Exploring the Improvement of HTGR Economics with Heat Storage for Variable Electricity Output at Base-Load Operations

by

Charles T. Inman

Submitted to the Department of Nuclear Science and Engineering
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Abstract

Nuclear power plants operate most efficiently at a constant power output. This creates problems for nuclear power plants operating in electricity markets with large amounts of non-dispatchable energy generation, where the price of electricity can reach zero as a result of supply overload. Nuclear reactors must sell electricity for extremely low prices or complicate operation by adjusting the output of the reactor core. Heat storage can serve as a solution to this problem by enabling nuclear power plants to store the thermal output of a reactor and convert it to electricity at more profitable times. This study considers multiple design options for a sensible heat storage system with the intent of limiting capital investments required to construct the heat storage system. A novel design based on existing heat recuperator is proposed. This design is integrated into the primary loop of an HTGR reactor to minimize the use of inefficient heat exchangers. The proposed system is connected to the reactor outlet and inlet and operates a separate turbine loop once charged. The heat storage media is chosen to be ceramic brick made of alumina or magnesia, though cast iron and graphite are also considered as candidates. The system is housed in a prestressed concrete pressure vessel with an approximate volume of $25000 - 27000m^3$. A detailed cost analysis must be performed on this system, or any variation, in order to assess the viability of the design in a market setting. By providing a framework for gigawatt-hour scale thermal storage in nuclear reactors, this thesis aims to prompt a greater design focus on coupling heat storage capacity to nuclear power plants.

Thesis Supervisor: Charles W. Forsberg
Title: Principal Research Scientist

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Roll Tech!

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Chapter 1

Introduction

Nuclear power plants (NPPs) are a potential source of bountiful, carbon-free energy, but face challenges when integrating with electric grids. NPPs require a large capital investment in order to be built because of the strict standards of construction and safety required. The operational costs associated with NPPs are also relatively low compared to other non-renewable energy production methods, as the energy obtained per unit of fuel is high. [5] Given these conditions, NPPs operate best at a constant, full power output. Constant operation also has the added benefit of limiting cyclic fatigue on reactor components. [6] [7] However, the variation in the supply, demand, and price of electricity due to market fluctuations makes the ability to vary electric output to the grid desirable.

Large-scale energy storage offers an opportunity to achieve both constant power output of NPPs and varied electrical output to the grid. The ability to store large amounts of energy allows NPPs to convert that energy to electricity at more profitable times of the day, when demand is high or supply is low. This becomes especially relevant as non-dispatchable renewable energy sources become more prevalent in energy production portfolios. [8] Markets with high solar and wind production often see the price of electricity reach zero (or negative as a result of market subsidies) during peak production hours when the sun is high. [8] Figure 1-1 shows this phenomenon in California, where a large amount of solar generating capacity was added between 2012 and 2017.

Figure 1-1: The price of electricity in California on a spring day in 2012 and 2017. Between these days, a large amount of solar generating capacity was added, leading to the price crash at midday in 2017. [1]

Types of energy storage for electricity production include thermal, potential, electrochemical, and magnetic. [6] Thermal energy storage provides multiple advantages in the context of NPPs. Unlike wind and solar photovoltaic, nuclear reactors produce heat and thus naturally couple to thermal energy storage systems. The high efficiency of thermal storage allows for increased electricity production from the stored energy. [6] The high energy density of thermal storage decreases the overall size of the storage system. [6] Given that NPPs produce thermal energy, utilizing thermal storage would minimize the inefficiencies associated with energy conversion.

Thermal storage can operate by storing latent heat or sensible heat. Latent heat involves the transition of the storage media from one phase to another (solid to liquid, liquid to gas, etc.). Latent heat storage allows for isothermal energy storage, which simplifies the recovery of the stored energy. The output of a heat storage system needs to be held at a constant, high temperature in order to maximize efficiency. [9] Latent heat storage couples well with systems that have a smaller temperature difference between the hot and cold components, such as sodium fast reactors or sodium-cooled reactors, as the usage of a phase change material only allows for deviation around the phase change temperature of that material. [6] Latent heat systems are also difficult and expensive to implement at the scale required for use with an NPP. Sensible heat storage involves the changing in temperature of the storage material as it is charged or discharged, without changing the phase of the material. This requires a storage system that changes temperature, which complicates energy retrieval. However, sensible heat storage couples well with systems that utilize a larger temperature difference between hot and cold components, and a larger change in temperature for these systems actually increases efficiency. Despite the challenges associated with varied temperature outputs, solid-state heat recuperators have been shown to operate successfully in multiple industrial-scale settings. [9]

This thesis will recommend a course of action for the implementation of a sensible heat storage system incorporated into the primary loop of a Gas Turbine High Temperature Reactor, a variant of an HTGR design which has a nominal capacity of 300 MWe (GTHTR300). [10] The GTHTR300 design uses helium as a coolant in a direct cycle. [10] A Brayton direct cycle places the turbine in the primary loop, and the turbine is driven by the reactor coolant directly. The GTHTR300 design operates with a hot-to-cold temperature difference of 263 °C. Potential sensible heat storage configurations in the context of a GTHTR300 design are discussed in Chapter 3, incorporating a sensible heat storage system into the primary loop. To charge, the system receives heated helium from the outlet of the reactor core and deposits it into a ceramic storage medium. To discharge, the system receives cooled helium from the outlet of the turbine and siphons energy from the ceramic storage medium. This recommended design seeks to limit the capital costs and operational complexity associated with the implementation of a sensible heat storage system, with other options highlighted if the circumstances that promote certain design choices change.

1.1 Market Influences on Design Choices

The ultimate goal of implementing a large-scale heat storage system within the primary loop of a nuclear reactor is to increase the amount of profit that can be made by selling electricity. The premise of this design is to mitigate the oversupply of electricity caused by non-dispatchable electricity generating sources, namely wind and solar. The exact capacity of the heat storage system (and any turbine modifications required to accommodate those changes) will be dependent on the particular needs of the energy market it is situated in. The system must also be suited to complement the typical behavior of the population, with variations in demand based on the daily, weekly, and seasonal requirements for electricity in that market.

Given that the initial costs of installing nuclear electricity generation are very high, the heat storage system that is designed must seek to limit the capital cost burden on the project. Ideally, the economic performance of the reactor is improved by delaying the conversion of heat to electricity to more profitable times of the day when the market is not over supplied by renewable resources. Additionally, the reactor would be able to earn revenue by supplying reserve capacity for the grid, and other services associated with response to real-time changes on the grid.

1.2 Basic System Overview

A heat storage system for the goal of containing heat for later electricity generation must be able to contain multiple hours of reactor heat generation (or any nuclear reactor that implements this method of heat storage), with a capacity on the gigawatt-hour scale (thermal). The type of technology must be readily available and easy to integrate into the primary loop, exchanging heat with high efficiency and minimal losses. Multiple heat exchanger components would ultimately likely limit the efficiency of the system, with losses incurred at each point of heat transfer. Given the low specific heat of helium compared to liquid coolant options, more heat exchangers would be required to add or remove heat from the multiple phase change components of a latent heat storage system [Fears]. As a result, sensible heat storage is investigated as the mode of heat storage.

The basic layout of the proposed heat storage system is a solid bulk configuration of storage media that is heated and cooled through convection of the helium coolant, known as a chimney style heat regenerator. [3] The storage medium resides in a pressure vessel in order to maintain the high pressure of the primary loop, and contains multiple channels that the helium passes through. The channels increase the amount of surface area available to experience convective heat transfer with the helium. Simple heat storage and retrieval is prioritized when deciding the layout of the heat storage system, to minimize operational complexity that could increase operating costs. The configuration of helium transfer explored in this thesis assumes a simple layout, with one inlet and outlet for the storage vessel, and one mass that is heated. Similar heat recuperator designs have been developed for grid-scale technologies, such as the Firebrick Resistance-Heated Energy Storage system. [9]

The capital costs of investing in a heat storage containment system will scale largely with the size of the vessel that will contain it. The vessel must be able to withstand the high pressures of the primary loop, The price of the pressure vessel will scale with the size of the pressure vessel required, making systems with higher volumetric heat capacity more preferable. In addition to the price of the vessel itself, the storage media of the heat storage system must be included in the price estimate of the final system. Additional costs may be incurred if the structural integrity of the storage medium is compromised and requires partial or total replacement.

Chapter 2

HTGR Design

Sensible heat storage, in the context of an HTGR, can be applied to a variety of reactor designs for the general HTGR framework. General attributes of the most rigorously defined designs remain the same, with helium as a coolant and fuel encased in solid graphite filling the core. The high temperature differences between the core inlet and outlet temperature of all HTGR designs make sensible heat storage more feasible, with higher temperature differences making heat storage and recovery more efficient. [9] Differences arise when comparing operating temperatures, pressures, and components of the primary and secondary loops. For example, Framatome presents the Areva HTGR, an HTGR design that utilizes a Rankine steam cycle, using a heat exchanger from the primary loop to power a secondary steam loop. The steam loop then powers a turbine to produce electricity. [11] The Japan Atomic Energy Research Institute (JAERI) presents the GTHTR300, an HTGR design that utilizes a direct cycle. In a direct cycle, the coolant of the primary loop powers a turbine directly. [10] Table 2-1 displays the general characteristics and design parameters of the Areva HTGR, the JAERI GTHTR300, and the Chinese HTR-PM designs.

In the context of this thesis, the GTHTR300 is chosen as the reactor design to explore the potential of heat storage. The primary motivation for this choice is the use of a Brayton direct cycle by the GTHTR300. By utilizing a direct cycle, the GTHTR300 primary loop can rapidly respond to changes in grid demand. Additionally, a heat storage system using a direct cycle has the flexibility to use the same

Table 2.1: Relevant parameters of the two different HTGR reactor designs that are considered.

Reactor Design	Areva HTGR [11]	JAERI GTHTR300 [10]	HTR-PM [12]
Pressure (MPa)	6.0	6.29	7.0
Reactor Inlet Temperature (°C)	325	587	250
Reactor Outlet Temperature (°C)	750	850	750
Core Temperature Difference (°C)	425	263	500
Cycle Type	Rankine Steam Cycle	Brayton Direct Cycle	Rankine Steam Cycle
Power (MWt)	625	600	500

turbine as the main primary loop or install a second turbine within the primary loop. The Rankine steam cycle used by the Areva HTGR requires the use of a heat exchanger in order to utilize the main steam cycle turbine. The use of a heat exchanger would add inefficiency to the heat storage system. [13] This problem could potentially be avoided by adding an additional direct cycle turbine to the heat storage system, though more difficulties may arise when altering the primary loop to operate two different types of cycles simultaneously. In the case of the GTHTR300 the primary loop is already designed to utilize a direct cycle, leaving open the possibility of using the same precooler and recuperator designs to power a second turbine. As a result of these advantages, the GTHTR300 has been chosen to investigate despite the lower temperature difference.

Other HTGR variants exist that may also be compatible with a heat storage system. The Chinese have developed and built a test reactor, the High Temperature Gas-Cooled Test Reactor (HTR-10) as a precursor for a larger design named the HTR-PM. [12] This design utilizes a pebble-bed fuel design and reaches a temperature difference of 500C across the core which is higher than both the GTHTR300 and the Areva HTGR designs, improving the potential performance of a sensible heat storage system. The current iteration of the HTR-PM uses a Rankine steam cycle but the adoption of heat storage as a priority may prompt a change in the reactor design if it is shown to be viable.

This thesis only considers readily available designs for HTGR variants, all of which have not been designed with the utilization of sensible heat storage as a priority. A reactor designed from scratch to maximize the utility of a sensible heat storage system would seek to optimize storage efficiency while also maintaining the ability to supply baseload electricity production. In order to maximize the capabilities of a heat storage system, a new reactor design would maximize the temperature difference across the core. Efficiency of the heat storage system increases with the temperature difference it operates with, as is described in Section 6.2 Higher operating pressures would increase the efficiency of the sensible heat storage system, as is described in. Maximizing the temperature and pressure of the system would allow for the heat storage system to operate with less heat storage media, allowing the size of the pressure vessel to decrease. Reducing the volume of heat storage media and the pressure vessel would also reduce the cost of implementing sensible heat storage.

Chapter 3

Turbine Configuration

Two power cycle options were examined for use in this preconceptual design of the primary loop. The first would utilize the original layout of the GTHTR300 while adding the heat storage system in parallel with the reactor core, as seen in Figure 3-1. This system would also have a connection between the reactor core and the heat storage vessel for the reactor outlet to charge the heat storage system. This shared turbine configuration would make use of a turbine that is rated to accept a larger flow rate input, given that it would need to be able to accept the full output of the reactor while also accepting the full discharge of the heat storage system. However, the output of these two systems would be mixed, and the maximum temperature that the heat storage system can reach is the output temperature of the reactor. This would lead to a flow that is cooler than the reactor outlet temperature as the heat storage system is discharged. This flow mixing method has been shown to be possible, but may require additional overhead to clear nuclear regulatory standards [9]. The larger concern is the lowering of the input temperature of the turbine, which may decrease performance while adding costs through the use of a more expensive turbine. Additionally, turbines that operate at a power lower than their maximum rated load typically experience inefficiency in electricity production. [7] An outline of this configuration can be seen in Figure 3-1.

Another possible turbine configuration requires a separate turbine system entirely. In this configuration, seen in Figure 3-2, the heat storage system discharges using its

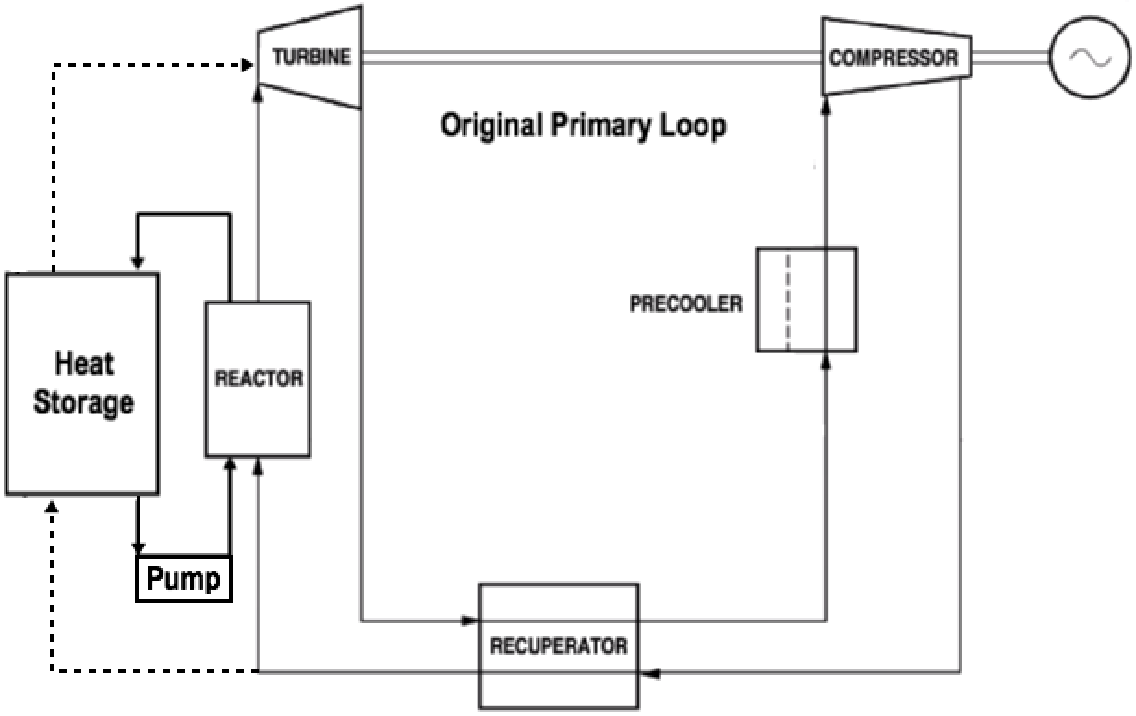

Figure 3-1: A diagram of the primary loop where the heat storage system and the reactor core share one turbine. Coolant would be redirected to the heat storage system in order to charge or discharge the system. Additional circulation components would be required to manage pressure drops due to temperature changes that are not included in the diagram.

own turbine loop while staying connected to the reactor core for charging. The original turbine would only see less than its nominal input while the reactor switched between charging the heat storage system and powering the turbine, an amount of time that should be comparable to powering the reactor on or off. This design would also allow the existing design of the original primary loop to be used, with all of the design choices to be made in the implementation of the heat storage system turbine loop. For the design of the heat storage system turbine loop, more flexibility is added to the system operation depending on the desired behavior of the discharge. Since the temperature of the heat storage system will strictly decrease while discharging from its peak temperature, a turbine that is optimized for varied temperature inputs could be used. Lower temperatures would decrease the efficiency of the output, but may allow the rated temperature output to be produced for longer. [9] The optimization of this turbine configuration would require additional research,The use of the extended primary loop also creates additional options for safety bypass systems, as is discussed in Section 3.1.

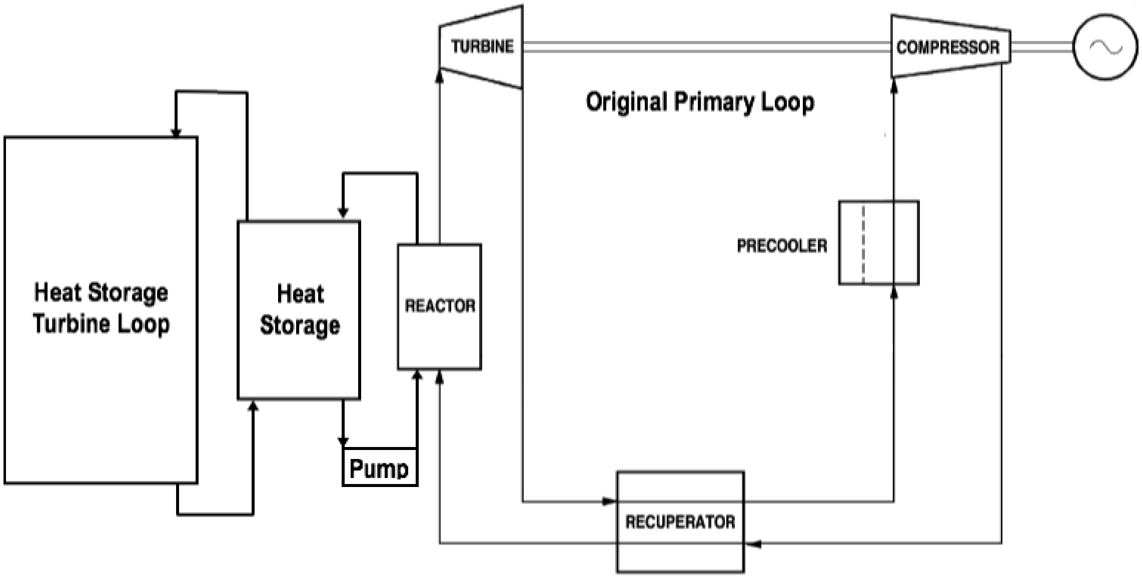

Figure 3-2: A diagram where the nuclear reactor is connected to the original primary loop (right) and a separate loop containing the heat storage system and its accompanying turbine system (left). Additional circulation components would be required to manage pressure drops due to temperature changes that are not included in the diagram.

For the purposes of this thesis, the multi-turbine design will be used for the analysis of the primary loop. This is meant to minimize the design changes that must happen with the behavior of the recuperator, precooler, turbine, and overall flow of coolant in the original primary loop. Transient behavior with the charging of discharging of the heat storage system are easy to qualitatively describe on their own, but add a layer of complexity when mixing with the output of the reactor core. The ultimate goal is to maximize the profitability of this system, which is more likely to be achieved by keeping the original turbine running at full efficiency as much as possible. The additional flexibility made possible by the multi-turbine system may also make the reactor safer, and therefore cheaper to operate and insure. The operating temperatures of any reactor design are well below the possible temperatures that industrial turbines are capable of handling.

3.1 Safety Considerations

The presence of a heat storage system may also increase the safety options of the chosen reactor in various shutdown situations. By adding the heat storage system to a new section of the primary loop, the reactor will be able to operate using one loop at a time depending on which segment of the loop the reactor is powering. If a situation arises where one section of the primary loop must be shut down, the possibility would exist to keep the reactor operating at normal power output while using just one segment of the primary loop. To shut down the heat storage segment of the primary loop, the reactor would simply run under typical conditions by constantly powering the main turbine in the original primary loop. To shut down the original primary loop, the reactor would ideally have the option of using the heat storage loop as it would use the original primary loop. For periods of time shorter than that which exhausts the maximum storage capacity, this would charge the heat storage system. Coupled with potential variation in reactor power, the time to reach full storage capacity could be extended. As the heat storage system reaches maximum capacity, it would ideally reach the outlet temperature of the reactor. If the main loop needed to be shut down for an additional period of time, the system could simply pass through the heat storage vessel as if it were a pipe to power the secondary turbine. Figure 3-3 demonstrates this potential operating mode.

The increased flexibility of primary loop operation would also increase the options available during emergency events when the core is shut down. Decay heat would be able to be directed to the heat storage loop, allowing natural convection to remove the heat from the core. By removing the decay heat from the core, cooling systems would also have greater flexibility in removing the heat from the primary system, such as a potential cooling system used for maintaining the exterior temperature of the pressure vessel. During a loss of coolant accident (LOCA) outside of the core, the reactor would have the ability to cease using the failed component of the primary loop by redirecting the coolant flow, as described above. By implementing a secondary segment of the primary loop, this would reduce the likelihood of a LOCA becoming

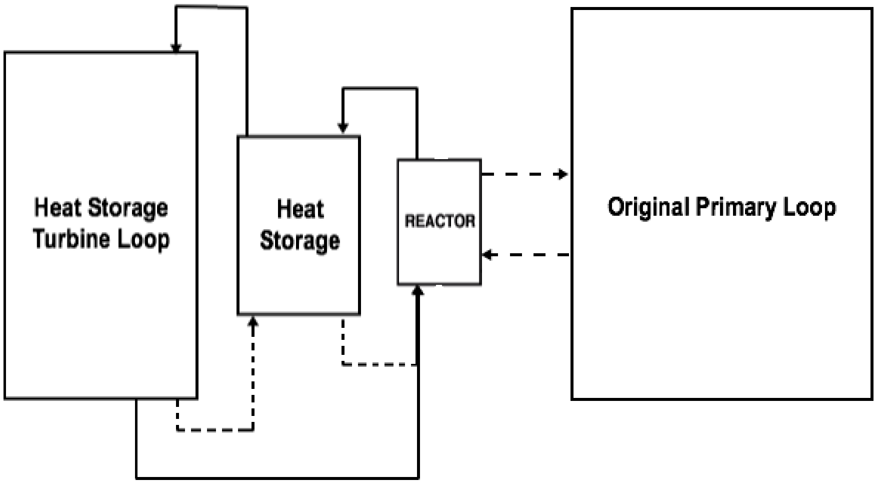

Figure 3-3: A potential operating configuration where the reactor powers the heat storage turbine loop. Solid arrows show where coolant flows and dashed arrows show where coolant does not flow. Additional circulation components would be required to manage pressure drops due to temperature changes that are not included in the diagram.

a "single point failure", where a single disruption in the system causes a total system failure. [14]

HTGR reactor designs do not encounter catastrophic failure in the event of a LOCA, but is unable to function properly when it occurs. In the event of a LOCA where the system is unable to utilize other portions of the primary loop, the accident would still be managed by dumping heat into the exterior pressure vessel of the core. In this event, the pressure vessel would incur significant damage and would need to be replaced, but the core would not melt. [15] By allowing for the flexible utilization of a two-turbine system, a LOCA in one portion of the primary loop would still allow for limited operation in other sections of the loop, sparing the other components of the reactor that would have been damaged otherwise.

Chapter 4

Pressure Vessel

In order to effectively utilize sensible heat storage, a pressure vessel must be used to contain the heat storage medium. The high pressure of the heat storage vessel allows the heat storage system to reside in the primary loop with minimal disruption to the primary loop itself. By placing the heat storage vessel in the primary loop the design also eliminates the use of heat exchangers to transfer the heat to a secondary loop, which would add inefficiency to the system. Maintaining high pressure within the heat storage system also promotes efficient heat transfer due to the increased convective heat transfer between the helium coolant and the surface of the heat storage bulk. [13] The expected volume required for the heat storage system varies with the material that is used and ranges from 20000m^3 to 35000m^3 in the materials that are examined in this thesis. The pressure that must be maintained within the vessel will be close to 6 MPa. Table 2.1 lists the designed pressure requirements of each nuclear reactor considered. The volume requirements of the heat storage system will range from 23000 m^3 to 34500 m^3 depending on the material used and is discussed further in Chapter 5.

Pressure vessels of the scale required to implement gigawatt-hour scale heat storage have existed for decades. The power divisions of General Electric (GE) and Rheinisch-WestfÃďlisches ElektrizitÃďtswerk (RWE, a German utility company) are currently developing a new design of large pressure vessels for heat recuperation. The designs, a part of the companiesâĂŹ Project Adele, seek to implement a large scale prestressed concrete pressure vessel as a part of a Adiabatic Compressed Air Storage (ACAS) system. Volume estimates of the Project Adele pressure vessel are not available, but are expected to be on the same order of magnitude of the volume requirement for a pressure vessel of the proposed heat storage system. Once completed, the pressure vessel under development for the GE/RWE Project Adele will meet a higher level of performance than a pressure vessel designed to contain the proposed sensible heat storage system. The design requirements of the Project Adele pressure vessel include an operating temperature of 600C and an operating pressure of air at 100 MPa. The pressure vessel must also use a ceramic liner, as any metal used will corrode from contact with oxygen under such intense conditions. The requirements of the proposed sensible heat storage system coupled to an HTGR include an operating temperature of 750-850 C and an operating pressure of helium at 6 MPa. [5] [2] An early representation of this design released by GE can be seen Figure 4-1.

The pressure vessel coupled to the chosen HTGR design will see higher temperatures, but nearly an order of magnitude decrease in the maximum pressure. There may be concerns about the maximum temperature that the pressure vessel can withstand, but proper insulation would be sufficient for managing the high temperatures. If insulation is not enough to maintain low temperatures on the exterior of the heat storage pressure vessel, simple cooling systems may be added to lower the temperature. The use of helium as the contained fluid would allow for the use of mild steel in the design of the pressure vessel. A clad of stainless steel may be used if mild steel is not sufficient for the interior of the pressure vessel in the event of oxygen contamination. More research must be done or released by GE to assess the viability of the long-term use of a single pressure vessel under the conditions required for nuclear heat storage. Given the investment of GE and RWE into this system as a reliable grid-scale operation indicates that this project, though not yet complete, will likely be possible.

The British Advanced Gas-Cooled Reactor (AGR) design already implements a smaller, yet comparable pressure vessel system. The AGR reactor core operates at an internal pressure of 4.57 MPa at a temperature of 639 °C, occupying a pressure vessel with an internal volume of $7000m^3$. The pressure vessel of the core is made of prestressed concrete with an interior liner of stainless steel. The AGR design is also engineered to contain multiple penetrations for various components of the AGR core, demonstrating the ability of this structure to be engineered to meet heightened specifications, particularly those associated with British nuclear regulatory requirements. [16] Other nuclear reactor designs have utilized prestressed concrete pressure vessels successfully, such as the Fort St. Vrain experimental HTGR. [17]

The size and scale of the AGR pressure vessel demonstrates the feasibility of creating such a pressure vessel to operate as a heat storage vessel in the primary loop. If scaling for size proves prohibitively difficult or expensive, there remains the possibility to utilize multiple pressure vessels of similar size to the AGR core. The AGR pressure vessel is 3 to five times smaller than the desired volume of a pressure vessel for sensible heat storage, assuming the design time for storage is 8 hours of HTGR reactor output as is discussed in Section 6.2.1.

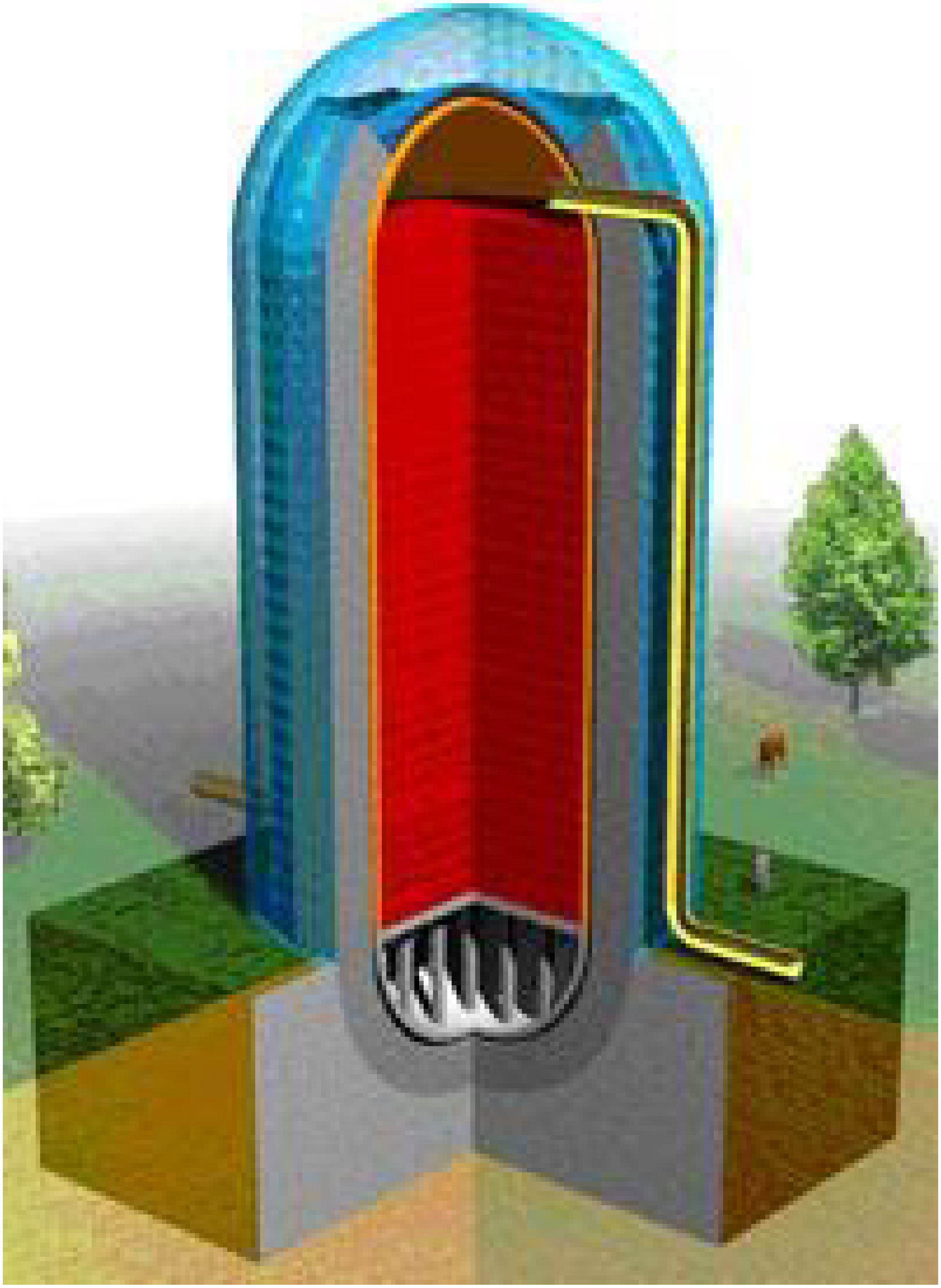

Figure 4-1: A representation of the pressure vessel for the planned GE/RWE Project Adele adiabatic compressed air storage (ACAS) system. [2]

Chapter 5

Storage Medium

The materials chosen as potential storage media include alumina brick, magnesia brick, cast iron, and graphite, with the key properties of each material shown in Table 5.1. The the values listed for cast iron are estimates taken from the average values of multiple grades of cast iron. [18] These materials were chosen with the goal of rapid deployment and construction in mind. All of the selected materials vary in price but can be built into multiple geometries and can manage the highest temperatures produced by any existing HTGR design.

The final recommendation of storage material will depend on which has the best combination of properties that result in a minimal price and cost of a heat storage system. The density of a given material influences both the amount of material that will need to be purchased and the overall size of the pressure vessel required to contain it. Manufacturing abilities also play a role in the selection of a material. For idealized heat transfer, the pressure vessel would contain a large number of long, thin channels as described in Section 6.2, maintaining a relatively high height to diameter ratio. The chosen storage material would ideally be able to achieve this type of structure without needing additional support while configured into an ideal geometry for heat transfer. Vertical orientation would also be ideal, allowing natural convection to aid coolant flow. The ability of the material to withstand thermal cycling and other aspects of the HTGR environment over the long term are also important when determining the viability of any heat storage investment.

Table 5.1: Key properties of the potential heat storage media options.

Material	Alumina [19]	Magnesia [19]	Cast Iron [18]	Graphite [20]
Density (kg/m^3)	3980	3580	7300	1820
Specific Heat ($kJ/kg-K$)	0.795	0.962	0.72 [21]	1.400
Thermal Conductivity ($W/m-K$)	20	30	50	140
Price per Ton (US\$)[1] [9]	100	100	300-600	2000-5000 [22]
Expansion Coefficient ($10^{-6}/K$)	7.5	11.5	12	30 [23] [2]
Melting Temperature (°C)	2072	2852	1538	4600
Estimated Volume of Storage Media Required (m^3) [3]	26000	25500	23000	34500
Estimated Total Price of Storage Media (US\$ * 10^6)	11.4	10.8	55.5-111	138-346
Price per MWh Stored ($\$USD/MWh$)	1796	1571	13579	37721

5.1 Alumina and Magnesia Ceramic

Alumina and magnesia brick are both ceramic materials with similar physical properties. Both have a long history of use in industrial heat recuperators and other high temperature and high performance applications. [24] Their price relative to the other materials would be very cheap, estimated to be \$100/ton (USD) [9]. Alumina and magnesia also offer very low thermal conductivity, which would decrease the lengthwise heat transfer in the storage medium. The decreased heat transfer would assist in maintaining thermal partitioning and improve efficiency, as discussed in Section 6.2. Both materials can be manufactured to have a range of densities, but would be close to $4kg/m^3$ at their densest states for heat storage applications. Comparative values for alumina and magnesia can be found in Table 5.1.

The thermal and physical properties of alumina and magnesia are well beyond the requirements for a viable heat storage system operating with a nuclear reactor.

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[1] Prices do not reflect nuclear grade specification and vary based on quality of material used.

[2] Value derived from a model, not experimental

[3] Assuming a storage media volume fraction of 0.9 and 4800 MWh of thermal output stored.

Alumina and magnesia both have relatively high melting points, a characteristic of most ceramics, with high-performance grades operating comfortably at temperatures as high as 2000C. [19] The highest rated operating temperature for any existing HTGR design is 950C, leaving 1000C of buffer between normal operation and temperature-related failure modes for the system if high-performance ceramic bricks are used. Ceramics also exhibit excellent corrosion resistance at high temperatures and have favorable stiffness properties. Alumina and magnesia are susceptible to thermal shock due to their low thermal conductivity, but the rate of heat transfer of the heat storage system is low enough to negate the threat of thermal shock to the system. By using a gaseous coolant instead of a liquid coolant, the relative rate of heat transfer is much lower. [25]

Alumina and magnesia are both susceptible to failure from small defects, which may be exacerbated at high temperatures and pressures. [26] These defects may present a risk to the structural integrity of the heat storage media over time as the system experiences thermal cycles. Ceramics are susceptible to microfractures when undergoing significant thermal expansion and contraction, which have the potential to build up over the lifetime of operation of heat storage system. These small defects may also lead to the production of ceramic dust within the primary loop, which would require filtration to prevent damage to the turbines. Significant structural failures of the heat storage bulk may prevent an evenly distributed flow of helium through the system. These irregularities in flow would create inefficiencies in heat storage and removal and limit the capacity of the overall system by blocking portions of the bulk from experiencing coolant flow. Any system utilizing alumina or magnesia would need to be engineered to minimize this adverse effects of cracking over long periods of time. Modular components can prevent this issue from being prohibitive, as the pressure vessel will also be able to be opened for repairs to the heat storage system.

The geometric configuration of a ceramic heat storage medium would likely draw from established designs used in other industrial-scale heat recuperators. Figure 5-1 shows a typical internal geometry for industrial heat recuperators using ceramic storage media, such as the Cowper stoves used for blast furnaces. [3] Though ceramic materials are unable to match the structural integrity of steel, the strength of brick is suitable for chimney-style heat recuperator applications. Heat recuperators using ceramic heat storage media have regularly been built to heights exceeding 55 feet, though the overall height of the ceramic heat storage medium might be limited without additional structural components. Additionally, the use of thin-walled, long, narrow coolant channels greatly increases transfer efficiency. By using ceramic components, the ability to create these channels may be limited by the material properties of the materials. The diversity of geometries allowed by using ceramic bricks may be limited to what is capable using standard molds and presses to form ceramic bricks, but modular designs like the ones displayed in Figure 5-1 would allow the use of simple repeated components to construct the larger heat storage bulk.

Project Adele, the Adaiabatic Compressed Air Storage (ACAS) project that is being pursued by GE and RWE, utilizes ceramic materials for the interior of the pressure vessel. [2] At the high temperatures and pressures used to operate the conceptual ACAS system, any metal exposed to the air in the system would oxidize quickly. With ceramic options, the threat of oxidation is low, and is further diminished by the presence of helium as the coolant instead of air. Specific details related to the material choice of Project Adele are sparse due to the proprietary nature of the project.

5.2 Cast Iron and Steel

For analytical purposes, average values of different grades of cast iron are considered when discussing the use of iron as a storage media. As a storage material, cast iron would be the densest option of all materials considered, as seen in Table 5.1. The increased density of iron over ceramics and graphite would allow the pressure vessel containing the heat storage system to be smaller for the same amount of heat stored. The price of cast iron is higher than that of ceramic bricks, as seen in Table 5.1, and using cast iron would increase the capital costs associated with constructing the heat storage system. The higher thermal conductivity of any metal used would a

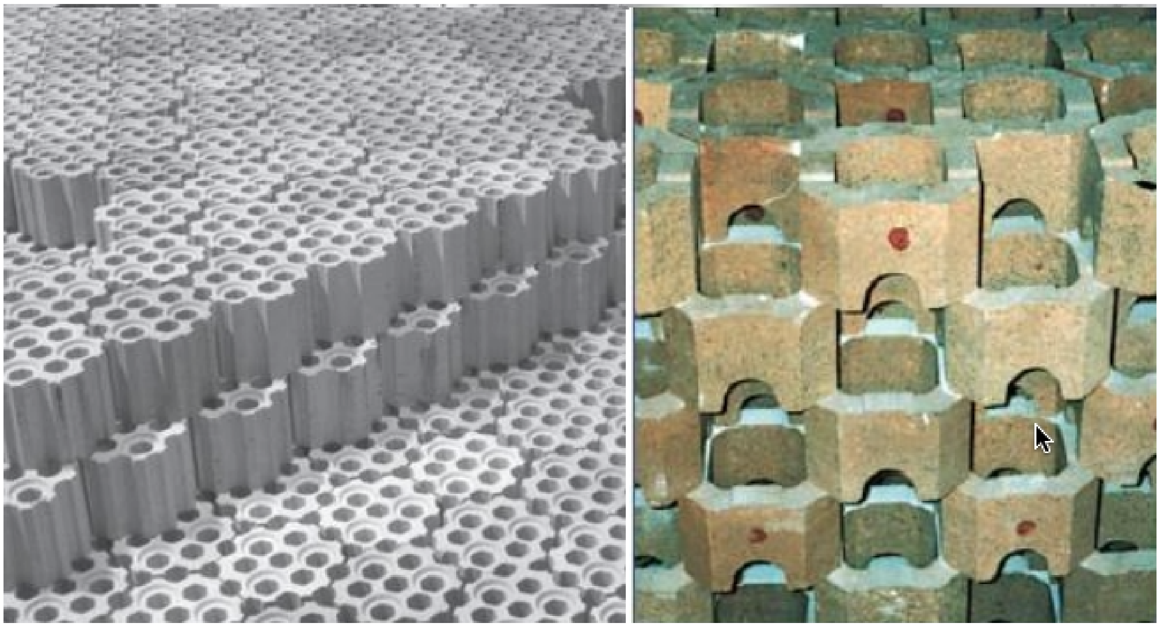

Figure 5-1: Common geometries for ceramic heat storage materials. At higher pressures, the channels would decrease in size as heat transfer becomes more efficient. [3]

detriment to the performance of the system, increasing the lengthwise conduction of heat throughout the channels. However, manufacturing methods would be able to circumvent this by stratifying the bulk with metals or composites of different thermal conductivity. Concerns about thermal diffusion through the system may also be abated if the charge and discharge cycle operate quickly enough to make lengthwise heat transfer negligible.

Corrosion is a greater risk when using any metal instead ceramic brick or graphite. However, the cast iron structure of the heat storage system would be wrapped with a layer of stainless steel or another metal in order to prevent corrosion. In the Areva HTGR design, an alloy of 2Âij Chromium - 1 Molybdenum is the anticipated material for the heat exchanger, and would likely be a viable option for a coating in a metal heat storage medium. [27] In an inert environment with helium as the primary gas, corrosion from the helium coolant is not anticipated as a threat during typical operation. The lack of corrosion provides less area for radionuclide deposition, which may limit contamination. The reduction of contamination could possibly lower decommissioning costs for the heat storage system if the waste material of the used system is less dangerous.

Fission products released into the coolant stream may be a corrosive agent with the steel components of the heat storage system if high enough levels are present in the coolant stream. [28] The deposition of fission products may lead to structural instabilities and cracks in the structure that may be exacerbated by thermal cycles. However, given the high tensile strength of steel, smaller deformations in the system are not likely to lead to incapacitation of the entire system. Given the high degree of flexibility provided by metals in shaping and machining, the geometry of a metal storage medium would have the freedom to be shaped into a wide range of structures promoting heat transfer.

The structural capabilities of cast iron would allow for greater freedom in designing and constructing the geometry of the heat storage bulk. Compared to the other materials being analyzed, cast iron is much less susceptible to brittle fracture at higher temperatures. This allows the cast iron components that would create the bulk to extend lengthwise through the heat storage vessel. As discussed in Chapter 6.2, extending the length of the heat storage system allows for greater thermal partitioning and overall performance. With cast iron as the heat storage medium, structural integrity of the bulk would be less of a concern than a ceramic or composite material.

Long hexagonal assemblies could be used with grooves in the corners that would create cooling channels. This geometry would be be very similar to the reactor core geometry of Russian VVER light water reactor fuel assemblies and sodium fast reactor fuel assembliesâĂŤexcept solid metal rather than a fuel assembly. [4] A photo of the assemblies can be seen in Figure 5-2 with an accompanying graphic to show the general change to the structure in figure 5-3. This geometry implies significance experience in design, testing, and analysis of this type of structure in terms of heat transfer, structural strength, thermal expansion and other types of behavior. However, this system is much simpler, with low rates of heat transfer relative to a fuel assembly and no effects of radiation fields. It is a robust design that maximizes heat storage per unit volume. Geometries could include flat sheets with grooves pressed into them, bundled horizontally in order to create the channels that allow the helium to pass through, as seen in Figure 5-3. Long hexagonal components could also be used, with grooves at the corners that would create channels when combined with other components, as seen in Figure 5-4.

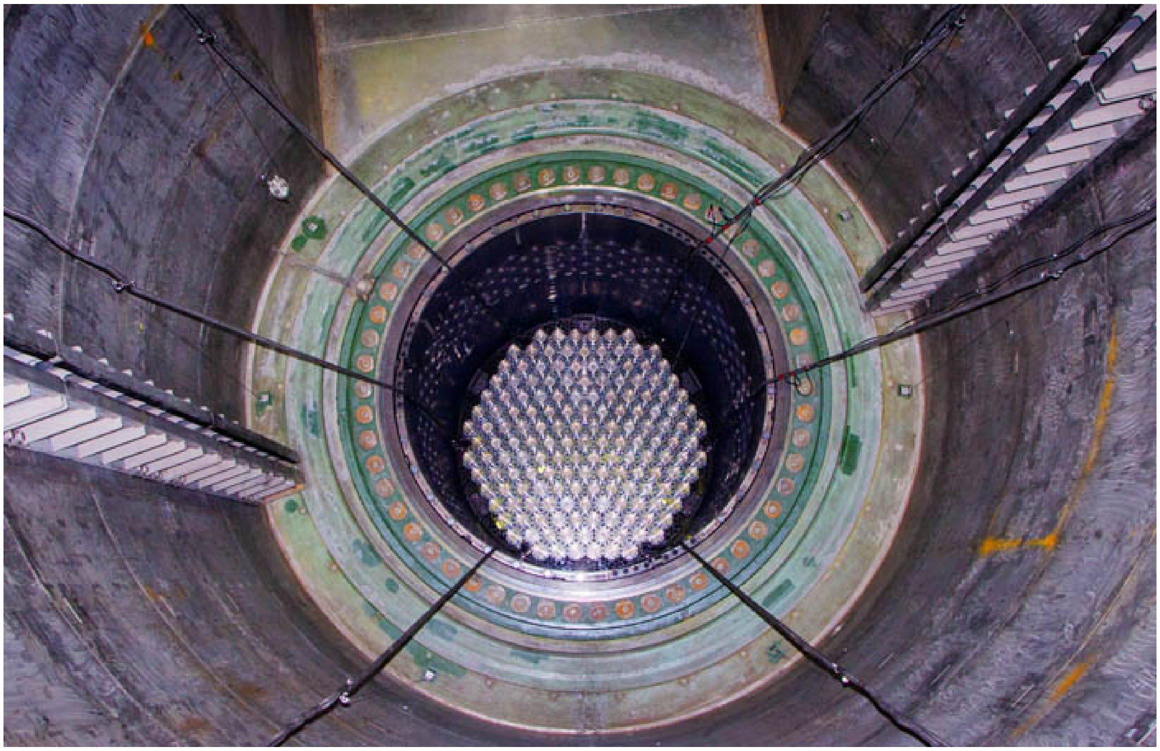

Figure 5-2: A photo of the Russian VVER core, with hexagonal fuel assemblies packed together. A heat storage system using this design could replace the fuel assemblies with blocks of metal in the same shape and configuration. [4]

5.3 Graphite

Graphite is considered as an option for the heat storage medium since it is already used in the reactor core of the GTHTR300. Block graphite forms the bulk of the core, with the reactor fuel embedded inside of it. In the heat storage vessel, the graphite would not contain the fuel pins of the reactor core. The solid blocks of graphite would instead be shaped with multiple long, narrow channels that would assist in facilitating heat transfer between the bulk and the coolant. Since solid graphite is used in the core, it would be compatible with the conditions of the primary loop in a heat storage setting.

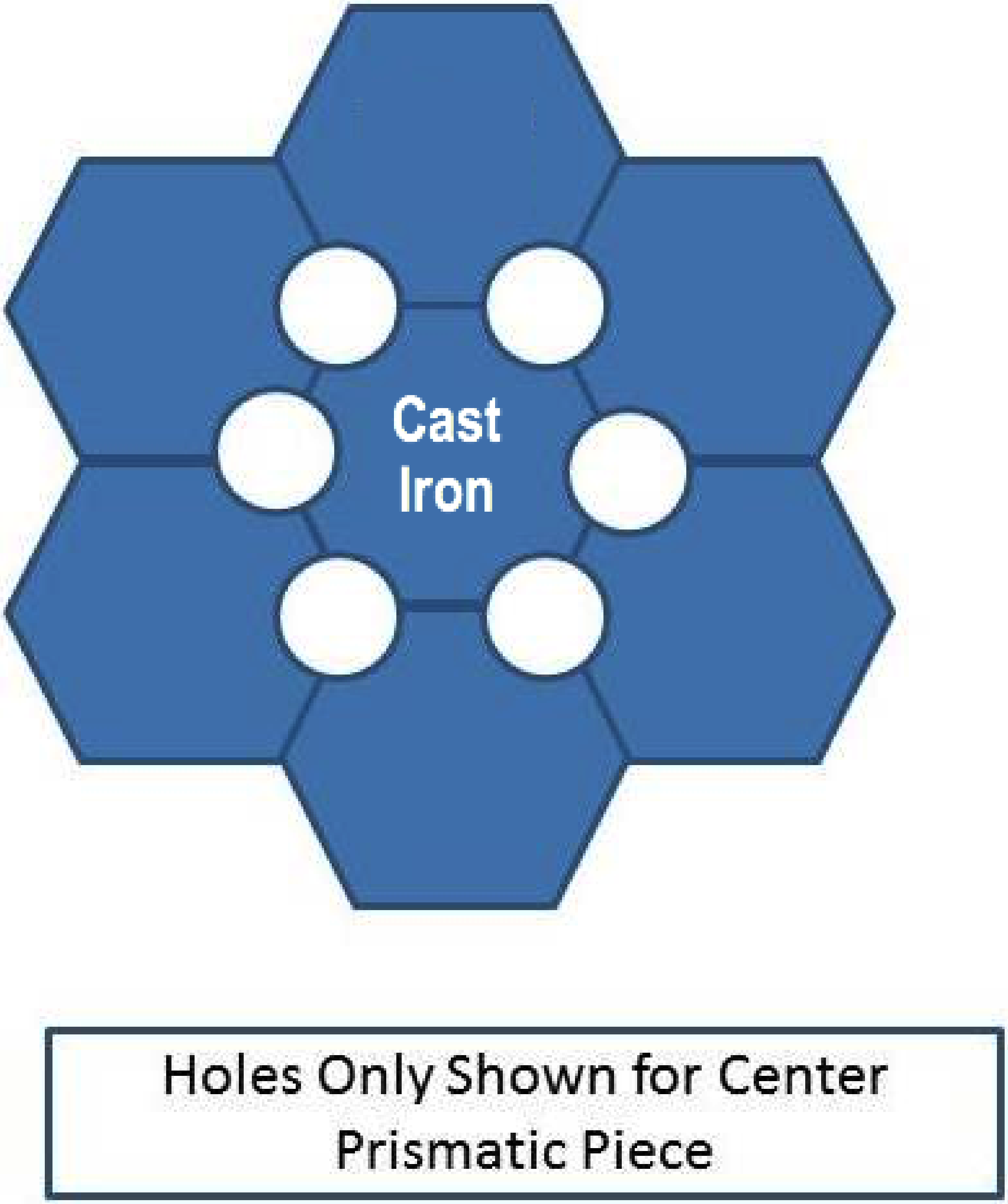

Figure 5-3: A simplified, birds-eye view of a prismatic configuration of steel for heat storage, adapted from the VVER hexagonal geometry seen in Figure X.x.. Long, hexagonal components are packed to form the bulk, while the cutouts on the corners form the channels for the coolant.

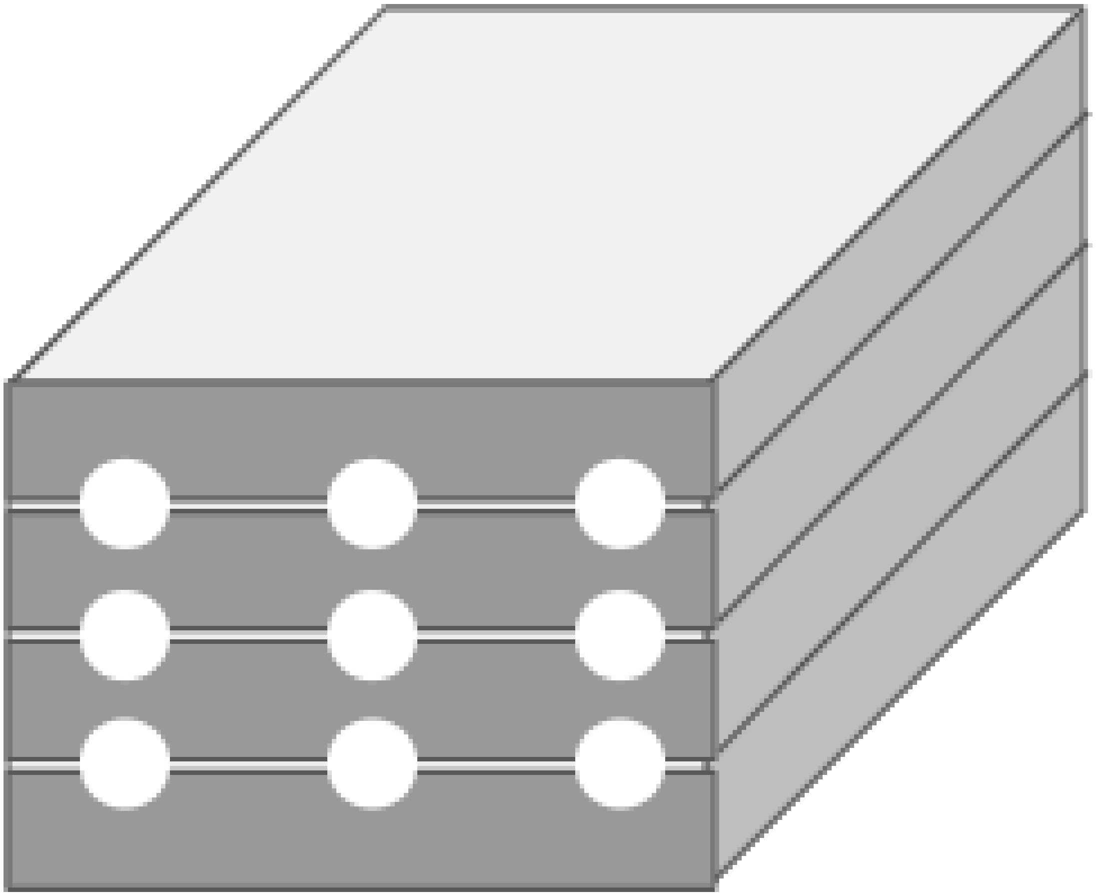

Figure 5-4: A possible corrugated sheet configuration of metal for heat storage. Sheets of metal are packed together and the open space forms channels for the coolant to flow through.

Experimental designs have been made using graphite as both a moderator and heat storage system in the reactor core of an HTGR reactor. The nature of this core heat storage operates on a much shorter timescale than the heat storage system described in this thesis. The core storage takes advantage of the thermal capacity of the core to make small changes to the power output of the reactor. The pressure of the core coolant is adjusted to change the amount of heat that is removed by the coolant flow. These adjustments help account for fluctuations in the energy supply to the grid due to the unpredictability of non-dispatchable resources over short periods of time without changing the power output of the reactor itself. This system is not feasible for gigawatt-hour scale storage, but demonstrates graphiteâĂŹs ability to operate under fluctuating temperatures. [29]

Within the setting of a heat storage system, the graphite components would also be subject to less difficult conditions than the core of a nuclear reactor. Without the fuel components of the reactor, the temperature gradients experienced by the graphite would be lower. In the core, the peak fuel pin temperature can reach 1400C in the GTHTR300 [10], while the exterior coolant ranges between 587C and 850C under normal operating conditions. Removing the extreme temperature gradients that the graphite components in the reactor core would allow for greater range in the design of the graphite components to suit the needs of the heat storage system.

Graphite would likely have multiple limitations as a heat storage medium. Graphite is less dense than both ceramic options and steel, leading to a large increase in the required volume to store a given amount of energy. By increasing the size of the pressure vessel by nearly 50% over the other options examined, the pressure vessel costs associated with the construction of a heat storage system would be larger. In addition to the increased amount of graphite that would be needed, the price per unit of graphite is expected to be an order of magnitude larger than steel, the next most expensive material. This cost may be able to be reduced by using a lower grade of graphite than is necessary for the reactor core. Graphite dust, produced by coolant erosion, is also anticipated as a problem in HTGR designs. [10]

The structural properties of graphite components may also add further limitations to the use of graphite as a heat storage medium. The optimal geometry of the heat storage system incentivizes a longer, narrow channel. Graphite may encounter limitations as a structural material and would likely require additional support within the desired structure, given the relative brittleness of graphite compared to steel or ceramic brick. This brittleness would also lead to problems when manufacturing the graphite components that would create the heat storage medium. However, the structural properties of graphite (brittleness, fracture strength) improve as the temperature of the graphite increases. The final geometry of a graphite bulk design would likely resemble the fuel components of an HTGR design, with an aspect ratio close to one.

The idealized channel shape and vertical orientation would likely require long pieces of graphite. The success of drilling through graphite without compromising the structure would depend on the grade and shape of the graphite pieces used. Ultimately, defects in the manufacturing process would become more likely, exacerbating other issues related to dust generation and cracking. Figure 5-1 shows a potential hexagonal configuration that would eliminate the need for drilling through the graphite pieces. To attain the thin channel walls and elongated structure the hexagonal prisms would have to be made relatively thin, which returns to the problem of brittleness and structural stability.

5.4 Material Selection

Given that the main criteria for selection of different heat storage system features is price reduction, the recommended material for use in the heat storage system is either alumina or magnesia brick. The price of alumina and magnesia per megawatt hour of stored energy is an order of magnitude less than that of graphite or steel and iron. The specific materials used will depend on the selected geometry of the heat storage bulk and the manufacturing limitations of those materials. Ceramic brick is not the densest option available, meaning the size of the pressure vessel will have to increase to accommodate the same capacity. However, the increased pressure vessel size will be compensated for by the large decrease in media price. Table 5.1 outlines the price estimates of all materials considered, where both ceramic options projected to be an order of magnitude less expensive than graphite or steel.

Chapter 6

Modelling Charging and Discharging

6.1 Background

The volume of filler material required to contain a given amount of energy from a reactor is given by the equation

$$Volume_{Filler} = \frac{Q}{\rho \times \Delta h} \tag{6.1}$$

where Q is the amount of heat that must be stored by the system, ρ is the density of the filler material, and Δ h is the difference in enthalpy of the charged and discharged states of the heat storage system. [9] The difference in enthalpy can also be written as

$$\Delta h = c_p \times \Delta T \tag{6.2}$$

Where c_p is the temperature-averaged specific heat capacity of the filler material and ΔT is the difference in temperature of the charged and discharged states of the heat storage system.

To analyze the charge and discharge temperature of the heat storage system over time, a lumped capacitance simplification is used. The lumped capacitance equation is given by

$$T(t) = \Delta T \times e^{(t/\tau)} + T_{cold} \tag{6.3}$$

where ΔT is the difference in temperature of the charged and discharged states, t is the amount of time the system has spent charging or discharging, and T_{cold} is the temperature of the discharged state. The time constant τ is given by

$$\tau = m_{media} \times c_{media} +$$

Where m_{media} is the mass of storage media used, c_{media} is the specific heat of the storage media used, m_{helium} is the mass of helium that fills the system, cv_{helium} is the volume-constant specific heat of the helium, $\dot{m_{helium}}$ is the mass flow rate of helium through the system, and cp_{helium} is the pressure-constant specific heat of the helium. The helium mass term is shown to be negligible, with the calculated values of τ being six orders of magnitude larger than the changes made by accounting for helium mass. The resulting equation that is used for τ is given by

$$\tau = \frac{m_{media} \times c_{media}}{\dot{m_{helium}} * cp_{helium}} \tag{6.5}$$

The time constant τ can also be understood as the ratio between Q and $\dot{Q}$, values given by

$$Q = m_{media} \times c_{media} \times \Delta T \tag{6.6}$$

And

$$\dot{Q} = \dot{m_{helium}} \times cp \times \Delta T \tag{6.7}$$

For the analyses done in this thesis, the value of Q is taken to be a constant and the volume of different storage media required to hold that amount of heat changes. Additionally, the value of $\dot{m}$ is a constant dictated by the design of the GTHTR300 reactor, causing the value of $\dot{Q}$ to remain constant. As a result, the value of τ is material-independent.

6.2 Lumped Capacitance Model

A lumped capacitance model is used to analyze the potential charge and discharge characteristics for the basic heat storage mechanism that is proposed. The lumped capacitance model assumes constant properties of the storage medium, uniform temperature distribution throughout the storage medium, and that the outlet temperature that matches the system temperature. [3] Real systems would have temperature gradients within the system and the material properties of the storage media change with temperature. The lumped capacitance assumption also ignores the internal geometry of the storage medium. However, previous analyses of heat recuperators show that the limitations of the lumped capacitance model does not impede the predictive capability of the model. Charge and discharge curves of the lumped capacitance model matches finite difference models of the entire heat recuperator system with slight variations based on the qualities of the system being modeled. Equation 6.3 governs the behavior of the lumped capacitance model. [3]

In some cases, the lumped capacitance model presents a conservative output of the heat storage system. Figure 6-1 shows the expected output of the lumped capacitance model with Curve A surrounded by various simulations of a heat recuperator system. [3] The lumped capacitance model presents a reasonable estimate of the recuperator performance. Curve B shows a variation that improves the overall performance of the system, as opposed to the Cluster A of simulations that operate according to the governing equation. More channels are added, and the walls of those channels are made thinner than the original simulations. The output temperature maintains a hot stream of coolant for longer, despite tapering off earlier than the other curves. Ideally, outlet temperature profile resembles Curve B in Figure 6-1, with the outlet maintaining a relatively high temperature for as long as possible in order to maximize turbine efficiency.

Certain parameters of the storage bulk geometry can alter the output of the system in order to achieve more ideal behavior of the temperature output. Factors that increase convective heat transfer through the system will improve the overall perfor-

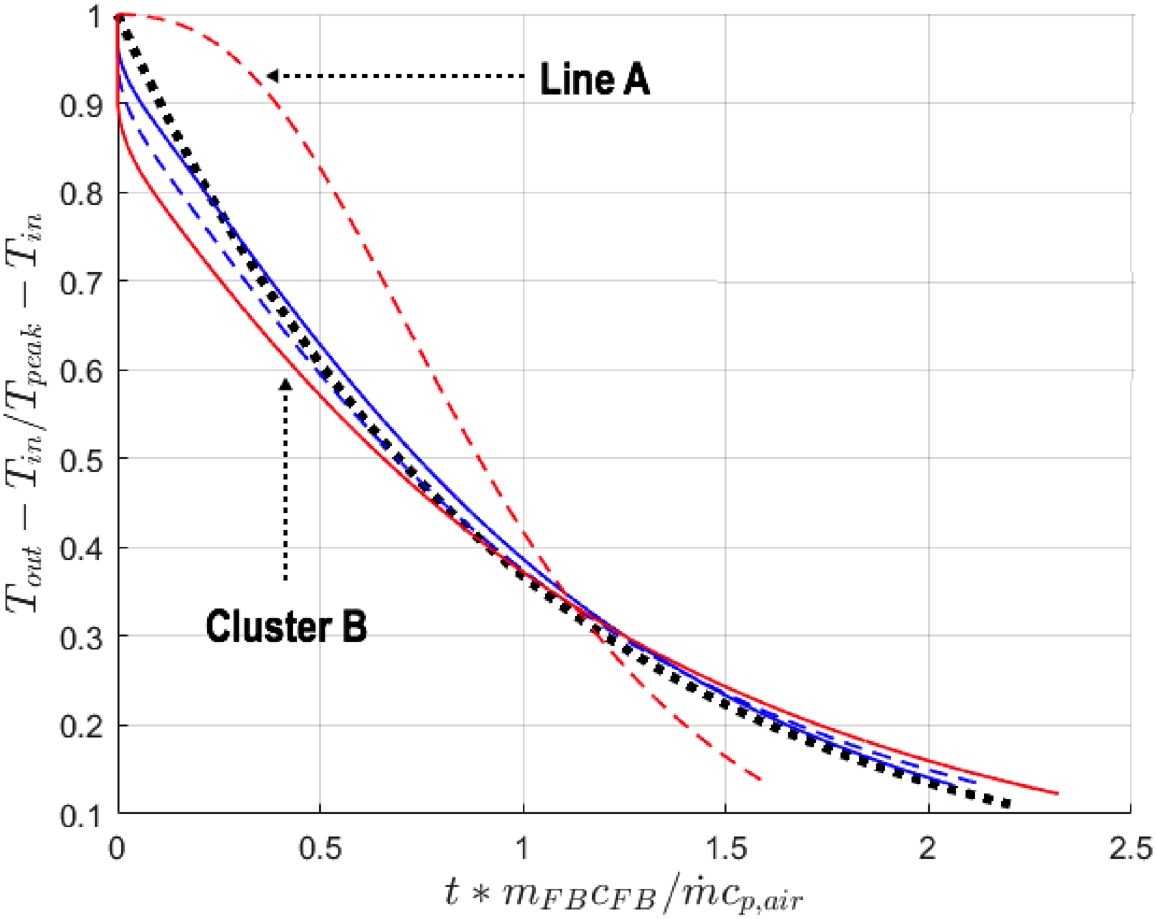

Figure 6-1: Lumped capacitance model of a sensible heat storage system. Line A shows the performance of the model with improve parameters, such as thinner cell walls and longer channels. Cluster B shows models with standard cell dimensions.

mance of the heat storage system. The convective heat transfer is improved with increasing pressure and mass flow of the coolant. Higher pressures allow for the same performance of the system with a higher volume fraction of storage media. The decrease in volume fraction would be achieved by decreasing the size of the channels, decreasing the overall volume of the system. Geometries that have a larger ratio of height to diameter also demonstrate an improvement in performance, with greater improvements being seen at higher operating temperatures. [9] Longer channels, the result of a higher height to diameter ratio, allow for more convection to take place and increased thermal partitioning in the system. [9] The assumption of a uniform temperature distribution leads to conservative estimates of the system performance, providing a floor to be improved upon for analytical purposes.

6.2.1 Charge and Dischagre Characteristics

The timescale that the heat storage system operates on will be a key factor of its use in any energy storage context. The premise of combining gigawatt-hour scale energy storage with a nuclear reactor is shifting the time that the thermal energy produced by the nuclear reactor is converted into electricity. If a nuclear reactor can shift the time that the produced thermal energy is converted into electricity, it can avoid selling electricity to the grid at times of low electricity prices. As non-dispatchable energy sources, namely solar and wind, continue to be deployed onto electricity grids collapses of electricity prices become longer and more common. To fully address this phenomenon the heat storage system of a nuclear reactor should be able to store energy for the entirety of a typical price crash. [30]

The nature and length of the price crash associated with an excess of non-dispatchable energy generation varies with the type of production method that is producing the surplus. For solar electricity generation, the amount of energy produced correlates directly with the amount of sunlight that is available. The productive period of solar generation can last up to 10 hours. If the solar generating capacity is great enough, solar energy can meet the electricity demand entirely and crash the price of electricity. Figure 1-1 illustrates this behavior in California, which added a large amount of solar generating capacity between 2012 and 2017. For solar energy capacity, this behavior is highly predictable. The only relevant variation in production comes from seasonal daylight changes, daily weather patterns such as cloud coverage and humidity, and factors at the generating site.

Wind turbine production has a similar capacity to crash the price of electricity if there is enough wind capacity on the grid to meet the demand for electricity. However, the wind patterns that dictate the amount of electricity produced by wind turbines vary on a less predictable timeline than solar energy generation. Weather patterns that dictate the ability of wind turbines to generate electricity vary on the order of days. Wind speed and direction patterns are also much more variable than solar exposure As a result, predicting wind patterns become a task that is more complex than simply identifying times of the day where wind turbines will likely be able to produce electricity.

For designing and modelling a heat storage system, markets that have high penetration of solar energy are desirable. The relative predictability of solar generation simplifies the operation of a potential heat storage system coupled to a nuclear reactor. As a result, in this thesis, the heat storage system is designed to optimize for conditions where the primary force behind the price crash of electricity is increased solar generation. For markets where this is true a simple pattern of charging and discharging the heat storage system is possible. The charging period, where solar production causes a crash in the price of electricity, is chosen to be 8 hours. The time period of 8 hours is subjective, and does not account for seasonal and daily differences in the amount of sunlight that is available to be captured. However, it represents an average value that captures much of the information required to model the behavior of the system.

6.2.2 Price Crash Consequences

By defining the typical price crash of electricity to last 8 hours during the day, some behaviors can be deduced. Assuming that the heat storage system accepts the full flow of heated coolant from the reactor and a system efficiency that matches the lumped capacitance model, the heat storage system would take 18.5 hours to charge to 90% capacity from an empty state. This would require more than two days of charging in order to complete a full discharge cycle.

The 18.5 hours required to reach 90% capacity may be a conservatively high assumption, and more realistic assumptions about the behavior of the system would likely allow it to charge over a period of two days. When discharging, the system will not return to 0% capacity as the coolant discharge at the lowest 10% of temperatures will not produce a significant amount of energy when powering the turbine. [stack] By not fully emptying the heat storage system, it will be able to save time charging by starting at a higher temperature. Additionally, the 8 hour window may be extended to

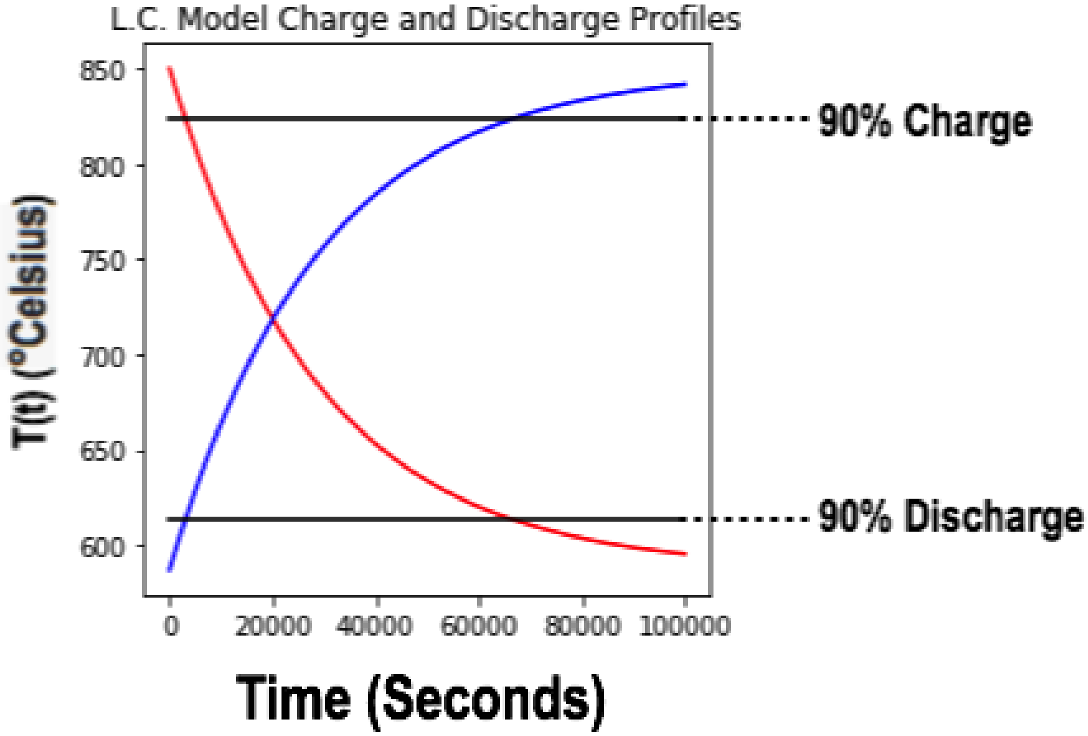

Figure 6-2: The general charging and discharging profile of the lumped capacitance heat storage system. The behavior of the system is material independent, as explained in section 6.1.

include the time where the price of electricity is not near zero, but is still cheap enough to justify sending energy to storage instead of converting it to electricity. Other factors may lead to other charging periods outside of the window of the solar price crash, including supply contributions from other non-dispatchable energy sources or fluctuations in demand.

Storage losses will likely be close to 2-3% of the stored heat per day due to inefficiencies of insulation [stack]. The precise amount of daily losses can be changed by the amount of insulation that the heat storage system is equipped with, reducing losses by adding insulative material. This amount of loss, while small, would add up significantly if the storage period was extended beyond a small number of days. As a result, the ideal cycle that emerges from the combination of the charge time frame and the rate of heat loss minimizes the amount of time that heat is spent in storage, converting heat to electricity as soon as possible. Given the small but non-negligible rate of heat loss, the heat storage system would aim to convert its stored heat to electricity immediately after a charging cycle ends.

The heat storage system would complete the charging cycle over two to three days, depending on the length of the price crashes on those days and the supply and demand profile over that time. Once full, the system would likely be able to discharge fully in the 16 hour window between price crash periods. A discharge from the maximum temperature of the system to 10% capacity would take roughly 18.5 hours, but the system would likely be discharging from below maximum capacity and returning to a temperature above the 10% capacity mark. Depending on the turbine used by the heat storage system, the ability of the system to maintain a hot and pressurized coolant flow may be difficult as the capacity of the system diminishes. At the lower end of capacity, it may be more beneficial to cease discharge and leave the temperature slightly higher to reduce the charge time of the following cycle. The time spent discharging may also vary depending on changes in the supply and demand of electricity to the grid. The activity of the population using the grid may cause spikes in electricity prices, such as the mornings and evenings where both domestic and industrial spaces are active. Variations in the supply of electricity due to weather-related circumstances may also create more profitable times to discharge. These comments are qualitative and require a more advanced analysis, but lay out general concerns about the implementation of this system.

Chapter 7

Conclusions

This thesis outlines multiple design options for a gigawatt-scale heat storage system while narrowing down to certain choices given current circumstances. The final proposed system that is expected to achieve the most improvement of profits would be contained in a prestressed concrete pressure vessel. The pressure vessel would be connected to the primary loop of the GTHTR300 nuclear reactor for charging purposes, but utilize a separate turbine loop for discharging. The storage media of the heat storage system would be either alumina or magnesia depending on which is easier to manufacture into the desired geometry.

The construction of this system would require a relatively high capital investment, on the order of tens of millions of dollars. This price would depend on the raw materials required to fill the storage system, the pressure vessel of such a large size, and the design labor required to integrate this system with a nuclear reactor design while meeting the standards for nuclear operation. However, a reactor equipped with a successful energy storage mechanism stands to gain a significant increase in profits. Ideally the operating cost associated with damage to the core would decrease as the reactor is allowed to operate at steady-state output indefinitely. In markets with high renewable penetration, the reactor would avoid selling electricity at low prices, instead selling electricity at more profitable times of the day. The profit margins and break-even time for an investment into this technology must be developed further before any significant investment can be made in the construction of this system.

Though significant research must be done before a sensible heat storage system of this scale could be implemented, the framework established in this thesis aims to provide a starting point for sensible heat storage system designs. If considered in the early stages of HTGR designs, optimizations may be made for the reactor to operate at baseload output while providing variable electricity to the grid. By establishing that these systems could possibly be applied to existing reactor technologies further exploration into the design space of gigawatt-hour scale heat storage may be explored. If implemented successfully, nuclear power plants that utilize gigawatt-hour scale thermal storage may see a significant improvement in their economic performance. Opportunities exist to incorporate current designs of ACAS systems with nuclear reactor designs, further reducing the development costs of these conceptual plants.

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