular velocity of the shaft putting rotation work into the fluid, \( d \) is the impeller diameter, \( S \) is represents the pump stages, \( Q \) is the volumetric flow rate through the compressor, and \( k_1, k_2, \) and \( k_3 \) are default coefficients that are used to match a specific pump curve. By setting a volumetric flow rate, head, and rotational velocity, the work out of the system can be solved for.

The mass flow rate found using this set of equations can be found in Table 14.

**Heat Exchangers**

Again, due to the added complexity of modeling a supercritical fluid, the standard heat exchanger components were unusable in this model. As a substitution, several simpler components were assembled to represent the overall heat transfer process. The three components used to model the heat exchangers are pipe components, general empirical relationships, and a heat transfer component.

---

Figure 59. Compressor assembly with centrifugal pump and flow restrictor.
The empirical relationship component is used to model a pressure drop through a heat exchanger. It follows the same equation as Equation 29, with $\alpha$ and $\beta$ still at the same values of 2 and 1. The pipe components are where the heat transfer occurs and can be seen in connection with the heat transfer element in Figure 54. The heat transfer element is used to facilitate heat transfer between the two pipes. The rate of heat transfer can be altered to create the correct outlet temperature of the pipe system by changing the heat transfer coefficient. The rate of heat transfer is determined by

$$\dot{Q} = \frac{(T_A - T_B)}{\frac{1}{A_1 h_1} + \frac{1}{A_2 h_2}}. \quad (36)$$

The overall heat transfer coefficient $U_A$ is determined by

$$\frac{1}{UA} = \frac{1}{A_1 h_1} + \frac{1}{A_2 h_2}. \quad (37)$$

This value for both heat exchangers in the system was solve for and can be seen in Table 15. It should be noted that the thermal conductivity of the pipe was not accounted for in this coefficient due to the possibility of variable pipe thicknesses and materials.
**Overall System Optimization**

Once all components were individually sized, the designer tool was used to link each component together to model the system as a whole. The parameters used in solving the entire system together can be seen in Table 12.

Table 14. Variables used for optimization and sizing in Flownex.

<table>
<thead>
<tr>
<th>Set Value</th>
<th>Optimized Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Turbine Work Out (W_{LT})</td>
<td>Large Turbine Discharge Coefficient (C_d)</td>
</tr>
<tr>
<td>Small Turbine Work Out (W_{ST})</td>
<td>Small Turbine Discharge Coefficient (C_d)</td>
</tr>
<tr>
<td>Reactor Outlet Temperature (T_{16})</td>
<td>Heat In from Reactor (Q_{reactor})</td>
</tr>
<tr>
<td>Reactor Outlet Pressure (P_{16})</td>
<td>Flow Admittance (A_f)</td>
</tr>
<tr>
<td>Hot Heat Exchanger Outlet Temperature (T_{11})</td>
<td>Heat Transfer Coefficient (h_h)</td>
</tr>
<tr>
<td>Cold Heat exchanger Outlet Temperature (T_{9})</td>
<td>Heat Transfer Coefficient (h_c)</td>
</tr>
<tr>
<td>Large Compressor Pressure Out (P_{8})</td>
<td>Mass Flow Rate (\dot{m}_{LC})</td>
</tr>
<tr>
<td>Small Compressor Work In (P_{15})</td>
<td>Mass Flow Rate (\dot{m}_{SC})</td>
</tr>
</tbody>
</table>

The software ran several hundred iteration of the model throughout assembling all of the components. The final results of this sizing and optimization is noted in Table 13. Using these values, a tangible model of this design could be theoretically constructed. This design however does not take into account industry standards and sizes. Further optimization of this system would involve working with outside industries to size this system in order to match common sizes and industry standards.
Table 15. Thermal system sizing parameters.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Turbine</td>
<td>Diameter</td>
<td>0.500 m</td>
</tr>
<tr>
<td></td>
<td>Mass flow rate</td>
<td>761 kg/s</td>
</tr>
<tr>
<td></td>
<td>Discharge Coefficient</td>
<td>0.217</td>
</tr>
<tr>
<td>Small Compressor</td>
<td>Diameter</td>
<td>0.500 m</td>
</tr>
<tr>
<td></td>
<td>Mass flow rate</td>
<td>370 kg/s</td>
</tr>
<tr>
<td>Large Turbine</td>
<td>Diameter</td>
<td>1.00 m</td>
</tr>
<tr>
<td></td>
<td>Mass Flow rate</td>
<td>2150 kg/s</td>
</tr>
<tr>
<td></td>
<td>Discharge Coefficient</td>
<td>0.157</td>
</tr>
<tr>
<td>Large Compressor</td>
<td>Diameter</td>
<td>1.00 m</td>
</tr>
<tr>
<td></td>
<td>Mass Flow rate</td>
<td>2540 kg/s</td>
</tr>
<tr>
<td>Reactor</td>
<td>Heat Requirement</td>
<td>558 MW</td>
</tr>
<tr>
<td>Heat Recovery 1</td>
<td>Overall Heat Transfer Coefficient UA</td>
<td>2430 W/m²K</td>
</tr>
<tr>
<td>Heat Recovery 2</td>
<td>Overall Heat Transfer Coefficient UA</td>
<td>6540 W/m²K</td>
</tr>
</tbody>
</table>

After sizing and optimization of all components in the system are completed, the pipe sizing is conducted to account for high pressures in the pipes. Using the Flownex modeling software, as seen in Figure 48, component sizing of the turbines and compressors allowed for the determination of the pipe diameters as well as the pressures and temperatures throughout the entire system. Using these parameters, the thicknesses of the pipes are determined for maximum tensile stress in the pipes at the maximum pressures in the system and using the yield strength of the pipe material as the maximum allowable stress [158]:

\[
\sigma_t = \frac{a^2 p_i}{b^2 - a^2 \left(1 + \frac{b^2}{\rho^2}\right)},
\]  

(38)
where \( a \) is inner diameter, \( b \) is outer diameter, and \( \rho \) is a boundary condition that, if only internal pressure exists, equals \( a \). Given an inner diameter of 0.5 m, a pressure of 13.5 MPa, represented by the green line in Figure 49, and a yield stress of the Incoloy material 544 MPa after 12,000 hours of use at high temperatures, the thickness of the pipes should be approximately 7.5 mm.

![Graph showing the effect of stress on required pipe thickness](image)

**Figure 61.** Effect of stress on required pipe thickness.

### 3.5. Testing

Physical construction and testing of a nuclear reactor is not in the realm of possibility for this project. However, simulations can be run. In the spring semester, the team plans to investigate the use of UNISIM, a chemical engineering modeling program. If nothing else, the steam-side cycle can be modeled, analyzed, and tested given a heat input from the nuclear reactor. The team hopes to simulate nuclear reactions in a reactor model as well.

Finally, the team plans to attend and present at the TEA Conference in Palo Alto California in June of 2015. This will provide an opportunity to share what we have learned, receive critique on our research and design, and learn from experts on thorium nuclear fuel.
3.6. Implementation

It is the intention of this project that the reactor power plant meet the needs of a real world energy need. The actual customer base and location of implementation will be decided once the reactor design specifications, such as power output, have been determined.
4. Economics

The economic considerations for this plant included both a capital and operating cost estimate and a hypothetical business plan development.

4.1. Design Results

The costs of each system were combined; see Table 16.

Table 16. Summary of costs for nuclear power plant.

<table>
<thead>
<tr>
<th>System</th>
<th>Capital Costs</th>
<th>Operation &amp; Maintenance Costs</th>
<th>Overall Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Loop</td>
<td>$100 million</td>
<td>$40 million</td>
<td>$140 million</td>
</tr>
<tr>
<td>Reactor Loop</td>
<td>$33 million</td>
<td>$60 million</td>
<td>$93 million</td>
</tr>
<tr>
<td>Fuel Reprocessing</td>
<td>$2 million</td>
<td>$1 million</td>
<td>$3 million</td>
</tr>
<tr>
<td>Total Annual Cost</td>
<td></td>
<td>$236 million</td>
<td></td>
</tr>
<tr>
<td>Cost of Electricity</td>
<td></td>
<td>15.8 ¢/kW-hr</td>
<td></td>
</tr>
</tbody>
</table>

The calculated electricity selling cost such that a 30-year loan with 12% interest could be paid off was 16 cents/kW-h, a price higher than is currently offered by utilities companies. To be competitive, the team would need to cut costs. The use of a cheaper salt than LiF is suggested as a starting place. The specific cost is also affected by the size of the plant, indicating that, while incurring a smaller capital cost, the small modular reactor may not be profitable in the long run.

4.2. Business Plan

Team 16 completed a business plan for a hypothetical company called Fissionary Energy. For the business project, it was assumed that the company’s design was successful and repeatable. A summary of the report is included in the following section.
Mission and Vision

A vision and mission statement outlines the founding principles of Fissionary Energy and the goals which Fissionary Energy strives to achieve.

Entrepreneur's vision for the company

Fissionary Energy’s vision is to sell the design of small modular thorium power plants. The company envisions a source of power that mitigates the energy crisis, operates safely, and is environmentally friendly.

Values and principles on which the business stands

The three design principles on which Fissionary Energy was founded are caring, stewardship, and trust. The first design principle is caring. The company demonstrates caring by addressing the world energy crisis. We hope to lessen this issue by providing a source of clean, long-lasting energy. The second design principle is stewardship. Unlike burning coal, nuclear power does not contribute to the carbon footprint. Radioactive waste is a popular source of dissent with nuclear power. By employing thorium, nuclear fuel can be recycled, all but eliminating radioactive waste. Most importantly, the aforementioned design norms are meaningless without trust. A lot of negative stigma surrounds nuclear power because of its association with nuclear plant disasters and nuclear weapons. To combat this view, Fissionary Energy must design safe, efficient, and environmentally-friendly reactors and convey this reality to the skeptical public.

Fissionary Energy’s mission

Our mission is to:

- Contribute to the advancement of nuclear technology while maintaining safety, efficiency, and environmental health.
- Promote trust, caring, and stewardship through our designs.

Industry Profile and Overview

Nuclear power has been around since the 1960s as a result of the Manhattan Project. Despite its 50-year history, only 19% of the United States’ power is supplied by nuclear energy. This is true mostly because of the public’s perception of nuclear power and the government’s refusal to fund research and development. Until the last month, France was pushing for 100% electricity generation from nuclear
sources. There are currently 62 nuclear power plants located in the U.S. producing just over 100,000 MWe. In France, there are 20 operational nuclear power plants, supplying 75% of the country’s needs.

**Company Objectives**

The objectives of Fissionary Energy include operational, financial, and anastigmatic goals. This section addresses the company’s desire to create a consulting firm with enough income to support further research and development. We also hope to address public concerns regarding nuclear energy.

The operational goal of Fissionary Energy is to consult with electric power companies on the design and implementation of small modular molten salt reactors (SMMSR). The financial goal is to turn enough profit from design sales and consulting fees to fund continual improvements on our design. The anastigmatic goal is to combat the stigma of nuclear energy through transparency. The management team will promote communication between the public and nuclear engineers and will dedicate time to creating a positive online and physical presence in the community.

**Strengths Weaknesses Opportunities Threats (SWOT) Analysis**

SWOT is a form of analysis which aids the development of a business plan. It stems from the mission, vision, and goals of the company. By performing this analysis, Fissionary Energy acknowledged the challenges the company will face and highlighted the strengths on which Fissionary Energy should capitalize to combat these challenges. These features include considerations both internal and external to the company. Figure shows a graphical outline of the SWOT analysis. Figure shows a graphical outline of the SWOT analysis. A more detailed description of each facet follows in its respective section.
**Competitive Strategy**

The primary modes of competition are cost, differentiation, and response. Cost refers to the price-value relationship of the product, differentiation to its uniqueness, and response to the company’s ability to adjust to the demands of the market in a timely fashion. The team evaluated Fissionary Energy’s ability to compete on each of these principles and the company will be competing primarily on differentiation due to the unique, cutting-edge design.

**Market Size and Trends**

For the United States, the market size of energy production is on the order of 4,000 billion kilowatt hours per year. As seen in Figure , the energy production has been increasing until the past ten years where it has leveled off likely due to the economic recession.
Total U.S. electricity net generation from 1950 to 2013 (in billion kilowatt hours)*

![Graph showing total U.S. electricity net generation from 1950 to 2013](image)

Figure 50. The annual energy produced in the United States [159].

This 4,000 billion kilowatt hours per year of generation is worth over 430 billion dollars. Over the past couple of year the production of energy has hit a standstill due to the energy crisis, yet the demand continues to increase to the point where large energy companies suggest to their customers ways to reduce their energy use. With the increase of power production, there will be an increase in demand and thus an increase in the size and number of large energy companies looking for new ways to produce additional energy.

**Advertising and Promotion**

Fissionary Energy's message is show that nuclear energy is safe and cost effective. The current lull in energy production can be overcome safely through the implementation of nuclear power plants. Thus, an increase in business will likely result.

In the media, Fissionary Energy will emphasize the nuclear plants’ passive and active safety precautions to counteract the sigma surrounding nuclear power. For example, in the event that the reactor core reaches a critical temperature, an automatic shutoff will commence without the initiation of a technician.
Specifically, safety features will be shown through an online lecture series hosted by the engineering management team.

Fissionary Energy will outsource marketing tasks to an independent specialized company. However, we will rely heavily on the communication of large energy companies to overcome the public’s stigma of nuclear power plants. Much of the selling of the nuclear power plant design will be done by Fissionary Energy reaching out to large energy companies, which will not require a large allocation of money.

**Existing competitors**

Current direct competitors with our product are other power plants. The primary good that the reactors will produce is electricity which is readily acquired from existing technologies. Westinghouse Nuclear is the world’s current leading provider for nuclear power plants.

**Potential competitors**

FLiBe Energy is a company that is dedicated to making thorium reactors a reality. They are in the development phase of their own small modular molten salt reactor that makes 50 MW of power. The company is headed by Kirk Sorensen, a thorium activist, who already has many years of experience in the nuclear industry.

While renewable energies are not a direct competitor with Fissionary Energy, with advances in renewables technologies they could reduce the need for nuclear energy by supplying more power to the grid.

**Company structure**

Fissionary Energy is a limited liabilities company (LLC). It is owned and operated by its current employees, due to the fact that only its six employees (named in Figure ) have invested time and money into the company. The company management outline is modeled as a consulting firm.
Figure 51. Shown is hypothetical management structure of Fissionary Energy.
5. **Project Management**

Project management is the underlying structure that determines the success of a project. To ensure the completion of timely and quality deliverables, organization is necessary. This process includes the organization of team interactions and documents, adherence to a proposed schedule, and evaluation of budgetary requirements. From the analysis of these aspects, the plan of attack was developed.

5.1. **Organization**

5.1.1. **Team**

Team 16 is comprised of four senior engineering students: Meredy Brichford, Christina Headley, Joel Smith, and Thane Symens. These members are responsible for the research, design, analysis, writing, and presentation aspects of this project. They are guided by a Calvin College faculty advisor, Jeremy VanAntwerp, and an industrial consultant, Sigval Berg. The team members meet thrice weekly for senior design class time and at least one additional time. The additional meetings were predicated on the work load of a given week. At these team meetings, each member presented his or her accomplishments for the week and new tasks were assigned to be complete by the following meeting. To keep with the dominance of the French nuclear industry, weekly French phrases were presented by Joel and used by the entire team throughout the week. Individual work time was scheduled on Google calendars; team members were held accountable for the expected time commitment by placing stickers on the team calendar.

Team 16 also regularly consults with their advisors. Meetings with Jeremy VanAntwerp occur on a roughly weekly basis. In these meetings, the previous week’s accomplishments, problems, and the next week’s goals were reviewed. Meetings with Sigval Berg were sparser, as he resides in Maryland. However, the group was able to meet with him for a preliminary evaluation of the project scope and necessary research, followed by two checkups in the second semester. Further communications were conducted telephonically.

5.1.2. **Documents**

All project documents are kept in a senior design shared folder in Microsoft OneDrive. Each team member has editing capabilities to these documents. The project’s subcategories are organized in folders within the parent folder. These categories include meeting minutes, research notes, presentations, and reports.
5.2. Schedule

At the beginning of the first semester, a work breakdown schedule (WBS) was created to organize the sequence of required tasks and deadlines; see Figure 62.

![Figure 62. Preliminary WBS for first semester.](image)

The duration of each task was estimated by the required finish date and the difficulty of the task. From the duration and the finish date, the start date was determined. A similar method was used to develop the schedule for the second semester; see Figure 63.
Figure 63. WBS for second semester.

5.3. Project Budget

Team 16’s deliverables will include reports, posters, and presentations. A physical model will not be built, thus construction material is unnecessary. Therefore, the use of the project budget is limited to TEA Conference expenses. The team will present at the seventh annual TEA Conference in Palo Alto, CA. Expenses include registration and transportation.

5.4. Approach

The team recognized that significant background research was needed in the realm of nuclear science and engineering. The first semester was spent building the knowledge equivalent to that of an introductory nuclear engineering course. The reactor type was also chosen in the first semester. Reactor research was divided and conquered: each member researched three thorium-compatible nuclear reactors, focusing on environmental impact, safety, efficiency, and feasibility within the project scope.

The second semester was focused on design. The plant design was split into reactor loop and thermal systems design.
6. Conclusion

The team investigated the design of a nuclear fission power plant using the thorium fuel cycle. The MSBR was selected as the reactor, and the reactor and reprocessing systems were studied. A supercritical CO$_2$ recompression Brayton cycle was selected for the thermal loop, and the system was optimized. Upon performing an economic analysis, it was determined that the plant was not economically feasible with the current design.

The scope of this project was limited by the data available on the selected systems. Modeling and simulation were inhibited by the lack of structure for the designs. Therefore, the design work was limited to analysis of other institutions’ designs. However, the experience of completing the senior design project was beneficial. The team learned communication skills, especially across the concentration lines, a skill-set which will be helpful in industrial work, where different types of engineers collaborate regularly. The team also learned the importance of accepting help from those with more experience. The individuals who helped the team are acknowledged on the next page.
7. Acknowledgements

The Nuclear Family would like to thank

Professor Jeremy VanAntwerp for serving as the team’s faculty advisor and for his guidance in the process of completing this project.

Sigval Berg for serving as the team’s industrial consultant, especially for his nuclear expertise, informative documents, and continual support.

Professor Aubrey Sykes for his input on project ideas.

Professor Matthew Heun for consulting on the power cycle calculations.

Stephen Theron for providing assistance in the Flownex simulation of the power cycle.

Dr. Alan Waltar for discussing reactor type alternatives with the team and for providing information on modular reactors.
References


[14] Ibid.


[17] Ibid.


[35] Martin, pg. 11.


[41] Ibid, p 401.


[43] Ibid, p 403.


[88] Ibid.
[89] Ibid.
[90] Ibid.
[91] Cameron
[92] Canada
[93] Cameron
[94] Canada
[96] Ibid
[101] Ibid
[102] Ibid
[103] Ibid
[105] Miller, pg. 78
[114] Thorium fuel cycle book

[155] Ibid.


[157] Ibid.


Appendices

Appendix A: Index of chemical symbols

Appendix B: Cost models

Appendix C: State points for S-CO₂ recompression cycle

Appendix D: TH and TS diagrams for thermal system components
## Appendix A: Index of chemical symbols

<table>
<thead>
<tr>
<th>Ac</th>
<th>Actinium</th>
<th>Es</th>
<th>Einsteinium</th>
<th>Na</th>
<th>Sodium</th>
<th>Se</th>
<th>Selenium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>Silver</td>
<td>Eu</td>
<td>Europium</td>
<td>Nb</td>
<td>Niobium</td>
<td>Sg</td>
<td>Seaborgium</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminum</td>
<td>F</td>
<td>Fluorine</td>
<td>Nd</td>
<td>Neodymium</td>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
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Appendix B: Cost models

Reactor Systems: Guthrie cost estimation

Power Cycle

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<td>$1.55 \times \dot{m} \ln \left( \frac{P_{in}}{P_{out}} \right) \left( 1 + e^{0.0337 \ln^{-54.4}} \right) \frac{1}{0.92 - \eta_s}$</td>
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<td>Heat Exchanger</td>
<td>$6389 \times \left( \frac{E_{trans}}{LMTD \times U} \right)^{0.8}$</td>
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Appendix C: State points for supercritical CO₂ recompression cycle

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<th>Pressure (kPa)</th>
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Appendix D: TH and TS Diagrams for Thermal System Components

Small Turbine

TS Diagram: Small Turbine

TH Diagram: Small Turbine
Large Turbine

**TS Diagram: Large Turbine**

**TH Diagram: Large Turbine**
Small Compressor

TS Diagram: Small Compressor

TH Diagram: Small Compressor
TS Diagram: Large Compressor

TH Diagram: Large Compressor
Hot Heat Exchanger

**TS Diagram: Hot Heat Exchanger**

- **Statepoint 3 (584 °C)**
- **Statepoint 11 (525,30000 °C)**
- **Statepoint 4 (153 °C)**
- **Statepoint 10 (133 °C)**

**TH Diagram: Hot Heat Exchanger**

- **Statepoint 4 (153 °C)**
- **Statepoint 10 (133 °C)**
- **Statepoint 11 (525 °C)**
- **Statepoint 3 (584 °C)**
Cold Heat Exchanger

TS Diagram: Cold Heat Exchanger

TH Diagram: Cold Heat Exchanger
Heat Rejection

TS Diagram: Heat Rejection

TH Diagram: Heat Rejection