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Abstract

Concerns of climate change and sustainable energy policy are driving the deployment of wind and solar energy towards the goal of reducing fossil fuel emissions. In liberalized (deregulated) markets, the large-scale deployment of wind or solar energy results in electricity price collapse at times of high wind or solar output to below the price of fossil fuels. This revenue collapse limits economic large-scale use of wind and solar and reduces the revenue for nuclear plants. The current electrical energy storage options are too expensive to be deployed in sufficient quantity to prevent the price collapse. A less expensive approach to energy storage is required to enable a low carbon-energy grid.

This thesis explores the potential of a new energy storage technology to address the challenges of a low-carbon energy grid: Firebrick Resistance-heated Energy Storage (FIRES). FIRES is a storage technology that takes in surplus electricity, stores the energy as high temperature sensible heat (1200°C-1700°C) in a firebrick storage medium, and outputs the stored heat as hot air when the energy is desired. The stream of hot air can be used to (1) provide heat to high temperature industries in place of natural gas, or (2) be added to a power cycle to produce electricity when it is in demand. FIRES heat storage is nearly two orders of magnitude less expensive than the current energy storage options (on the order of dollars per kilowatt-hour capital cost). Cheap electricity transferred to the heating market by FIRES reduces heating costs and carbon emissions by offering industries cheaper energy than that of the competing fossil fuel, while ensuring revenue to the solar, wind and nuclear power plants. FIRES has “unlimited” storage capacity. If the firebrick is fully charged, FIRES electric resistance heaters will provide hot air to furnaces as long as electric prices are less than fossil-fuel prices. In the long term, FIRES stored heat may be used for peak electricity production in advanced nuclear plants with air-Brayton power cycles, with roundtrip storage efficiencies (electricity-to-heat-to-electricity) near 70%, in class with that of existing electrical energy storage options. Conceptual designs of FIRES heat storage on the megawatt-hour scale were found to be chargeable and dischargeable over periods of several hours or several days as needed. FIRES technology is ready for applications under 1200°C using existing technologies; research is required for higher temperature and high pressure (Brayton power cycle) applications. The applications, conceptual designs, system modeling and preliminary performance and economic evaluations are detailed in the following study.

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I would like to thank my advisor, Professor Charles Forsberg, for his invaluable supervision over the course of my research. His constant forward thinking and willingness to challenge conventional wisdom has led to many new concepts and innovative ideas for harmonizing our energy systems; FIRES is one such idea. It was a pleasure exploring the potential of this concept, and was only made possible by his guidance and insight. I would also like to recognize my thesis reader, Dr. Richard Lanza, for his feedback on this document, as well as his enthusiasm and guidance in the early days of conceptual design.

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I would like to extend my gratitude to Professor H. Ezzat Khalifa, my mentor from Syracuse University, whose teachings and guidance both pushed and inspired me to work hard and learn more about energy systems, and ultimately led me to apply to MIT. I would also like to thank my dear friends Alicia Elliott and Yongsoo Park, who both offered their loyal support and entertained many hours of conversation about heating up a pile of bricks. Finally, I thank my family for their unconditional love and support during my time at MIT and all the years prior.
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<th>Abbreviations</th>
<th>One-dimensional</th>
<th>Intercontinental ballistic missile</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
<td>INL Idaho National Laboratory</td>
</tr>
<tr>
<td>ACAS</td>
<td>Adiabatic compressed air storage</td>
<td>LWR Light water reactor</td>
</tr>
<tr>
<td>AGR</td>
<td>Advanced gas-cooled reactor</td>
<td>MgO Magnesia</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Alumina</td>
<td>MgO-C Magnesia-carbon</td>
</tr>
<tr>
<td>Al₂O₃-C</td>
<td>Alumina-carbon</td>
<td>MoSi₂ Molybdenum disilicide</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed air energy storage</td>
<td>MWe Megawatt (electric)</td>
</tr>
<tr>
<td>CAISO</td>
<td>California Independent System Operator</td>
<td>MWh Megawatt-hours</td>
</tr>
<tr>
<td>CQR</td>
<td>Charge-rate-to-storage-capacity ratio</td>
<td>NACC Nuclear air-Brayton combined cycle</td>
</tr>
<tr>
<td>CQRnet</td>
<td>Difference between CQR and DQR</td>
<td>NETL National Energy Technology Laboratory</td>
</tr>
<tr>
<td>CTAH</td>
<td>Coiled-tube air heat exchanger</td>
<td>NGCC Natural gas combined cycle</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
<td>Ni-Cr Nickel-chromium (Also called Nichrome)</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
<td>RT Room temperature</td>
</tr>
<tr>
<td>DQR</td>
<td>Nominal discharge-rate-to-storage-capacity ratio</td>
<td>NIST National Institute of Standards and Technology</td>
</tr>
<tr>
<td>DQReff</td>
<td>Effective discharge-rate-to-storage-capacity ratio</td>
<td>PV Photovoltaic</td>
</tr>
<tr>
<td>DRH</td>
<td>Direct resistance heating</td>
<td>RFI Radio frequency interference</td>
</tr>
<tr>
<td>EAF</td>
<td>Electric arc furnace</td>
<td>RMS Root mean square</td>
</tr>
<tr>
<td>Fe-Cr-Al</td>
<td>Iron-chromium-aluminum (Also called Kanthal®)</td>
<td>RT Room temperature</td>
</tr>
<tr>
<td>FHR</td>
<td>Fluoride salt-cooled high temperature reactor</td>
<td>RWE Rheinisch-Westfälisches Elektrizitätswerk</td>
</tr>
<tr>
<td>FIRES</td>
<td>Firebrick Resistance-heated Energy Storage</td>
<td>SCR Silicon-controlled rectifier</td>
</tr>
<tr>
<td>GE</td>
<td>General Electric</td>
<td>SiC Silicon carbide</td>
</tr>
<tr>
<td>Gen IV</td>
<td>Generation four (nuclear reactor technology)</td>
<td>TDFₚ Total discharge fraction at constant discharge rate</td>
</tr>
<tr>
<td>HDR</td>
<td>Height-to-diameter ratio</td>
<td>TiO₂ Titania</td>
</tr>
<tr>
<td>HRSG</td>
<td>Heat recovery steam generator</td>
<td>VR High-to-low voltage ratio</td>
</tr>
<tr>
<td>HTGR</td>
<td>High temperature gas-cooled reactor</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>Air channel width</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;fan&lt;/sub&gt;</td>
<td>Delivered fan power</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
<td></td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Specific heat</td>
<td></td>
</tr>
<tr>
<td>PUC</td>
<td>Public Utilities Commission</td>
<td></td>
</tr>
<tr>
<td>D&lt;sub&gt;h&lt;/sub&gt;</td>
<td>Hydraulic diameter</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Heat</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Equivalent surface roughness</td>
<td></td>
</tr>
<tr>
<td>q&quot;</td>
<td>Heat flux</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>Channel friction factor</td>
<td></td>
</tr>
<tr>
<td>Q&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Storage capacity</td>
<td></td>
</tr>
<tr>
<td>F&lt;sub&gt;v,FB&lt;/sub&gt;</td>
<td>Volume fraction of firebrick</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>Resistivity</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Mass flux</td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Gravitational constant</td>
<td></td>
</tr>
<tr>
<td>RR</td>
<td>Relative roughness</td>
<td></td>
</tr>
<tr>
<td>h&lt;sub&gt;air&lt;/sub&gt;</td>
<td>Convective heat transfer coefficient of air</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>HDR*</td>
<td>Product of HDR and the square root of Q&lt;sub&gt;s&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td>H&lt;sub&gt;FB&lt;/sub&gt;</td>
<td>Brickwork height**</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Bulk average velocity</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity</td>
<td></td>
</tr>
<tr>
<td>V*</td>
<td>Ratio of V&lt;sub&gt;max&lt;/sub&gt; to the square root of CQR</td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>Length</td>
<td></td>
</tr>
<tr>
<td>V&lt;sub&gt;max&lt;/sub&gt;</td>
<td>Maximum required voltage</td>
<td></td>
</tr>
<tr>
<td>MISO</td>
<td>Midcontinent Independent System Operator</td>
<td></td>
</tr>
<tr>
<td>V&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>RMS voltage</td>
<td></td>
</tr>
<tr>
<td>N&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Number of firebrick sections</td>
<td></td>
</tr>
<tr>
<td>w</td>
<td>Firebrick wall half-width</td>
<td></td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
<td></td>
</tr>
<tr>
<td>w&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>Effective firebrick wall half-width</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td></td>
</tr>
<tr>
<td>w&lt;sub&gt;INS&lt;/sub&gt;</td>
<td>Insulation thickness</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Time-rate of energy (thermal or electrical)</td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Charge rate</td>
<td></td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Discharge rate</td>
<td></td>
</tr>
</tbody>
</table>

** simply denoted as "h" rather than "H<sub>FB</sub>" in some figures

*** whole word subscripts are not listed
1 Introduction

1.1 Motivation

The energy demand of the world is continuously trending upwards, especially with the rapid development and industrialization of countries such as India and China. As our demands increase, there is rising concern regarding the sustainability of energy sources, in terms of economics, resource availability, and environmental impact. In response to the threat of climate change, there is a drive for a low-carbon energy infrastructure, in which fossil fuels are replaced by low-carbon energy generators, the major candidates of which are wind, solar, and nuclear generators. Emerging energy policies in different areas of the United States and worldwide are mandating a larger portion of carbon-free energy on a yearly basis, typically supportive of the deployment of more wind turbines and solar photovoltaic (PV) panels.

Whereas fossil fuel generators, especially modern natural gas plants, can quickly ramp up or down their power output as needed to match the instantaneous demands of society, each low-carbon energy source is less practically controllable to match this changing demand. Wind and solar generators are intermittent and non-dispatchable energy sources, which can only be controlled by disconnecting them from the grid, essentially wasting capacity, and cannot operate at all when the wind or sun are unavailable. Nuclear plants, although dispatchable and reliable (i.e. not intermittent), typically operate at constant load in the U.S. due to their relatively slow response time, and are less economical to operate at partial load due to their effectively wasted capacity. The wasted capacity of nuclear, wind and solar generators dramatically damages their economics when compared to their fossil fuel counterparts. This is because the major cost of providing fossil fuel energy is the cost of the fuel itself, such that ramping down or shutting off the plant does not imply much waste of capital investment. In contrast, the major cost of providing energy from wind, solar or nuclear is the capital cost of the plant, i.e. the wind turbine, PV panel, or nuclear power plant itself, each of which has a limited lifetime and must recover their capital investment by operating with as high capacity as possible. Lost operating time is therefore lost revenue, and loss of profitability.

Although each of these technologies are used today, the relatively small fraction of energy that low-carbon sources provide to the energy grid when compared to fossil fuels means
that their limited control characteristics can be accommodated by controlling fossil fuel plant output. However, the mandated increase in non-dispatchable intermittent wind and solar energy have already begun to produce mismatches in energy supply and demand that burden the economics of the energy grid in markets of the U.S. and worldwide. Moreover, to ultimately replace fossil fuel generation with low-carbon sources, the challenging logistics of matching supply with instantaneous demand in a low-carbon grid must be addressed.

Under the conditions of increasing market penetration (i.e. market share) of wind and solar energy, fast-responding and high capacity energy storage has the potential to be economically attractive in systems requiring large amounts of energy, enabling the purchase of low-price electricity during surplus periods to be put to use during high-price periods. This benefits both the energy consumer as well as the electricity producer, by enabling the sale of energy that would otherwise not be demanded, but at an economically advantageous price to the consumer. To this end, different approaches to energy storage are being developed, with the goal of improved economics and large scale deployability, the current state of which is prohibitively expensive. Among the many storage technologies being investigated for affordable large scale energy storage, heat storage is an attractive option, with three considerations:

1. **Affordability**: Components for a heat storage system stand to be orders of magnitude cheaper than other technologies such as batteries and more deployable than systems such as pumped hydro or compressed air stations.

2. **Heat Market Sales**: Heat storage enables the easy transfer of surplus energy from the electricity market to the heating market, with essentially 100% conversion efficiency.

3. **Efficient Heat to Electricity (70+%)**: Stored heat using advanced gas turbine cycles can be converted back to electricity via heat addition to an operating power cycle for peak electricity production, at a round-trip storage efficiency (electricity to heat to electricity) comparable to pumped storage efficiency.

A new concept for large scale energy storage, “firebrick resistance-heated energy storage” (FIRES), is being developed with the above considerations in mind, to be coupled with (1) industrial sites (i.e. furnaces and kilns) for cheap industrial heating in place of natural gas, (2) next generation nuclear plants that run Brayton power cycles for the addition of topping heat to
the power cycle with high round-trip efficiencies of 70+%, and (3) other potential applications for converting heat to electricity.

1.2 Thesis Objectives and Scope

In this study, the concept of the firebrick resistance-heated energy storage (FIRES) system was investigated for its viability as a large scale energy storage technology, with the following objectives:

1. Develop a conceptual design of the FIRES system, especially in terms of candidate storage materials, charging system configuration, discharge system configuration, and insulation and containment materials.
2. Propose candidate designs for several specific applications.
3. Evaluate candidate system performance in terms of achievable charge rates and discharge rates with respect to system size, capacity and geometry, and determine design limits.
4. Determine the economic potential of the industrial heat system in terms of cost indicators and market data of candidate deployment locations and projected market data.

Because FIRES is a new approach to large scale energy storage, the objectives of the study were primarily to obtain a breadth of knowledge regarding the possibilities of the technology and answer questions of its viability, rather than optimizing a detailed design for a specific application. Detailed design work could only come after preliminary exploration of the concept warrants further development; this study aims to lay the groundwork for such work.

1.3 Thesis Organization

The following sections of this thesis will proceed as follows:

- **Section 2: Market Implications of Low-Carbon Energy:** The need for affordable energy storage in the case of large scale renewable and nuclear deployment will be demonstrated. The phenomenon of electricity price collapse and the change in market behavior will be described, as well as the market response to the deployment of energy storage.
• **Section 3: System Description and Applications:** The FIRES system will be described, including the basic components, functions, and operations relative to different applications.

• **Section 4: Conceptual Design of FIRES:** Candidate storage materials, charge and discharge systems, insulation and containment will be discussed, and the design space of the chosen configuration will be established.

• **Section 5: System Performance Models:** With the establishment of the candidate configuration and design space, the system performance modeling methods will be discussed, including key assumptions and approximations, which will be used to determine the performance of a given design.

• **Section 6: Preliminary System Performance:** The important performance parameters are identified, most especially the charge and discharge rates achievable for a selected capacity tested with different design parameters. Performance over the option space is mapped, such that the range of capabilities of the technology is determined.

• **Section 7: Preliminary Economic Evaluation:** With the knowledge of system capabilities in terms of its charge discharge and storage capacity, revenue generation is modeled for a given application in specific energy markets using historical data. Estimations of system cost are made and compared to revenue to make a case for economic viability based on several cost scenarios.

• **Section 8: Conclusions and Recommendations for Future Work:** A review of what has been learned, conclusions regarding the potential of FIRES as a storage solution, and a description of the path forward for the technology, including future work required for answering remaining questions regarding the system design and performance.
2 Background: Electricity Price Collapse

2.1 The Low-Carbon Electricity Market

In most electricity markets today, the price of electricity is dictated by the cost of generation from fossil fuel plants. The varying customer demand in deregulated electricity markets is met with changes in fossil fuel electricity generation, and the price is typically set according to the most expensive generator required to satisfy demand. All other generators in the market, including wind, solar, and nuclear generators, also sell at this price. The typical resulting market behavior can be seen in Figure 2.1, which shows the number of hours at which electricity was purchased at different prices from the California independent system operator (CAISO) from July 2011 to June 2012.

A fossil fuel electricity grid is characterized by a normally distributed price curve such as the one shown. Variance in prices are primarily due to times of peak and low demand, where additional fossil fuel plants (“peaking” plants) come online or offline respectively, the ramping and limited
operation of which cause a higher price for their electricity. This market behavior is therefore the result of load following with dispatchable generation.

This behavior is dramatically altered in the transition to a low-carbon electricity grid, most especially due to the introduction of sizable portions of non-dispatchable wind and solar generators. Figure 2.2 shows the changes in energy mix as a result of the addition of solar energy to the California market.

In the base case, electricity is supplied primarily with fossil fuels, in the form of imports from other markets, and simple and combined cycle gas turbines. Small amounts of solar energy, around 2% on an annual energy basis, contribute to matching peak demand in the middle of the day and reduce some of the fossil-fuel electricity production on the market. However, with as little as 6% solar penetration on an annual energy basis, solar PV generates nearly 50% of the demand in the middle of a spring day, reducing imports to zero at that time. At 10% penetration, solar generates approximately 80% of total demand, at which point excess electricity is generated by the remaining combined cycle, hydro, nuclear, and geothermal capacity. In this time of uncontrolled surplus electricity, the market price of electricity will collapse to zero due to the lack of demand relative to supply, or even turn negative such that generators must pay the grid to
take their electricity and transmit it at a financial loss. Even in the case where all other generators were to shut down during peak solar periods, the solar generation itself would produce surplus and collapse the market above 15% penetration on an annual energy basis. Based on analyses in European markets, a similar price collapse in the case of wind generators is found to occur in excess of 30% penetration on an annual basis [3,4].

Despite generally modest renewable penetration nationwide, price collapse already occurs in US markets with renewables today. Indeed, Figure 2.1 above shows an appreciable portion of hours of the year in CAISO that electricity was sold at negative prices. In such cases of price collapse, generators that do not shut down during these periods will sell their electricity at zero or negative prices, resulting in loss of revenue and crippled economics. The most susceptible generators are the low-carbon sources themselves: nuclear, wind and solar energy. Because they have no cost to operate, wind and solar generators will sell electricity at any price above zero. However, in some cases, such as in California, renewable generators can continue earning revenue at prices below zero due to state and local government subsidies and mandated feed-in tariffs that guarantee fixed prices for renewable generation even in a collapsed market [5]. Although operating at a loss, nuclear plants would generally remain online so that they are able to generate electricity when the sun sets and demand is restored. In the case of nuclear and renewable generators, electricity price collapse becomes a major barrier to the economic viability of a low-carbon electricity market, where the introduction of renewables introduces many hours of low-carbon electricity that will be sold at a price near zero [3,4,6].

Beyond the periods of price collapse, all fossil fuel generators that were shut off to accommodate peaking solar power during the day are still required to provide electricity for the rest of the evening or anytime the day becomes cloudy, such that their capacity must always be available for grid reliability. Although the cost of fossil fuel electricity is typically dominated by fuel cost and is not expended while offline, the added expense of cycling plants on and off and the desire to recover capital investment with a reduced capacity factor result in higher fossil fuel generation costs than when compared to the prices that are typically seen in a market without renewables [6]. The result is many hours of higher priced fossil fuel electricity. Figure 2.3 shows the impact of these market changes on the average market price of electricity, as perceived by the whole market and by the owners of solar PV plants, i.e. “solar owners.”
With low penetration, solar owners experience a higher sales price than the average market because they sell at times of relatively high demand. This advantage rapidly drops for higher percentages of penetration of solar due to market collapse. While the average market price also falls initially with the solar owner price, beyond approximately 30% peak penetration by solar the average market price experiences a net rise. This is attributed to the increasing price of electricity produced by fossil fuel plants that are cycling on and off in response to the higher solar penetration. It is therefore understood that, in the absence of storage, an increasing the penetration level of renewable energy becomes a detriment to its own economics as well as the economics of systems that are incapable of responding to electricity market collapse.

2.2 Current State of Energy Storage

Presently there are three widely considered energy storage solutions to meet the storage demands of large scale renewable energy integration. These include pumped hydroelectric storage, compressed air energy storage (CAES), and batteries. Both pumped hydro and CAES have specific geographic requirements making their installation site-dependent [7]. Traditional pumped hydro storage has been developed in those parts of the country with appropriate terrain.
and water supplies; but deployment is limited elsewhere placing large constraints in terms of meeting future demands of rising renewable energy penetration.

Batteries are the most deployable energy storage option, but presently cost approximately $200/kWh to $300/kWh. These prices make the use of electricity storage for preventing price collapse too expensive in the short term, even as renewable penetration continues to rise. The United States Department of Energy (DOE) has set the long term goal of $150/kWh capital cost for electricity storage technologies, with levelized costs\(^1\) under $100/MWh \([7]\). In the context of wholesale electricity market prices, even these long term goals of storage represent a significant increase in cost of a unit of energy that is stored, where typical wholesale market values in places such as California range between $15/MWh and $35/MWh. As higher penetration is reached all renewable generation beyond the point of market collapse will require storage. There is therefore incentive to further reduce these target costs to improve the economics of low-carbon energy sources that require storage.

### 2.3 Effects of Heat Storage Deployment

Heat storage is an alternative option to electricity storage in combatting price collapse and improving the economics of solar, wind, and nuclear generation. There are two key advantages of heat storage when compared to that of electricity storage. The first is that it has the potential to be significantly cheaper, with capital costs on the order of only dollars per kilowatt-hour. The second is that by converting electricity into heat via resistance heating, and storing this energy at high temperatures for on-demand use by the industrial sector, surplus electricity that is of low value in the electricity market may be sold to the heating market instead.

Industrial users would charge their heat storage units with electricity whenever the price of electricity is below the price of the competing fossil fuel, typically natural gas. With small deployment of heat storage, industrial users may take advantage of electricity prices near zero dollars, and experience large savings on heating costs by avoiding the purchase of natural gas. With large deployment of heat storage, the heating market will take full advantage of surplus electricity as an alternative heating source, and electricity prices will no longer collapse near zero dollars. Instead, the lowest price of electricity will be near the price of natural gas. In the long

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\(^1\) Equal to the capital cost per unit storage capacity divided by roundtrip efficiency and lifetime number of storage cycles
term, stored heat may also function as a substitute for natural gas in power cycles, thereby achieving roundtrip storage of electricity with efficiency equal to the cycle efficiency of the power plant or greater, while remaining a fraction of the price of the present electricity storage options.

There is one other feature of heat storage. The industrial heat demand in the United States is larger than the production of electricity. If the heat storage system is full and electricity prices are less than natural gas prices, the electric resistance heating systems can continue to operate to produce hot air to match the industrial furnace needs. In effect, FIRES has an “unlimited” capacity to productively use low-price electricity.

2.4 Conclusion

Electricity price collapse caused by increases in renewable energy penetration is damaging the economic competitiveness of solar, wind, and nuclear power. The current electrical energy storage options are too expensive to be deployed in sufficient quantity to prevent the price collapse. Heat storage charged via electrical resistance heating enables the sale of electricity to the heating market at the price of the competing fossil fuel, thereby preventing electricity price collapse. Heat storage also holds the potential to be used for electricity production. With the considerations of the large potential of heat storage relative to the current options of electricity storage in improving the economics of a low-carbon grid, the new heat storage concept of firebrick resistance-heated energy storage (FIRES) was developed. The system description and applications follow in Chapter 3.
3  FIRES Description and Applications

3.1 System Description

FIRES is a storage technology that converts electricity to heat by the process of resistance heating, and stores the heat at high temperatures in a well-insulated firebrick mass. The stored energy is discharged as needed by blowing cold air through channels within the firebrick mass, heating the air as firebrick is cooled, and providing the hot air to an industrial process as a full or partial replacement to the fossil fuel heat, typically natural gas. The system is collocated with the industrial plant (kiln, furnace, chemical plant, etc.), and serves as a high temperature stored heat source to be charged or discharged at times of economic advantage, such that heating costs are reduced. The goal of the FIRES design is to be an affordable and deployable energy storage option that enables the transfer of energy from the electricity market to the heat market, and, in the long-term, the efficient affordable conversion of heat back into electricity for load following applications.

During times of cheap electricity, FIRES may be heated up to design temperatures as high as 1800°C. The storage medium is surrounded by multi-layer insulation that will allow for the thermal expansion of the firebrick over approximately 1000°C temperature range. If one allows a 1000°C temperature range from cold to hot temperature, the heat storage capacity ranges from 0.5 MWh/m$^3$ to 1 MWh/m$^3$, depending on the material. The ceramic firebrick is used because of its low cost and durability, while also having large sensible heat storage capabilities.

The firebrick, insulation systems, and operating temperatures are similar to high-temperature firebrick industrial regenerators first developed in the 1920s for open hearth furnaces, and used in many applications today. Firebrick regenerators absorb and store the heat from the hot offgas of furnaces that is otherwise wasted and sent out the stack. This stored heat is then transferred to the incoming cold stream of air, thereby preheating it and reducing the combustion heat required. Figure 3.1 depicts the operation of the open hearth furnace with firebrick regenerators. In the case of the open hearth furnace and other applications, two regenerators may be used with a periodically changing flow direction, such that when one regenerator is fully “charged” by the heat of offgas and the other fully discharged, the flow
direction will switch so the incoming air is heated by the hot regenerator and the offgas is cooled by the cold regenerator.

Figure 3.1: Open hearth furnace operating with two firebrick regenerators [8]

Firebrick regenerators for the steel and glass industry operate to temperatures near 1800°C. This is far above heat exchangers that typically have peak temperature limits near 700°C. Furthermore, they operate with continuous large temperature swings over periods of decades. Such regenerators have been used in industry for over a century.

Firebrick with electric heating has been used at low temperatures for home heating in Europe and elsewhere on a non-industrial scale. At times of low electricity prices, the firebrick is heated. The hot firebrick then provides hot air when needed for room heating. Figure 3.2 shows an example of a firebrick heat storage unit. The FIRES concept is a marriage of high temperature industrial regenerator technology and the electrical heating approach of residential firebrick heating storage systems.
3.2 Applications

There are two general applications of FIRES: heat supply to industrial processes in place of fossil fuels, and heat addition to a power cycle for electricity production. In the case of industrial heat supply, the electricity that charges FIRES is used typically in place of natural gas to produce a variety of products, whereas in the electricity production applications, the electricity that charges FIRES is used to produce electricity at a time when it is demanded. When discussing the latter, there is an interest in both the economic advantage (from the perspective of the power cycle owner) and the roundtrip electric storage efficiency (from the societal perspective). Operating modes and specific considerations of each application will be discussed.

3.2.1 Industrial Heat Supply

In the industrial heat supply application, FIRES is coupled to a natural-gas-fired furnace, and replaces the heat supplied by the combustion of natural gas. The furnaces may be producing glass, cement, steel, or providing heat to chemical facilities including refineries and ethanol plants. To recover the heat, cold air is blown through FIRES—the firebrick is laid in a pattern that includes air channels. If the exit air is above the temperature limits for the furnace, the hot air is mixed with cold air to match furnace requirements. If the FIRES temperature is below the temperature needed for the furnace, natural gas heating is used to raise temperatures to the required furnace temperature. Figure 3.3 shows a simple schematic of operation of FIRES coupled with an industrial process.
Figure 3.3: Schematic of FIRES coupled with industrial heating application

From the perspective of the furnace, FIRES is a partial or full substitute for a natural gas flame. When the temperature output of FIRES exceeds the required temperature of the furnace, temperature can be adjusted by adding cold air, and no natural gas is required. When the temperature output of FIRES drops below the required temperature of the furnace, temperature may be increased by adding natural gas heat. Electric heating of the firebrick may be done at the same time FIRES is providing heat to industrial processes—that is, it may be charged and discharged at the same time.

Typical industrial heat supply applications run at or near atmospheric pressure, and over a large range of temperatures. Glass, steel and cement production require temperatures ranging from about 1400°C to 1550°C, with flame temperatures up to 1900°C [10]. Processes such as ethanol distillation that operate with steam systems require heat supply at temperatures high enough to generate near-atmospheric steam, i.e. only a few hundred degrees Celsius. The size, materials, and configuration of the FIRES unit will be designed to the requirements of each industrial user.

### 3.2.2 FIRES with Natural Gas Combined Cycle (NGCC) Plant

FIRES may be coupled with a natural gas combined cycle (NGCC) power plant to replace natural gas heat in the production of electricity. Similar to the industrial heat supply application, FIRES is seen as a partial or full substitute for a natural gas flame. The output
temperature of FIRES may be adjusted as needed by adding cold air or natural gas heat. Figure 3.4 shows a simple schematic of FIRES coupled with a natural gas combined cycle plant.

![Figure 3.4: Schematic of FIRES implemented with natural gas combined cycle plant](image)

Because the product of NGCC is electricity, it is nonsensical for FIRES to charge and discharge at the same time. The NGCC will shut down and charge FIRES when electricity prices drop below the price of natural gas due to low demand, thereby switching from a supplier of electricity to a consumer. When prices rise again due to sufficient demand, the NGCC will ramp up and produce electricity, and discharge FIRES’ stored heat to the power cycle until depleted. From a roundtrip electrical efficiency perspective, the electricity used to charge FIRES produces electricity at an efficiency of the NGCC cycle efficiency, typically between 50% and 60%, or above 60% in newer plants (note that the resistance heating process is approximately 100% in all cases).

High efficiency natural gas turbines operate at pressures between 20 and 25 atmospheres, with turbine inlet temperatures of approximately 1000 to 1400°C. The temperature inlet of FIRES will be that of the compressor outlet, typically between 450 and 600°C, depending on compression ratio and compressor efficiency. As a result of the high peak temperature and pressures, the firebrick regenerator must be contained within the pressure boundary of the power cycle, and will be built within a pressure vessel. The cost of FIRES units with pressure vessels will be sensitive to the size of the required pressure vessel, and should be designed to maximize energy density within the vessel. For the large volumes of firebrick being considered, it is expected that pre-stress concrete pressure vessels are the most cost effective option, with steel vessels as an alternative.
3.2.3 FIRES with Fluoride Salt-Cooled High Temperature Reactor (FHR) and Nuclear Air-Brayton Combined Cycle (NACC) [11]

3.2.3.1 Background

Brayton power cycles, which require higher temperatures to run efficiently than is currently achievable with LWR technology, will likely be the power cycle of choice with high temperature generation IV (Gen IV) reactor technology, as is already the case with modern natural gas power plants. This is because of the continued improvements in gas turbine technology relative to other power conversion cycles. FIRES may be coupled with a nuclear air-Brayton combined cycle (NACC) to provide heat to the power cycle during times of peak power demand, increasing the turbine inlet temperature above what is reachable with Gen IV reactors (approximately 500°C to 750°C). This capability enables nuclear reactors to produce and sell peaking power to the grid, while operating the reactor at constant power.

Several Gen IV candidates may potentially be coupled with FIRES. This study focuses primarily on the fluoride salt-cooled high temperature reactor (FHR). The fluoride salt-cooled high temperature reactor (FHR) is an advanced high temperature reactor that uses graphite-matrix coated particle fuel (the same fuel as an HTGR) and liquid salt coolant. Liquid salt coolants were developed by the Aircraft Nuclear Propulsion program in the 1950s and 1960s to couple nuclear reactors to jet engines on bombers. The program was cancelled because of the development of the Intercontinental Ballistic Missile (ICBM) that was faster and cheaper. Work continued on the molten salt reactor coupled to a steam cycle because of the very low efficiency of Brayton power cycles at that time. In the 50 years since then there have been extraordinary advances in gas turbines. These advances now make it practical to couple a reactor to a gas turbine where the salt coolant delivers heat over the temperature range of 600 to 700°C.
3.2.3.2 Operating Characteristics

The FHR power cycle is shown in Figure 3.5. In the power cycle external air is filtered, compressed, heated by hot salt from the FHR while going through a coiled-tube air heat exchanger (CTAH), sent through a turbine producing electricity, reheated in a second CTAH to the same gas temperature, and sent through a second turbine producing added electricity. Warm low-pressure air flow from the gas turbine system exhaust drives a Heat Recovery Steam Generator (HRSG), which provides steam to either an industrial steam distribution system for process heat sales or a Rankine cycle for additional electricity production. The air from the HRSG is exhausted up the stack to the atmosphere. Added electricity can be produced by injecting fuel (natural gas, hydrogen, etc.) or adding stored heat (FIRES) after nuclear heating by the second CTAH. This boosts temperatures in the compressed gas stream going to the second turbine and to the HRSG.

Figure 3.5: schematic of FIRES implemented with the FHR NACC [11]
Figure 3.6 shows the breakdown of energy input and output in the case of base power generation and peak power generation. The base-load thermodynamic cycle efficiency from nuclear heat to electricity is 42.5%. The incremental natural gas, hydrogen, or FIRES stored heat-to-electricity efficiency is 66.4%\(^2\) – far above the best stand-alone natural gas plants. The reason for these high incremental natural gas or stored heat-to-electricity efficiencies is that this high temperature heat is added on top of “low-temperature” 670°C nuclear-heated compressed air. Likewise, the roundtrip electrical efficiency of FIRES is 66.4%. However, advances in combined-cycle gas turbines by the time the FHR is developed will likely increase this efficiency to 70%. This efficiency is comparable to many other electricity storage devices such as pumped hydro and CAES [7,12]. For comparison, the same GE F7B combined cycle plant running on natural gas has a rated efficiency of 56.9%.

Similar to FIRES with NGCC, the FIRES unit with NACC will not charge and discharge simultaneously, because it would be nonsensical to use FIRES to produce peak electricity (i.e. highly demanded electricity) at the same time as attempting to purchase low price electricity (i.e. lowly demanded electricity); these two things will not happen simultaneously. When the price of electricity is low, the FHR reactor will continue to operate at constant thermal output, and produce base-load electricity. The base-load electricity, as well as low price electricity purchased from the grid, will be used to charge FIRES directly. This changes the FHR plant from a supplier of electricity to a consumer, with no change to the reactor output. By virtue of the FIRES unit,

\(^2\) Note that the overall thermodynamic cycle efficiency is 53.7%.
the FHR is granted the flexibility to rapidly “shut down” from the perspective of the grid, and avoid selling electricity to an unfavorable market, which current LWRs are unable to do.

In the case of FIRES with NACC, the definition of “low price” electricity will depend on whether or not natural gas is an option for providing peaking heat. In the case where natural gas injection to the NACC for peak electricity production is an option, the NACC will charge FIRES whenever the electricity price drops below that of natural gas, because the base-load electricity is worth more as a heating substitute for natural gas later than as electricity now. In the case where natural gas is not considered as an option, the “low price” of electricity should be considered the highest price at which one would expect to sell electricity multiplied by 66.4%, the FIRES roundtrip electrical efficiency. If the price drops below this value, FIRES should be charged, because 66.4% of this electricity will be worth more later than 100% of it is now, since the price will increase by more than 150.6% (1/0.664).

The FHR operates at a pressure of approximately 18 atmospheres. The air that flows through FIRES first passes through the high pressure turbine and reheat stage, and is approximately one-half this pressure. Like the NGCC, a steel or pre-stress concrete pressure vessel will be required. The air temperature after reheat is 670°C, with a desired temperature of 1065°C to produce peaking power, at a heat rate of 214 MW. This heat is converted to 142 MW\textsubscript{e}, and sold to the grid in addition to the 100 MW\textsubscript{e} base-load generation, for a total output of 242 MW\textsubscript{e}.

3.2.4 FIRES with Adiabatic Compressed Air Storage (ACAS) [13, 14]

3.2.4.1 Background

Much of the firebrick heat storage technology in pre-stress concrete pressure vessels is being developed for adiabatic compressed air storage systems (ACAS) as shown in Figure 3.7; in particular, the GE\textsuperscript{®}/RWE\textsuperscript{®} Adele project that will complete a demonstration project in several years. At times of low electricity prices air is adiabatically compressed to 70 atmospheres and sent through firebrick to lower its temperature from 600°C to about 40°C before being stored in an underground salt cavern. The compressed air must be cooled before storage to avoid damaging the storage caverns. At times of high electricity demand the compressed air from the underground cavern goes through the firebrick, recovers heat from the regenerator and is sent to a turbine to produce peak electricity. The key differences between FIRES coupled to a NACC and the brick regenerator in the ACAS are that with NACC FIRES operates at lower pressure
and higher temperature, and uses electric heating. In ACAS the firebrick is not electrically heated. However, the designs are similar in that both store heat in a firebrick medium within a pressure vessel, and transfer this heat to air for electricity generation in a gas turbine.

Figure 3.7: GE®/RWE® Adele adiabatic compressed air storage (ACAS)
Heat storage firebrick contained in pressure vessel (similar vessel design for FIRES coupled to an FHR with NACC) [13] and ACAS flowsheet. Optional FIRES system could be coupled with ACAS (dotted lines). The recuperator schematic (left) courtesy of Zublin.

3.2.4.2 Operating Characteristics

The option exists for an advanced ACAS system to include FIRES. The FIRES would be added (dotted lines) after the firebrick regenerator to further heat the compressed air before going to the turbine – potentially up to the temperature limits of modern gas turbines. As with the NGCC and NACC systems, FIRES with ACAS will only charge or discharge at one time. Because FIRES’ stored heat is added on top of 600°C heat similar to the NACC application, the round-trip efficiency for the FIRES component could be potentially above 60%. The inlet of FIRES is equal to the outlet of the ACAS firebrick regenerator: 600°C or cooler. The desired outlet temperature of FIRES will be similar to that desired by NGCC, approximately 1000°C to 1400°C. However, the pressure seen by FIRES will also be a maximum of 70 atmospheres –
significantly higher than other applications. The heat rate FIRES would add to ACAS would likely be on the order of what the ACAS system is designed to output: approximately 90 MW_e [14]. Adding FIRES would bring incentives to add a heat recovery steam generator to this system because of higher gas turbine exit temperatures. Because the ACAS technology itself is under development, the prospects of coupling FIRES with ACAS is still relatively unknown. However, the technological parallels between the two are worthy considerations in the design of each moving forward.

3.2.5 Summary of FIRES Applications

There is a wide variety of applications that FIRES may be coupled with for advantages of improved economics, increased flexibility, and reduced environmental impact. Some of the major industries that may benefit from the coupling of FIRES with their kilns and furnaces have been mentioned, but the list of industrial heat supply applications is non-exhaustive, with many other potential niches in which FIRES may be practically coupled. FIRES’ heat addition to power cycles is a promising avenue for efficient roundtrip storage of electricity using the very cheap heat storage methods that FIRES employs, especially as cycle efficiency continues to improve from advances in turbine technology. The operating characteristics of several candidate FIRES applications are summarized in Table 3.1. The different characteristics will inform the design choices for each application.

Table 3.1: Summary of FIRES Applications operating characteristics

<table>
<thead>
<tr>
<th>Application</th>
<th>Temperature Inlet</th>
<th>Desired Outlet (Process Temperature)</th>
<th>Operating Pressure</th>
<th>Heat Rate Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Kiln</td>
<td>ambient</td>
<td>1480</td>
<td>atmospheric</td>
<td>10s</td>
</tr>
<tr>
<td>Glass Furnace</td>
<td>ambient</td>
<td>1100-1550</td>
<td>atmospheric</td>
<td>10s</td>
</tr>
<tr>
<td>Steel Furnace</td>
<td>ambient</td>
<td>1550</td>
<td>atmospheric</td>
<td>10s</td>
</tr>
<tr>
<td>Ethanol Distillation</td>
<td>ambient</td>
<td>200-500</td>
<td>atmospheric</td>
<td>10s</td>
</tr>
<tr>
<td>NGCC</td>
<td>450-600</td>
<td>1000-1400</td>
<td>20-25</td>
<td>100s</td>
</tr>
<tr>
<td>NACC</td>
<td>670</td>
<td>1065</td>
<td>8-10</td>
<td>100s (214)</td>
</tr>
<tr>
<td>ACAS</td>
<td>600</td>
<td>1000-1400</td>
<td>70</td>
<td>10s</td>
</tr>
</tbody>
</table>
4 Conceptual Design of FIRES

4.1 Design Space

The design space for FIRES is large, with possible variations in size, materials and geometry, as well as different configurations for storage media, heating elements and blowers. Many aspects of the system design will be customized for the specific needs of each industrial user. Specific systems will be designed with respect to three performance characteristics of interest (Figure 4.1), each of which is largely independent of the others: storage capacity, charge rate, and discharge rate.

- **Storage Capacity:** Storage capacity of FIRES is governed by the sensible heat capable of being stored in a volume of material over a chosen temperature range (minimum and maximum temperatures). The chosen temperature range and material will typically be predetermined by the needs of the industrial process. Then the desired capacity can be achieved by simply designing the system with the correct volume of firebrick. More firebrick will store more energy.

- **Charge Rate:** FIRES is charged by resistance heating. The charge rate will be determined by the electrical market. If solar causes electricity price collapse and most of the low-cost electricity is available for only a few hours per day, the system may require high charging rates. If wind causes electricity price collapse, low-price electricity is likely to be available over a longer period of time and lower charging rates may be chosen. Technically, the firebrick itself may have electrical current run directly through it, i.e. the firebrick acts as the resistance heater in addition to its role as the storage media\(^3\). The charge rate will be determined by voltage drop and electrical current flow through the heating elements, which are related by Ohm’s law to its resistance. The resistance of the system can be designed by specifying the geometry of the firebrick; a current path with larger flow area and shorter distance will result in smaller resistance, and greater charge rate. Resistance can therefore be designed with respect to the desired power and the

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\(^3\) The system may also have electric heaters to distribute heat throughout the storage medium. However this results in stronger coupling of charge and discharge rates, since both require heat transfer.
limitations of the electrical transmission system, which will typically determine the regime of allowable voltage drop or current.

- **Discharge Rate:** The output of FIRES is hot air, which will be heated or cooled as needed for the given application by adding natural gas heat or cold air, respectively. The required discharge rate is determined by the furnace that FIRES is coupled to. Within FIRES, the nominal discharge rate is determined by the heat transfer from the hot firebrick to the air, which is a function of air channel geometry and fan power. The channel width, number of channels, and fan speed are all independent design variables. Depending on the application, a damper system and variable speed fan may also be chosen to offer desirable control with which to increase or decrease throughput to maintain discharge temperature or discharge power.

![Figure 4.1: Independent performance aspects of FIRES](image)

4.2 Storage Materials

In all applications, FIRES requires a high temperature storage media capable of temporarily storing electrical energy as heat and discharging heat via forced convection and conduction during periods of demand. Desirable properties of storage materials are identified and discussed, and candidates are reviewed.

4.2.1 Properties of Good Storage Media

The energy storage material of FIRES must have properties that enable an energy storage technology with affordable abundant storage, and excellent charge and discharge characteristics. Towards this goal, the desired properties are as follows:
• **Inexpensive:** Affordability on a per-unit-energy basis is a prerequisite for a material to be a candidate. The pricing goal of FIRES is on the order of dollars per kilowatt-hour.

• **High operating temperature:** A high operating temperature is required to power high temperature applications. It also results in greater energy storage per unit volume for a given specific heat, and greater heat discharge rate. Both reduce the size of the unit.

• **High specific heat:** A high specific heat has greater energy storage per unit volume for a given density, reducing the size of the unit.

• **High density:** A high density has greater volumetric energy storage density, reducing the size of the unit.

• **Low or high electrical resistivity:** Low electrical resistivity enables the direct resistance heating of firebrick, without the use of separate heaters. Lower resistivity allows for greater current through firebrick for a given voltage. This allows for greater charge rate, and for efficient distribution of heat throughout the storage medium. If separate resistance heaters are used, high electrical resistivity is preferred. This allows the firebrick to be used as the electrical insulator without the requirement for insulation to be associated with the resistance heater.

• **High thermal conductivity:** Greater discharge rate is possible with higher thermal conductivity due to greater heat flux through the brick to the air. This allows for less flow area, smaller flow channels, and greater effective energy density, reducing the size of the unit. This also allows for greater charge rate in the case where independent resistance heaters are used.

### 4.2.2 Candidate Storage Materials

In terms of the above desirable properties, the industrial refractory ceramics used in high temperature furnaces and regenerators were found as the most promising materials for energy storage media. These include alumina, magnesia, silicon carbide and titania. These candidates fit firmly into two categories: electrically resistive materials, the FIRES units of which would use resistance heaters, and electrically conductive materials, which show promise for FIRES units that use direct resistance heating of the storage media.
4.2.2.1 Electrically Resistive Materials: Alumina (Al$_2$O$_3$) and Magnesia (MgO)

Alumina and magnesia are both commonly used as the liners for high temperature furnaces of many of the applications previously discussed. As such, they are abundant and inexpensive. Each can be operated at temperatures of 1800°C while maintaining high margins to their respective melting points of approximately 2000°C and 2800°C. Although they are typically manufactured as bricks with high porosity to improve their insulating quality, pure alumina and magnesia are thermally conductive compared to most refractory materials, with room temperature values of approximately 35-39 W/mK and 50-75 W/mK, respectively [15]. High purity bricks of low porosity should be able to reach values similar to these. Neither alumina nor magnesia is electrically conductive enough to be directly resistance-heated without very high voltages, even if non-porous and continuous. The addition of contact resistances between bricks will further hinder the practicality of direct resistance heating of alumina or magnesia firebrick. However, their high heat capacity, operating temperatures and thermal conductivity make them good candidates for coupling with electric heaters. The low electrical conductivity of these materials allows for the use of resistance heaters such as metallic wire heaters without the need to further electrically insulate the resistance heating unit.

One possible option to enable direct resistance heating of alumina and magnesia is the addition of carbon, which can significantly improve electrical conductivity and thermal conductivity of the firebrick. Magnesia-carbon bricks are the material of choice for the liners of direct current (DC) electric arc furnaces (EAFs), where electrical current is passed directly through the brick [16,17,18]. A key challenge of alumina-carbon (Al$_2$O$_3$-C) and magnesia-carbon (MgO-C) bricks is the oxidation of carbon, which would strip the electrical conductivity of the bricks over the course of operation. Factors that contribute to fast rates of oxidation of carbon by the air include high temperature, high partial pressure of oxygen, and large surface area [19], all of which are characteristic of FIRES. In environments with oxygen, a combination of antioxidant additives or barriers would be required to maintain the charging functionality of the firebrick, the feasibility of which should be investigated further. In environments without oxygen, such as a helium cycle coupled with the HTGR, MgO-C or Al$_2$O$_3$-C bricks may be the most attractive option.
4.2.2.2 Electrically Conductive Materials: Titania (TiO$_2$) and Silicon Carbide (SiC)

Titania and silicon carbide are ceramics used in a variety of applications, including as refractory materials. Titania powder is commonly used as a white pigment for paper and paints, and is also frequently included in small weight percentages in high-alumina firebrick [20]. Silicon carbide brick is used commonly as an abrasive and in high temperature furnace applications where high thermal conductivity is desirable. It is also used as a high temperature resistance heating element in furnace applications. Titania and silicon carbide are both less energy dense and typically more expensive than alumina and magnesia, making them comparatively unsuitable for coupling with electric heaters. However, they possess the potential to be directly resistance heating by virtue of their high electrical conductivity.

As a proven industrial heating element, silicon carbide is already commonly resistance heated to high temperatures. Heaters are more expensive than bulk silicon carbide brick, but are designed with specific characteristics intended for heat transfer and convenience, such as large heat radiation per unit area, fast temperature ramping, low voltage requirements, and small modular installations for a variety of applications [21]. DRH of silicon carbide in FIRES requires no heat transfer because the heat is being generated directly in the mass of interest, which will gradually heat up over time due to high thermal mass. Moreover, inexpensive bulk silicon carbide brick of higher resistivity may be supplied high voltages of several kilovolts if necessary. It is therefore expected that bulk silicon carbide bricks of high enough purity will be suitable for DRH at low cost.

Although titania is electrically insulative at low temperatures, its resistivity drops exponentially with increasing temperature [22]. Experimental data reported by Hensler and Henry (1953) show resistivity of sintered titania on the order of $10^4$ohm-cm near 500°C (Figure 4.7), which is sufficient for fast rates of resistance heating with 10s of kilovolts. It is presently uncommon to find sintered titania bricks, but bulk 93% purity powders are commercially sold at prices of $0.60$-$1.20 per kilogram ($600$-$1200/ton) [23].

4.2.2.3 Comparison of Candidate Materials

Table 4.1 and Table 4.2 show properties and estimates of energy density and costs for each candidate material. Cost of materials on an energy basis was found to range over an order of magnitude, from $0.37/kWh to $3.04/kWh, based on the cheapest sale prices from online vendors. Of the prices shown, alumina and magnesia are the cheapest, with prices each near
$0.40/kWh each, while silicon carbide and titania cost $1.44/kWh and 3.04/kWh, a factor of 4 and 8 greater, respectively. Each material is on track for FIRES’ target price of $5/kWh. These prices do not take into account more competitive quotes that cannot be readily found online, or the economies of scale that may come with the purchase hundreds or thousands of tons of bulk materials.

In terms of energy density, all materials are in class, with a volumetric energy density ranging from approximately 0.5 MWh/m$^3$ to 1 MWh/m$^3$. These values were calculated assuming a 1000 °C temperature difference and constant specific heat. All of these materials have the potential to operate with a higher temperature difference depending on the application.

The thermal conductivity of each material, which ranges from approximately 9 W/mK to 52 W/mK, determines the relative volume of air channels in the regenerator to remove heat from the firebrick effectively. Silicon carbide is in class with alumina and magnesia, which are already proven as effective regenerator materials. The lower thermal conductivity of titania may require a larger system for the same discharge capability. Actual dimensions of firebrick regenerators are discussed in later sections.

### Table 4.1: Properties of candidate storage materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical</th>
<th>Tmelt</th>
<th>Thermal Conductivity</th>
<th>Resistivity (@ 700°C)</th>
<th>Density</th>
<th>Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>°C</td>
<td>W/mK</td>
<td>ohm-cm</td>
<td>kg/m$^3$</td>
<td>kJ/kgK</td>
</tr>
<tr>
<td>Titania</td>
<td>TiO$_2$</td>
<td>1855</td>
<td>8.9</td>
<td>$10^3$</td>
<td>4240</td>
<td>0.71</td>
</tr>
<tr>
<td>Alumina</td>
<td>Al$_2$O$_3$</td>
<td>2054</td>
<td>37</td>
<td>$10^6$</td>
<td>3987</td>
<td>0.84</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>SiC</td>
<td>2093</td>
<td>42.5</td>
<td>$10^2$</td>
<td>3160</td>
<td>0.75</td>
</tr>
<tr>
<td>Magnesia</td>
<td>MgO</td>
<td>2852</td>
<td>52</td>
<td>$10^8$</td>
<td>3581</td>
<td>0.96</td>
</tr>
<tr>
<td>Silica</td>
<td>SiO$_2$</td>
<td>1710</td>
<td>1.4</td>
<td>$10^6$</td>
<td>2650</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Resistivity data for sintered oxides: [22], resistivity data for silicon carbide: [21]. All other data: [15]. Values are at room temperature unless otherwise noted.

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4 Actual energy density is a function of the changing specific heat of each candidate material over the temperature range of interest, which depends on the specific application. The specific heat of each material rises with temperature, such that the value shown is conservative for all temperature ranges of interest.
Table 4.2: Estimated energy density and cost per unit storage capacity for different candidate materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical</th>
<th>Energy Density (ΔT = 1000°C)</th>
<th>Estimated Material Cost (Sale Price)</th>
<th>Estimated Energy Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>MWh/m³</td>
<td>$/ton</td>
<td>$/kWh</td>
</tr>
<tr>
<td>Titania</td>
<td>TiO₂</td>
<td>0.84</td>
<td>600</td>
<td>3.04</td>
</tr>
<tr>
<td>Alumina</td>
<td>Al₂O₃</td>
<td>0.93</td>
<td>100</td>
<td>0.43</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>SiC</td>
<td>0.66</td>
<td>300</td>
<td>1.44</td>
</tr>
<tr>
<td>Magnesia</td>
<td>MgO</td>
<td>0.96</td>
<td>100</td>
<td>0.37</td>
</tr>
<tr>
<td>Silica</td>
<td>SiO₂</td>
<td>0.58</td>
<td>150</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Assumes a temperature change of 1000°C and constant specific heat capacity. Sale prices from alibaba.com [23,24,25,26,27].

4.3 Charging System

FIRES is charged by way of electrical resistance heating, which requires resistors, electrodes, and a power supply and control system. Two options exist for heating the firebrick: the integration of resistance heating elements within the firebrick chamber to provide heat by radiation and conduction, or the direct resistance heating (DRH) of the firebrick for the internal generation of heat, with minimal required heat transfer. Each option will be discussed, followed by the components required for power supply and control.

4.3.1 Resistance Heating Elements

The use of separate heating elements to heat FIRES is a straightforward option because of the commercial availability of heaters that are designed for similar applications, such as existing electrically powered furnaces. The first FIRES units used for industrial heat supply will employ this option for charging FIRES. Because heat transfer is required from the heater surface to the middle of the firebrick, acceptable charge rates will only be possible with sufficient distribution of heaters.

When choosing which heating elements to use in FIRES, there are many aspects to consider and compare between different kinds of heating elements. The three dominant heating elements used in industry today are metallic heaters, silicon carbide heaters, and molybdenum disilicide heaters. Each will be discussed. However, there are several characteristics that are
generally true of all heating elements, regardless of type. First, the hotter the heaters are operated, the less time they tend to last. Operating at peak rated temperatures can dramatically reduce the lifetime of heaters, resulting in potentially frequent replacement. Second, frequent and rapid temperature changes to the heaters will result in reduced lifetime, compared to a heater that is ramped slowly and left at constant temperatures. The ramp rate will determine how fast a FIRES unit can respond to less predictable changes in electricity supply on the grid, such as when the wind begins blowing or the sun breaks through the clouds. Heaters must therefore be chosen with respect to how FIRES will be operated, balancing performance with upfront cost and heater replacement cost. Table 4.3 summarizes the performance of candidate heater types.

### Table 4.3 Key performance aspects of the three different heating element types

<table>
<thead>
<tr>
<th>Heater Type</th>
<th>Peak Operating Temperature °C</th>
<th>Max Recommended Surface Load @ Typical Temp kW/m²</th>
<th>Max Recommended Surface Load @ High Temp kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nichrome (Ni-Cr)</td>
<td>1250</td>
<td>35-100 (800 °C)</td>
<td>10-25 (1100 °C)</td>
</tr>
<tr>
<td>Kanthal (Fe-Cr-Al)</td>
<td>1425</td>
<td>50-120 (800 °C)</td>
<td>20-35 (1300 °C)</td>
</tr>
<tr>
<td>Silicon Carbide (SiC)</td>
<td>1650</td>
<td>100-150 (1200 °C)</td>
<td>25-30 (1600 °C)</td>
</tr>
<tr>
<td>Molybdenum Disilicide (MoSi₂)</td>
<td>1850</td>
<td>200-220 (1500 °C)</td>
<td>80-120 (1750 °C)</td>
</tr>
</tbody>
</table>

From [28, 29, 30]

#### 4.3.1.1 Metallic Heaters

There are two main types of metallic resistance heating alloys: the nickel-chromium alloy (Ni-Cr, often called “nichrome”), and the iron-chromium-aluminum alloy (Fe-Cr-Al, often called by the trade-marked name “Kanthal”). Kanthal is generally regarded as longer lasting due to its superior oxide layer, and is capable of operating with higher power and at higher temperatures than nichrome [28], and is therefore the better candidate for most FIRES applications. Metallic heaters are typically wires or strips of various thicknesses that can be coiled or folded along the walls and supports within a furnace, with a peak operating temperature of 1425°C. They typically cannot support their own weight and will elongate and collapse when heated unless supported by hooks or grooves within the wall.
Metallic heaters are the least expensive option, with temperatures well-suited for applications that heat air starting from ambient conditions, up to temperatures of approximately 1200°C or less, such as ethanol plants. Higher temperature industries that use these metallic heaters would still benefit economically from the preheating offered by FIRES, but would require natural gas throughout operation to reach the necessary process temperatures. To avoid the issue of supporting the wires, FIRES units that are designed with metallic heaters may be laid with horizontal air channels, so the wires are supported by the firebrick channels themselves. This avoids the need for suspending hooks in each channel, or running wires within gaps between bricks, which would be more difficult to replace as needed. Thicker wires represent a greater upfront cost per unit power, but are potentially more economical in the long-term due to their longer lifespan.

4.3.1.2 Silicon Carbide (SiC) Heaters

Silicon carbide (SiC) heaters are solid ceramic rods that typically operate at 1300-1500°C but can reach up to 1650°C depending on the specific design. They have heated lengths typically between 1-2m and overall lengths up to 4m. They are self-supporting, such that they may be installed vertically from the ceiling or cantilevered from the walls of the chamber with their aluminized electrodes pointing outward. Heating elements are replaceable while operation of the furnace continues. The width and height of the chamber may cause difficulties in heating the center of larger firebrick regenerators with SiC heaters of limited length. The checkerwork may be laid for insertion of heaters from the walls, ceiling and floor if necessary. In applications where charge and discharge are not simultaneous, another option for aiding heat transfer to the center of the regenerator is recirculation of air through FIRES during heating. In such a design heaters may be more conveniently placed by relying more on forced convection and less on radiation.

SiC heaters are already used in high temperature furnace applications such as soda-lime glass furnaces and crucibles for non-ferrous metals [29]. They are well suited for applications of approximately 1600°C or lower. This includes FIRES with NACC, where temperature demands are less than 1100°C, and a constant heat supply without the need for natural gas is desirable. For applications such as steel and cement furnaces where process temperatures are close to the peak capabilities of SiC heaters, natural gas may or may not be required throughout operation. For
other industrial processes SiC heaters may still serve as a preheater. Figure 4.2 shows examples of SiC heaters and their installation.

![SiC heaters of Silit ED “rod” and “U” type (1625°C Peak), and furnace application](image)

Figure 4.2: SiC heaters of Silit ED “rod” and “U” type (1625°C Peak), and furnace application [29]

### 4.3.1.3 Molybdenum Disilicide (MoSi₂) Heaters

Molybdenum disilicide (MoSi₂) heaters are presently the hottest electrical heating solution available, with a peak operating temperature of 1850°C, and have a significantly higher power output per unit area [30]. MoSi₂ heaters are hung from the ceiling of furnaces or mounted parallel to the walls, and are replaceable during operation. They are typically rods with one or more “U” bends, with a length ranging from about 0.5-1.5m. However, higher temperatures are only achievable with shorter units. Compared to SiC heaters with a heated length up to 2.5m or potentially longer at 1625°C, MoSi₂ heaters can only reach 1.4m at the same temperature, and less than 1m above 1750°C (0.6m at 1825°C). Seeking higher operating temperatures causes a simultaneous reduction in heater surface area and maximum allowable power. The tradeoff between maximum operating temperature and heater length must be weighed against SiC heaters, which are generally less expensive than MoSi₂ heaters. As with SiC heaters, applications where charge and discharge are not simultaneous may use forced convection while charging FIRES to distribute the heat of MoSi₂ heaters.

If one can overcome the challenge of distributing the heat of many small wall- or ceiling-mounted MoSi₂ heaters through a large mass, then the higher operating temperatures of 1700-1800°C will comfortably power any of the previously proposed industrial applications, reduce dependency on natural gas, and improve the energy storage density of the firebrick by allowing a
larger temperature range. A larger energy storage density is especially valuable in high pressure applications, where the required size of steel or concrete pressure vessels influences cost. In particular, FIRES with ACAS would benefit from the high temperatures because natural gas is not expected to be available for backup heating. MoSi$_2$ heaters allow FIRES to supply constant temperature to the ACAS power cycle for improved reliability of the system. Figure 4.3 shows examples of MoSi$_2$ heating elements and their installation.

![Figure 4.3: MoSi$_2$ heaters with different mounting angles, and installation in furnace [30]](image)

4.3.2 Direct Resistance Heating of Firebrick

Direct resistance heating (DRH) of the firebrick medium has several advantages over distributed heating elements. By running electricity directly through the firebrick, heat is generated throughout the mass approximately uniformly, with no need for distributed installations or temperature gradients to drive heat transfer. Whereas heating FIRES to high temperatures such as 1700°C may require the most expensive heaters to operate near their temperature limits, DRH of FIRES means the peak temperature of the firebrick is only limited by the firebrick itself, rather than heaters. This allows for the full utilization of the energy storage capabilities of the firebrick (i.e. peak operating firebrick temperatures), while avoiding the cost of heaters. These advantages make DRH the preferred charging method for very high temperature FIRES units.

Because firebrick regenerators were never previously designed to conduct electricity, more research and development will be required before FIRES with DRH of firebrick is ready for deployment. The DRH of a mass of bricks introduces new variables that make it uncertain how the resistance of the mass will behave with operation. Non-uniformities of the firebrick and contact resistances may cause electricity to preferentially flow through certain areas of the
regenerator, resulting in uneven heating. Thermal expansion may cause locations of preferential heating to appear, disappear or migrate due to changes in the contact resistance throughout the mass as it is heated. Units must be designed to experience relatively uniform resistivity changes throughout the mass, for reliability and ease of control.

DRH requires electrodes placed on each end of the firebrick mass, which may be divided into sections. Good candidates for electrode materials are metals of high electrical conductivity and melting point such as nickel, titanium or tungsten, or a firebrick of higher electrical conductivity than the storage material. Specific design choices will depend on application and cost. There are several possible configurations for electrode placement and operation that influence system performance, three of which are shown in Figure 4.4.

<table>
<thead>
<tr>
<th>Charging Configurations for Direct Resistance Heating of Firebrick</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simple Stack</strong></td>
</tr>
<tr>
<td>( V_1 \rightarrow )</td>
</tr>
<tr>
<td>( V_0 \rightarrow )</td>
</tr>
<tr>
<td><strong>Switch Stack: Series</strong></td>
</tr>
<tr>
<td>( V_1 \rightarrow )</td>
</tr>
<tr>
<td>( \ldots \rightarrow )</td>
</tr>
<tr>
<td>( V_1 \rightarrow )</td>
</tr>
<tr>
<td>( V_0 \rightarrow )</td>
</tr>
<tr>
<td>( \ldots \rightarrow )</td>
</tr>
<tr>
<td>( { V_{drop} } )</td>
</tr>
<tr>
<td><strong>Switch Stack: Parallel</strong></td>
</tr>
<tr>
<td>( V_1 \rightarrow )</td>
</tr>
<tr>
<td>( \ldots \rightarrow )</td>
</tr>
<tr>
<td>( V_0 \rightarrow )</td>
</tr>
<tr>
<td>( \ldots \rightarrow )</td>
</tr>
<tr>
<td>( { V_{drop} } )</td>
</tr>
</tbody>
</table>

**Figure 4.4:** Several configurations of firebrick and electrodes for different charging capabilities

In order of increasing complexity: A more complex configuration maintains all capabilities of the simpler configurations.

The simplest design, called the “simple stack,” places the entire regenerator between two electrode plates. This configuration requires the least number of electrodes, but places the entire resistance of the firebrick in series, demanding the highest voltage for a given design power, and
no control over electricity flow path or circuit resistance. The firebrick will be heated uniformly throughout the charge.

A more versatile option is to place several intermediate plate electrodes through the firebrick, which create sections of firebrick that can be charged individually in either parallel or series. One such configuration is the “switch stack,” made up of several layers of firebrick and electrode plates. When operating in series, charging may begin by running electricity through only the first section of firebrick, preferentially at the air discharge outlet. When the first section is fully or partially heated, switches may be actuated to add unheated sections of firebrick to the circuit and remove fully heated sections, moving progressively upstream until the entire stack is fully heated. This configuration comes with the advantage of lower voltage requirements because the resistance of the circuit is always only a fraction of the entire firebrick mass. It also enables FIRES to reach its peak storage temperature when partially charged, which offers better discharge capabilities than a FIRES unit of uniform temperature, as is the case with the simple stack. Individual firebrick sections may also be removed from the circuit for any operational issues without halting the operation of FIRES.

The switch stack configuration also enables the charging of each firebrick section simultaneously in parallel. This dramatically reduces required voltage for the desired power, and holds the potential for charge rates that would be impractical with the switch stack or simple stack, but loses the advantage of reaching peak storage temperatures at partial charge.

In practice, all configurations of DRH will likely include portions of alumina or magnesia for their superior storage capacity compared to the prevailing DRH candidates such as silicon carbide or titania. Designs with a mixture of DRH firebrick and non-DRH firebrick will behave as a mixture of FIRES with DRH and FIRES with distributed heaters.

### 4.3.3 Power Supply and Control

The power supply to FIRES must provide control of the power, i.e. heat generation rate, over a large temperature range. Its design will depend on the heaters or bulk firebrick material used, relating to two characteristics: (1) the change in the resistance of the heating elements over the operating temperature range, sometimes referred to as the “hot to cold ratio” [33], and (2) the change in resistance of the heating element over its lifetime, commonly referred to as “aging” [29]. Characteristics of each heater control scheme are summarized in Table 4.4, and discussed below.
4.3.3.1 Control Fundamentals

Power will generally be transmitted to FIRES via three-phase alternating current (AC) from power lines. Modern day resistance heating is most commonly controlled by a combination of multi-tap transformers and thyristor rectifiers (Figure 4.5). Transformers are used to adjust the voltage from the primary power circuit (e.g. power lines) to deliver power at a voltage suitable for the heating element, as dictated by its nominal resistance. Heaters of greater resistance require higher voltage to generate the same power. Different “taps” of a transformer are intermediate points along its winding that may be switched between to produce different voltages. Heating elements that experience aging should be accompanied by a transformer designed with taps so voltage may be incrementally increased over the heater lifetime and the desired power remains achievable. A transformer may be designed with the ability to change taps during operation to respond to short-term resistivity changes during heating, but its response capability is limited by its discrete number of taps. More effective control is achieved using thyristor rectifiers.

Thyristor rectifiers, which are also called silicon-controlled rectifiers (SCRs), control power by rapidly switching open and closed (so-called “firing”) thyristors, thereby enabling or denying the flow of AC to the heating elements. The two general approaches to thyristor operation are (1) burst firing, in which thyristors alternate open and closed for a discrete number of AC cycles at a time, and (2) phase-angle firing, in which the thyristors are open and closed for a fraction of every AC cycle. Figure 4.6 shows both approaches to thyristor firing, as well as a combined firing mode.

<table>
<thead>
<tr>
<th>Resistance Heaters</th>
<th>Resistivity-Temperature Relationship</th>
<th>Aging</th>
<th>SCR (thyristor)</th>
<th>Transformer Taps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic</td>
<td>Positive</td>
<td>Small</td>
<td>No</td>
<td>Recommended</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>Negative, Positive</td>
<td>Large</td>
<td>Yes</td>
<td>Required</td>
</tr>
<tr>
<td>Molybdenum Disilicide</td>
<td>Positive</td>
<td>Large</td>
<td>No</td>
<td>Required</td>
</tr>
<tr>
<td>DRH Firebrick</td>
<td>Resistivity-Temperature Coefficient</td>
<td>(Unknown)</td>
<td>Required</td>
<td>Yes</td>
</tr>
<tr>
<td>Titania</td>
<td>Negative</td>
<td>Large Exponential</td>
<td>(Unknown)</td>
<td>Required</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>Negative, Positive</td>
<td>Large</td>
<td>(Unknown)</td>
<td>Required</td>
</tr>
</tbody>
</table>

Table 4.4: Basic characteristics of heating element power control
Phase-angle firing offers finer heater control due to its higher firing frequency, and is preferable for control of elements whose resistance changes dramatically over the operating temperature range, specifically during periods of very low resistances. The main drawback of phase-angle firing is the generation of radio frequency interference (RFI), which may cause malfunction in sensitive equipment if not properly managed [32]. Burst firing requires less frequent switching
and does not generate RFI, making it preferable when the fine control of phase-angle firing is not required.

4.3.3.2 Control of Resistance Heaters

Existing metallic, silicon carbide, and molybdenum disilicide heaters already have established power supply and control configurations to match their characteristics. Of the three, metallic heaters are the simplest to control due to their lack of appreciable aging and a modest resistivity increase of approximately 5% from 20°C to 1400°C [28]. Where one uses many lengths of metallic heaters (such as the many lengths that would be run along the brickwork channels of FIRES) it is possible to customize the overall resistance of the heaters by placing more wire length in series or parallel. In this way the resistance can be customized to match the available line voltage at the industrial site. This avoids the need for a transformer to change the voltage\(^5\). Thyristor control is still commonly used for more precise temperature control and increased lifetime of metallic heaters, but is not essential. Silicon carbide heaters undergo resistivity increases of 300% (factor of 4) over their lifetime, increasing by 50% after 1000 hours and 70% after 3500 hours [21]. They also exhibit variations in resistivity by a factor of 3 over the temperature range of 400°C to 1600°C, as seen in Figure 4.7. Silicon carbide heaters therefore use phase-angle firing thyristors for fine control of power during low resistivity, and multi-tap transformers to adjust for aging. Molybdenum disilicide heaters increase in resistivity by a factor of 10 from ambient to 1800°C [30], and use phase-angle firing for careful control during startup. Molybdenum disilicide heaters do not need multi-tap transformers to counteract aging, but may use them to more easily control startup in combination with thyristor firing.

---

\(^5\) This assumes the intermediate connection to the broader transmission system, if there is one, can handle the additional power transmission required by FIRES.
Figure 4.7: Resistivity as a function of temperature for titania and silicon carbide
Left: different mixtures of sintered titania and silica, by percent weight of titania: (A) 0%, (B) 1%, (C) 6%, (D) 10%, (E) 47%, (F) 76%, (G) 92%, (H) 100%. [22]. Right: silicon carbide. Resistivity at 1100°C is approximately 0.016 ohm-cm [21].

4.3.3.3 Control of DRH of Firebrick

As in the case of existing heaters, control of DRH of firebrick will be achieved primarily by a combination of multi-tap transformers and firing of thyristors. Multi-tap transformers with a large range of voltages may be used to accommodate aging of the firebrick as well as the change in contact resistance between bricks that will likely occur over many cycles of expansion and contraction. The specific values of bulk firebrick properties, such as resistivity, temperature coefficient and aging will depend on the bonding or sintering process used to manufacture the bricks. It is expected that significant aging and temperature coefficients will be observed in DRH of bulk silicon carbide as they have in SiC heaters, and may be accounted for similarly. Unlike any other candidate heating element, the resistivity of bulk titania has been reported to decrease exponentially with temperature, as shown in Figure 4.7. This drop in resistivity enables DRH with 10s of kilovolts around 500-600°C, but requires careful control when operating over the temperature range. By extrapolation of the exponential trend reported by Hensler and Henry (1953), the resistivity of titania decreases by a factor of approximately 400 from 700°C to
1700°C. To maintain nominal constant power over a 400:1 resistivity change, the effective voltage drop across titania must be decreased by a factor of 20. This control may be achieved with a combination of thyristor firing and online tap changing. Additional power control is possible by initially heating only a portion of the total firebrick mass, and adding progressively more firebrick to the AC circuit via switches and electrodes distributed in the mass, such as how the switch stack would be operated in series. When a given firebrick load is heated to temperatures where resistivity is significantly reduced, an unheated section of firebrick may be added in series to the circuit. The added resistance seen by the AC source counteracts the exponential drop in resistivity, regulating the power delivered. This option may be valuable for reducing the requirements of the multi-tap transformer and thyristor rectifiers. The control advantage is made possible by continually adding cold resistors to the circuit, which is lost if all of FIRES is charged simultaneously. Alternatively, resistance can be added when operating the switch stack in parallel by switching progressively more sections in series with one another, effectively elongating the resistance length and constricting the flow area. The control advantage offered by the switch stack will be described in further detail in later sections.

4.4 Discharge System

In terms of discharge, FIRES behaves essentially the same as firebrick regenerators used in industry since the early 1900s. Heat stored in FIRES is discharged by blowing cold air through channels within the firebrick mass, heating the air as the firebrick is cooled and ultimately delivering the heat to the industrial process or power cycle. The discharge system consists of the blower and dampers that supply and control the airflow through FIRES, and the firebrick and air channels where the heat is transferred. Each is discussed in the following section.

4.4.1 Temperature and Flow Control

As FIRES cools, flow must be controlled to ensure the temperature point desired by the coupled application are met. The blower and dampers enable the control of air flow and temperature output of the system such that desired operating points of the application can always be maintained. A diagram of how constant flow rate and temperature are delivered to the user is shown in Figure 4.8.
At the start of FIRES discharge, the firebrick will be at its hottest temperature, and air that flows through the firebrick chamber will typically exit at a temperature hotter than what is required of the application. The incoming cold airstream is therefore split (Figure 4.8a); only a fraction of the total air flow is passed through the firebrick chamber, and the remaining fraction bypasses. The cold bypass mixes with the hot air exiting the firebrick such that the temperature matches the requirement of the industrial user or power cycle. The fraction of air that is bypassed is regulated by two dampers: one upstream of the firebrick, and one upstream of the bypass. Each damper increases or constricts the air flow by opening or closing variably.

As the firebrick cools, the firebrick damper opens and the bypass damper closes such that steadily more air flows through the firebrick. The point is reached where the exit temperature of the firebrick exactly matches the temperature of the application, and the bypass damper is fully
closed. Beyond this point, the firebrick exit temperature drops below the application temperature, and fuel addition is needed to match the required energy demand (Figure 4.8b).

The blower upstream is sized to deliver the desired flow rate with pressure rise necessary to overcome the combined losses of FIRES and the downstream furnace or kiln. Such blowers are identical to the ones already employed in each respective application, with a requirement of greater pressure rise due to the addition of the firebrick air channels. If the additional pressure losses are significant, FIRES units coupled with a pre-existing industrial user may either upgrade the existing blower or add another blower to create the pressure rise required.

Blower pressure rise relates to discharge performance of FIRES in that a larger pressure rise accommodates the larger pressure drops associated with numerous narrow firebrick air channels, the larger surface area of which improves the effectiveness of the heat transfer. This increases the fraction of energy that is discharged from FIRES at the desired discharge rate, prolonging the operating time where fuel addition is unnecessary. Capabilities of the blower must be selected in relation to desired discharge performance.

4.4.2 Brickwork Design

Like firebrick regenerators, the individual bricks of FIRES are laid in a pattern to form numerous air channels distributed throughout the mass. Firebricks today are commercially available in a variety of shapes that form continuous channels as they are stacked. Figure 4.9 shows a partially built regenerator for a glass furnace constructed from cruciform firebricks that form square air channels when stacked. The gaps in the brickwork allow for thermal expansion of the firebrick.
The brickwork design determines the thermal resistance of the system. Major design variables are the channel width, wall thickness and height. Where the desired energy storage for the application is considered a known parameter, the channel variables define the number of channels and overall dimensions of the brickwork. Thicker firebrick walls allow for fewer channels and a more compact system, but have greater resistance to heat flow from the center of the firebrick to the surface. Thinner walls improve heat transfer but reduce energy density. For a constant total flow area, a large number of narrow air channels create more surface area compared to a fewer number of wider air channels, which is advantageous for fast heat transfer but causes greater pressure loss. The tradeoff between heat transfer and pressure loss is also characteristic of channel length, where longer channels have greater pressure drops.

The dimensions chosen for channel width, brick thickness and channel length depend on the demands of the application, including discharge rate, mass flow rate, and constraints on size or available fan power, as well as the thermal properties of the firebrick used, such as energy density, thermal conductivity and thermal shock resistance. Modeling of different firebrick-air channel configurations are discussed in chapters 5.1 (modeling) and 6.1 (performance results).

4.5 Containment System

The high temperatures of FIRES must be contained such that equipment is undamaged and heat leakage is minimized. The containment system of FIRES consists primarily of insulation for the bulk storage medium and electrodes and an outer airtight structure. The design
The design of the insulation and structure depends on the operating conditions of the application. Each is discussed.

### 4.5.1 Outer Vessel

The outer vessel of FIRES is the structure that houses the firebrick chamber. It serves as the boundary between the high temperature air in the brickwork and the surrounding site. In low pressure applications, the outer vessel may simply be a steel structure lined with firebrick insulation, as is commonly used in industrial furnaces. In high pressure applications, the outer vessel may either be a steel pressure vessel lined with firebrick, or a pre-stress concrete pressure vessel lined with thick firebrick and a thin steel membrane. The specific design will depend on the desired storage capacity and operating temperature and pressure of the application. Whereas concrete vessels become more cost effective than steel as the vessel size increases, the lower temperature rating of concrete requires thicker insulation to keep the concrete at acceptable temperatures, which reduces the functional volume of the vessel. It is also likely to require active water cooling between the insulation and the concrete, as has been done previously in the advanced gas-cooled reactors (AGRs) [35]. This option creates more space within the pressure vessel for energy storage capacity, and may significantly reduce the thickness of a steel vessel, but comes with the tradeoff of enhanced leakage and greater complexity. Detailed research and development is required to determine the performance and economics of the respective outer vessel concepts for high pressure FIRES units.

### 4.5.2 Bulk Insulation

The firebrick mass of FIRES is surrounded with layers of potentially several different insulation materials for two functions: to maintain design temperatures for the outer vessel material, and minimize heat leakage through the walls of the brickwork. Table 4.5 contains specifications of some candidate insulating materials up to 1760°C.
Table 4.5: Best performing insulation options from ambient to 1760°C

<table>
<thead>
<tr>
<th>Bulk Avg. Temperature °C</th>
<th>Thermal conductivity W/mK</th>
<th>Refractory Name</th>
<th>Peak Temperature °C</th>
<th>Density kg/m³</th>
<th>Specific Heat kJ/kgK</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>0.051</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>93</td>
<td>0.054</td>
<td>Thermo-12 Gold</td>
<td>650</td>
<td>230</td>
<td>-</td>
<td>Ca₃SiO₅</td>
</tr>
<tr>
<td>149</td>
<td>0.057</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>204</td>
<td>0.062</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>260</td>
<td>0.067</td>
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<tr>
<td>316</td>
<td>0.073</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>371</td>
<td>0.081</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>427</td>
<td>0.105</td>
<td>Super Caltemp Gold 1700</td>
<td>927</td>
<td>-</td>
<td>-</td>
<td>Al₂O₃, SiO₂, CaO</td>
</tr>
<tr>
<td>600</td>
<td>0.14</td>
<td>JM23</td>
<td>1260</td>
<td>480</td>
<td>1.05</td>
<td>Al₂O₃, SiO₂</td>
</tr>
<tr>
<td>800</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1000</td>
<td>0.19</td>
<td>JM26</td>
<td>1430</td>
<td>800</td>
<td>1.1</td>
<td>Al₂O₃, SiO₂</td>
</tr>
<tr>
<td>1200</td>
<td>0.35</td>
<td>JM26</td>
<td>1430</td>
<td>800</td>
<td>1.1</td>
<td>Al₂O₃, SiO₂</td>
</tr>
<tr>
<td>1400</td>
<td>0.6</td>
<td>JM32</td>
<td>1760</td>
<td>1250</td>
<td>1.1</td>
<td>Al₂O₃, SiO₂</td>
</tr>
</tbody>
</table>

Insulation is selected such that it does not experience temperatures greater than its peak rated temperature. The innermost layer of insulation will typically be alumina-silica firebrick insulation because of the high operating temperature required for materials directly exposed to the hottest temperatures of FIRES. Unlike the firebrick used for heat storage, the insulating firebrick is manufactured with high porosity for minimal thermal conductivity and low energy density. Alumina and silica mixtures with different proportions provide effective insulation over the average temperature range of approximately 600°C to 1400°C and peak temperatures near 1760°C. Mixtures of alumina, silica and calcium oxide are also promising insulators. They are usable at temperatures below approximately 927°C, and have lower thermal conductivity compared to alumina-silica mixtures when operating at an average temperature near 427°C. Calcium silicate (Ca₂SiO₄) offers further reduced thermal conductivity and is usable at peak temperatures below approximately 650°C.

Materials with lower thermal conductivity require less thickness to achieve the same insulation performance of materials with higher thermal conductivity, but also generally have
lower peak operating temperatures. In applications where overall size is a key constraint such as FIRES units contained in pressure vessels, different insulators may be layered such that the outer layers have progressively lower thermal conductivity. Systems without volume constraints will instead go with the least expensive option, which may only layer one or two types of insulation.

Beyond size and pricing, insulation design depends on the desired heat retention for a given time period storage within FIRES, which is determined by its charge and discharge cycle. A system with daily charge and discharge cycles will require less insulation than a system that stores heat on weekly cycles. Insulation sizing and performance for different FIRES designs is further discussed in the system performance modeling chapter (5.4) and performance results chapter (6.3).

4.5.3 Heat Recovery from Insulation and Electrodes

In all FIRES designs, wires and electrodes must penetrate the firebrick chamber walls to provide electricity for resistance heating. Electrodes serve as conduits for heat leakage out of FIRES. Each SiC or MoSi$_2$ heater has two terminals that penetrate the wall, whereas metallic heaters or DRH have fewer penetrations. To reduce heat loss through electrodes, SiC and MoSi$_2$ heaters may be anchored to the walls with air injection that travels along the electrodes into the brickwork. The injected air recovers heat that would otherwise be lost through the electrical system and delivers it to the brickwork. This cooling also ensures that the heater terminals are maintained at acceptable temperatures. In applications with low inlet temperatures to FIRES, heat loss through the insulation and electrode penetrations may also be reduced by designing the system with a baffle that directs incoming air over the exterior of the brickwork insulation, between the steel liner and the bulk of the insulation. Heat leakage is recovered by preheating the incoming airstream during periods of discharge. Figure 4.10 shows both schemes for reducing heat loss.
**Figure 4.10: Methods for heat recovery from heater electrodes and insulation**

Left: “Air cooling” anchor configuration for a MoSi$_2$ heater [31]. Air flowing down the penetrations removes heat from the terminals and delivers it to the brickwork. Right: Schematic of airflow through FIRES with baffle. During discharge, the large baffle directs airflow over the outer walls and electrodes of the MoSi$_2$ or SiC heaters, preheating the incoming air before it flows into the brickwork.

In industrial processes that run at constant heat demand for periods of weeks or months, FIRES will be discharged continuously at any time when it is hot, such that there is no time where FIRES is charging without also discharging. The baffle becomes less practical in high pressure applications where the incoming air is usually 450°C or higher, and charge and discharge do not happen simultaneously. A high pressure FIRES system that uses DRH rather than MoSi$_2$ or SiC heaters minimizes the challenge of heat loss through electrodes.

### 4.6 Conclusion

The design space for FIRES was explored with respect to storage materials, charging systems, discharge systems and containment. Each system has options of varying complexity, which generally increase with the temperatures, pressure and size of the application. Table 4.6 summarizes design options and candidate configurations and their relative deployment readiness.
The simplest FIRES designs consist of materials and technology that are well established within industrial heating systems: magnesia or alumina bricks coupled with metallic heaters that reach maximum temperatures of approximately 1200°C, and a low pressure insulated steel containment. Such designs will be the first deployment of FIRES. Intermediate designs include units of higher temperatures, but low pressures. Units with SiC or MoSi\textsubscript{2} heaters require development regarding heater configurations and operating points that minimize the frequency of costly heater replacements. The lifetime of heaters for the given environment, cycling, charge rate and desired peak temperature of an application will determine if they are practical. High pressure FIRES units with silicon carbide or titania DRH brickworks require the most development. Such designs represent the longest term deployment of FIRES, to be deployed for electricity production in existing NGCC plants, and later Gen IV reactors with NACC, which are expected to be deployed after 2030 [11].

<table>
<thead>
<tr>
<th>Readiness Term</th>
<th>Short (Today)</th>
<th>Intermediate</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Al\textsubscript{2}O\textsubscript{3}, MgO</td>
<td>SiC, TiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}-C, MgO-C</td>
<td></td>
</tr>
<tr>
<td>Heating Element</td>
<td>Metallic Heaters</td>
<td>SiC, MoSi\textsubscript{2} Heaters</td>
<td>Direct Resistance Heating</td>
</tr>
<tr>
<td>Containment</td>
<td>Insulated Steel</td>
<td>Heavily Insulated Steel</td>
<td>Steel or Concrete, Heavily Insulated or active cooling</td>
</tr>
<tr>
<td>Temperatures</td>
<td>Ambient - 1200\degree C</td>
<td>Ambient -1700\degree C</td>
<td>450\degree C-1700\degree C</td>
</tr>
<tr>
<td>Pressures</td>
<td>Atmospheric</td>
<td></td>
<td>1000s kPa</td>
</tr>
</tbody>
</table>
5 System Performance Modeling

5.1 Discharge Modeling

Preliminary heat transfer calculations were done considering a single air channel-firebrick “cell.” Heat flow through the firebrick and to the airstream during discharge was modeled using a finite difference approach. Details of the approach and the equations used follow. Chapter 6.1 contains the results and discussion of discharge simulations for different brickwork sizes and dimensions.

5.1.1 Finite Difference Approach

Firebrick is laid in a pattern that forms square channels through which air can flow. In the case that FIRES is charged to a laterally uniform temperature and is well-insulated, and air flow and pressure losses through all air channels are equal, analysis of one “cell” of an air channel and the surrounding firebrick describes the entire system. Modeling was done considering a FIRES design that employs square air channels, though other channel geometries are possible. Figure 5.1 depicts a portion of the brickwork and the characteristic cell that emerges.
Figure 5.1: Depiction of brickwork as “cells” comprised of air channels and their surrounding firebrick
Top: four cells that form symmetry boundaries with neighboring cells. Outermost cells of FIRES
would have well-insulated boundaries. Bottom: one cell, with characteristic dimensions that
determine performance: firebrick half-width $w$, channel width $a$, and total channel height (denoted
as $h$ in images and $H_{FB}$ in equations).

As a simplifying approximation, conduction through the firebrick was considered one-
dimensional (1D), perpendicular to the surfaces of the air channel; conduction from the corners
of the cell was neglected, and thermal mass was conserved by modeling the cell with a new
“effective” wall half-width that includes the mass of the corners, shown visually in Figure 5.2.
Figure 5.2: Approximation of cell with 1D heat conduction (four identical wall regions)

Cell is simplified to 1D by “removing” the firebrick corners and “adding” their mass to the outside of the cell walls, forming a new wall half-width of $w_{eff}$.

By symmetry, the heat transfer through each of the four walls is symmetrical, such that they may be considered as one region in calculations. The cell was discretized into uniform wall regions of width $\Delta w$, height $\Delta h$, and length $4a$, where the factor four arises from taking the four walls as one region. For discrete wall regions not in contact with the airstream, heat transfer is entirely via conduction, governed by Fourier’s Law:

$$ \frac{dQ}{dt} = -kA \frac{dT}{dw} $$

(5-1)

where $\frac{dQ}{dt}$ is heat transfer rate, $\frac{dT}{dw}$ is the temperature gradient through the wall, $k$ is the thermal conductivity of the wall material, and $A$ is the area through which heat flows. With constant properties of firebrick, the heat flow into a small wall region of width $\Delta w$, height $\Delta h$, and length $4a$ over a short time period $\Delta t$ can be approximated with the following explicit relation:

$$ \Delta Q_I = \left( (T_{I-1} - T_I) + (T_{I+1} - T_I) \right) \frac{k_{FB} \Delta A \Delta t}{\Delta w} $$

(5-2)

where $k_{FB}$ is the firebrick thermal conductivity, $\Delta A$ is the area through which heat flows between regions, and $T$ is the temperature of the relative subscripted regions. Because all symmetrical wall regions are treated as one region, the total heat flow area $\Delta A$ is:
The change in temperature $\Delta T_i$ of the region over time $dt$ is related to heat flow by:

$$\Delta T_i = \frac{\Delta Q_i}{m_i c_{FB}}$$

(5-4)

where $c_{FB}$ is the specific heat capacity of the firebrick and $m_i$ is the mass of the arbitrary region $I$. In terms of the firebrick geometric parameters the mass of the $Ith$ region $m_i$ is defined as:

$$m_i = \rho_{FB} * \Delta w * 4a * \Delta h = \rho_{FB} * \Delta w * \Delta A$$

(5-5)

where $\rho_{FB}$ is the firebrick density. By canceling terms and converting into matrix form, the change in temperature $\Delta T_i$ of any non-boundary region of firebrick during a time period $dt$ can be expressed as:

$$\Delta T_i = \begin{bmatrix} 1 & -2 & 1 \\ \end{bmatrix} \begin{bmatrix} T_{i-1} \\ T_i \\ T_{i+1} \end{bmatrix} * \frac{k_{FB} \Delta t}{\rho_{FB} c_{FB} \Delta w^2}$$

(5-6)

This forms the basis for the tri-diagonal matrix with which to simulate the evolution of temperature through all non-boundary regions of the firebrick over time. The boundary of the firebrick region at the outermost extremity of the cell, called region one, is treated as an insulated boundary due to the symmetry of FIRES, such that no heat flows through. Because it only interacts with region two, the temperature change of region one $\Delta T_1$ is simply:

$$\Delta T_1 = \begin{bmatrix} -1 & 1 \\ \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} * \frac{k_{FB} \Delta t}{\rho_{FB} c_{FB} \Delta w^2}$$

(5-7)
To fully describe heat transfer throughout the system, the evolution of the air temperature as it flows through the channel must also be included in the matrix, denoted as region N. This region is at the center of the cell. Heat flow into the innermost region of firebrick, N-1 (“N minus one”), is a mixture of conduction from the adjacent firebrick and convection from the air:

\[ \Delta Q_{N-1} = (T_N - T_{N-1}) h_{air} \Delta A \Delta t + (T_{N-2} - T_{N-1}) \frac{k_{FB} \Delta A \Delta t}{\Delta w} \]

(5-8)

where \( h_{air} \) is the convective heat transfer coefficient. Last is region N, the air channel at the center of the cell. Heat transfer to the air comes only from convection from the innermost region of firebrick, region N-1:

\[ \Delta Q_N = (T_{N-1} - T_N) h_{air} \Delta A \Delta t \]

(5-9)

These heat transfer relations can be manipulated in the same way as previously shown (divide by the heat capacity, convert to matrix form, etc.) to obtain the remaining boundary terms.

The convective heat transfer coefficient \( h_{air} \) is calculated using relations of Reynolds number and Prandtl number that are valid for the operating temperature range (670°C to 1700°C or 25°C to 1700°C) as seen below. The Reynolds number \( Re \) and Prandtl number \( Pr \) are defined as:

\[ Re = \frac{\rho_{air} V D_h}{\mu} = \frac{G D_h}{\mu} \]

(5-10)

and

\[ Pr = \frac{(c_{p,air} \mu)}{k_{air}} \]

(5-11)
where $k_{\text{air}}$ is thermal conductivity, $c_{p, \text{air}}$ is the specific heat capacity, $\rho_{\text{air}}$ is the density of air and $\mu$ is the dynamic viscosity of air. The channel friction factor $f$, which is necessary for determining convective heat transfer, can be calculated using the Reynolds number and relative roughness $RR$ by the S.E. Haaland relation:

$$ f = \frac{1}{\left(-1.8 \log_{10}\left(\frac{6.9}{Re} + \left(\frac{RR}{3.7}\right)^{1.11}\right)\right)^2} $$

(5-12)

where relative roughness $RR$ is expressed as the equivalent surface roughness $E$ of the firebrick walls divided by the hydraulic diameter $D_h$ of the channel:

$$ RR = \frac{E}{D_h} $$

(5-13)

The equivalent surface roughness $E$ is a measure of the root mean square (RMS) height of bumps or depressions in the wall surface, where a value of zero would be a perfectly “smooth” wall. The hydraulic diameter $D_h$ is a relation of the channel flow area and perimeter:

$$ D_h = 4 \times \frac{\text{Channel Flow Area}}{\text{Channel Perimeter}} = 4 \times \frac{a^2}{4a} = a $$

(5-14)

For a square channel, the hydraulic diameter simplifies to the width of the square, $a$. The friction factor, Reynolds number $Re$, and Prandtl number $Pr$ can be used to calculate the Nusselt number. The Nusselt number $Nu$ is the ratio of convective and conductive heat transfer normal to a surface, and is expressed as:

$$ Nu = \frac{h_{\text{air}}D_h}{k_{\text{air}}} $$

(5-15)
The convective heat transfer coefficient $h_{air}$ can therefore be calculated as a function of $Nu$, $Dh$ and $k_{air}$. The latter two are known; the value of $Nu$ can be calculated using the Gnielinski relation, which relates $Nu$ to $Re$, $Pr$, and $f$, expressed as follows:

$$Nu = \left(\frac{f}{8}\right) \frac{(Re - 1000)Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} \left(Pr^2 - 1\right)}$$

(5-16)

The Gnielinski relation is valid for $0.5 < Pr < 2000$, and $3000 < Re < 5\times10^6$ and is broadly satisfied by FIRES’ geometry and operating regimes.

The time step $\Delta t$ was parameterized with the air inlet velocity $V$ and the height step $\Delta h$, such that:

$$\Delta t = \frac{\Delta h}{V}$$

(5-17)

This ensures that the energy balance equations work appropriately, such that all the heat transfer from the $\Delta h$ region of firebrick is transferred to the mass of air that flows through $\Delta h$ in the discrete time step $\Delta t$. Although technically density and velocity are both changing along the channel, the height mesh can be uniform by virtue of the constant mass flow rate and the otherwise constant properties. The resulting heat transfer matrix is applied at every height step $\Delta h$ along the length of the channel at each time step $\Delta t$. The resulting temperature change in the $\Delta h \times a^2$ column of air is passed to the next region of firebrick, and repeated until the heat capacity of the firebrick is depleted, and minimum power is produced. Figure 5.3 shows this process.
During each time step, heat is transferred from the discretized firebrick wall to the discretized air column, as dictated by their relative temperatures at each height position. At the end of the time step the air is advanced exactly one discretized height position through the channel. The discharge rate is calculated using the temperature difference of the exiting and incoming air.

Pressure drop through the air channel is calculated by the sum of the frictional losses, gravity losses and acceleration losses:

$$p_{\text{drop}} = \left[ \int_0^{h_{\text{total}}} \left( \frac{f}{D_h} \frac{d_h \rho_{\text{air}} V^2}{2} + \rho_{\text{air}} \ast g \ast d_h \right) + \frac{G^2}{2} \left( \frac{1}{\rho_{\text{air, out}}} - \frac{1}{\rho_{\text{air, in}}} \right) \right]$$

To account for the changing density of the air through the channel, the pressure drop through the channel at a given time is calculated using the summation of pressure drops over the finite differences of the channel $\Delta h$ such that:

Figure 5.3: Schematic of discretization of air flow and heat transfer through FIRES channel

[Image of schematic diagram showing discretization process]
\[ p_{\text{drop}} = \sum_{l=1}^{N} \left( f \frac{\Delta h}{D_h} \frac{G^2}{2 \rho_{\text{air},l}} + \rho_{\text{air},l} * g * \Delta h \right) + \frac{G^2}{2} \left( \frac{1}{\rho_{\text{air, out}}} - \frac{1}{\rho_{\text{air, in}}} \right) \]  

(5-19)

5.1.2 Limitations and Other Considerations

The modeling sensitivity to different parameters was examined to both identify key parameters that influence performance and justify the validity of simplifying assumptions. The modeling capabilities and limitations that result from the approximations and assumptions made are discussed.

5.1.2.1 1D Heat Conduction of Single Characteristic Cell

Modeling heat conduction as 1D normal to the firebrick wall surface does not capture the temperature gradients experienced at the corner regions or heat flow longitudinally along the channel, as would be captured in full 3D modeling. Longitudinal heat flow was considered negligible due to the high length to width ratio of the channels considered, but would gradually reduce the relative longitudinal temperature gradient over time, resulting in generally less effective heat transfer. The influence of corners on discharge performance is not important for small corners, where they represent only a small fraction of the thermal capacity of the firebrick.

The effect of neglecting conduction through the corners and adding their thermal mass as additional wall thickness should be similar but increasingly over-predictive of system thermal resistance as the corner region size increases, yielding conservative discharge performance results. Greater resolution of temperature distribution and accuracy of discharge performance are not necessary for conceptual design and preliminary performance analysis of FIRES, but full 3D modeling may be used during the detailed design phase of FIRES units.

5.1.2.2 Constant Firebrick Properties

Constant firebrick properties were chosen such that results are conservative in terms of conductive heat transfer through the firebrick. Both specific heat and thermal conductivity of firebrick change considerably over the temperature ranges of interest for each candidate material. Figure 5.4 and Figure 5.5 show firebrick property data at different temperatures.
Figure 5.4: Specific heat trends of candidate materials with temperature
Specific heat data aggregated by National Institute of Standards and Technology (NIST) [38, 39, 40, 41]

Figure 5.5: Thermal conductivity trends of candidate materials with temperature
Thermal conductivity data from [42,43]

A temperature-averaged specific heat was calculated by summing the total enthalpy gain over the operating temperature range and dividing by the temperature difference. Modeling with an average value is conservative in terms of discharge performance because specific heat increases with temperature for all materials considered, such that more energy is stored at high
temperatures than at low temperatures. This implies higher quality storage and improved heat transfer capabilities during discharge due to the retention of high temperature. Thermal conductivity was kept at a constant value corresponding to the maximum operating temperature of the firebrick, which is generally the lowest value of thermal conductivity during operation. This causes the simulation to predict heat conduction accurately at maximum temperature, but under-predict heat conduction rates at lower temperatures, where in reality the rising thermal conductivity of the cooling firebrick would aid in higher discharge rates even as the temperature gradient is reduced.

5.1.2.3 Gneilinski Relation

The behavior of heat transfer coefficient \(h_{air}\) over the operating regime of FIRES was examined in terms of the parameters of the Gneilinski Relation. These include \(Re\), \(Pr\), and \(E\). The pressure, temperature, velocity, and roughness of the system were varied. The results are shown in Figure 5.6.

The dramatic temperature increase of the air as it flows through the air channel results in large changes in properties, but were ultimately found to have relatively little influence on heat transfer coefficient. Because the product of air density and velocity, also called the mass flux \(G\), is constant along the channel, \(Re\) is unaffected by density changes that result from the temperature increase of the air, and is only influenced by the changing dynamic viscosity of air \(\mu\). However the effects of thermal conductivity \(k_{air}\), specific heat capacity \(c_{p,air}\), and dynamic viscosity \(\mu\) largely balance one another over the temperature range of interest such that \(h_{air}\) can be calculated using properties at an average temperature value throughout the simulation, with local \(h_{air}\) values never deviating from the average value by more than 15%. This was found in both low pressure (101.3 kPa) and high pressure (1000 kPa) cases, over \(2 \times 10^4 < Re < 1 \times 10^5\). This approach is in fact consistent with how the Gneilinski relation is typically applied, and experiences little improvement from interpolating property data at local temperatures of each \(\Delta h\) region, even over temperature changes as large as 1500°C.
Wall surface roughness significantly influences the convective heat transfer coefficient. The lower plots of Figure 5.6 show that a roughness of 9mm has convective heat transfer coefficients that are enhanced by a factor of 3 or 4 compared to a smooth wall, depending on the velocity and pressure. This increased effectiveness of heat transfer allows FIRES to continue discharging at the desired operating points longer without using backup fuel. Models more accurate than the Gneilinski relation should be used to determine the exact advantage of roughness, but it is widely observed that an improvement in convective heat transfer coefficient
by a factor of 2 or greater is achievable from rough surfaces compared to smooth [44], which is of great advantage in FIRES. It is therefore beneficial to use rough bricks. Firebrick may have surface roughness ranging from less than one millimeter to several millimeters. In all simulations, a roughness value of 5mm was used, corresponding to enhancement factors generally between 2 and 3 in a 20cm channel width. Firebricks of different roughness will behave differently. Brickwork designs may improve heat transfer in other ways such as bricks with ridges or a slight offset in each course of bricks that promotes turbulence.

5.2 Charge Modeling of Resistance Heaters

Heat transfer from resistance heaters to firebrick was modeled with finite difference methods very similar to those used in modeling discharge. The key difference between heat transfer during charge with resistance heaters and discharge is that radiative heat transfer dominates between the heaters and the firebrick wall surface rather than convection, due to the high operating temperatures of the heaters. Whereas convection resistance between the air and the wall surface is comparable to the firebrick resistance during discharge, radiative resistance is small such that heaters can regulate temperature and generate the wattage required to match the heat conduction rate through the firebrick wall. For a given brickwork design one simply needs to distribute enough heaters of an appropriate wattage loading and operating temperature to achieve the charge rate desired. Chapter 6.2 contains the results and discussion of charging with resistance heaters.

5.2.1 Finite Difference Approach

Radiation resistance was considered negligible, and charge was modeled purely as conduction through the firebrick with a constant uniform heat flux at the channel surface, representative of metallic heater wires running along the channel walls. For a desired charge rate and a given surface area of the channels, the required uniform heat flux was calculated. Because the system is uniform along the channel height, the problem simplifies to one firebrick region (four symmetrical walls) of thickness \( w_{\text{eff}} \) discretized into \( \Delta w \) sections. The boundary condition for constant heat flux was input simply as:

\[
\Delta T_N = [1 \quad -1] \left[ \frac{T_{N-1}}{T_N} \right] \ast \frac{k_{FB} \Delta t}{\rho_{FB} c_{FB} \Delta w^2} + \frac{q'' \Delta t}{\rho_{FB} c_{FB} \Delta w}
\]

(5-20)
Where the $Nth$ section of firebrick is the section exposed to the heat flux of the metallic heaters, and $q''$ is the heat flux (i.e. heat rate per unit area) that the $Nth$ section of firebrick experiences. Combined with the finite difference expressions derived earlier, the temperature distribution in the firebrick can be calculated as a function of time. Charge simulations began with the firebrick wall at the nominal minimum temperature of the system, and ended when any point of the firebrick wall reached the peak temperature.

### 5.2.2 Limitations and Other Considerations

As was done in the discharge modeling, both the specific heat $c_{FB}$ and thermal conductivity $k_{FB}$ were approximated as constant in time. $k_{FB}$ was taken as the lowest value that the firebrick will experience over the charge period, and $c_{FB}$ was taken as the temperature-averaged value over the temperature range. The conservative value of $k_{FB}$ means that the temperature gradient through the firebrick wall is over-predicted for lower temperatures, where the thermal conductivity may be a factor of six or seven higher, but accurate for higher temperatures.

The validity of the assumption that heaters may be controlled to provide constant heat flux is dependent on two conditions: (1) the maximum recommended wattage loading of the heater surface is not exceeded, and (2) the peak operating temperature of the heater is not exceeded. Where the maximum temperature of Kanthal heaters ranges from 1300°C to 1425°C, the peak temperature of FIRES units coupled with metallic heaters was taken as 1200°C, such that heaters may operate at temperatures 100°C-200°C higher than the peak temperature of FIRES to provide the necessary temperature difference for heat transfer even as FIRES approaches its peak temperature. Because higher temperatures results in shorter life of heaters, heaters may in practice be controlled to lower peak temperatures to extend their lives and produce slower charge rates as FIRES approaches maximum storage capacity.

In reality FIRES will not experience a perfectly uniform heat flux due to the discrete positioning of the heaters. This will result in areas within the brickwork that experience different temperature gradients, the magnitude of which determines the thermal shock experienced by the firebrick. SiC heaters and MoSi$_2$ heaters are expected to produce larger differences in temperature gradient in the brickwork because they are not easily installed along the length of the channels like metallic heaters and would instead be mounted from the walls or ceilings of the
brickwork containment. Real systems will be designed with the minimum number of heating elements that produce acceptable local temperature gradients and thermal shock experienced by the firebrick.

5.3 Charge Modeling of Direct Resistance Heating (DRH)

Charge performance was modeled considering the DRH of candidate storage materials. Different electrode configurations and charging modes were considered. Chapter 6.2 contains the results and discussion of the DRH charge simulations.

5.3.1 Direct Resistance Heating Equations and Geometry

Charge rates of DRH of firebrick were modeled using Joule’s first law:

\[ P = V_{rms}I = \frac{V_{rms}^2}{R} \]

where \( P \) is the power dissipated in the firebrick section, \( V_{rms} \) is the root mean square (RMS) voltage drop across the firebrick section, \( I \) is the current flowing through the firebrick, and \( R \) is the resistance of the section. The resistance of a section of firebrick is modeled using its material resistivity and geometry:

\[ R = \rho_{FB} \frac{l_{FB}}{A_c} \]

where \( \rho_{FB} \) is the resistivity of firebrick, \( l_{FB} \) is the length of firebrick along the flow path of current, and \( A_c \) is the cross sectional area through which current flows. \( \rho_{FB} \) is a temperature-dependent property of the firebrick. \( l_{FB} \) and \( A_c \) are determined by the overall geometry of the brickwork and the positioning of electrodes within the brickwork. For a chosen storage material and desired storage capacity and operating temperatures, a required volume of firebrick \( \text{Volume}_{FB} \) may be calculated:

\[ \text{Volume}_{FB} = \frac{Q_{des}}{\rho_{FB}(h_{High} - h_{Low})} \]
where $Q_{des}$ is the desired energy storage capacity, $\rho_{FB}$ is the density of firebrick, and $h_{High}$ and $h_{Low}$ are the specific enthalpy values of the firebrick at the high and low temperature, respectively. For a cylindrical unit, the volume of firebrick may be written geometrically as:

$$Volume_{FB} = H_{FB} \frac{\pi D_{FB}^2}{4} = H_{FB} A_c$$

(5-24)

where $H_{FB}$ is the height of the brickwork and $D_{FB}$ is the diameter of the cylindrical volume of the brickwork without air channels. The option of placing intermediate electrodes throughout the brickwork reduces the resistance experienced in the circuit by either charging only a portion of the total firebrick at a time or charging portions of the firebrick in parallel. If electrodes are placed evenly along the height of the firebrick, then $l_{FB}$ of each firebrick section may be written as:

$$l_{FB} = \frac{H_{FB}}{N_s}$$

(5-25)

where $N_s$ is the number of sections of firebrick formed by the electrodes. The design variables $H_{FB}$ and $D_{FB}$ are constrained to satisfy the required firebrick volume, and are limited by the impracticality of a tall narrow unit (large height-to-diameter ratio), or a wide short unit (small height-to-diameter ratio). $N_s$ is limited by the impracticality of layering a large number of electrode plates in the brickwork, where charging advantage diminishes and electrode volume and cost may become significant.

Charging of FIRES with different electrode configurations was simulated with an explicit numerical scheme where in a small time step $\Delta t$ the temperature change of the firebrick section may be expressed by:

$$\Delta T_I = \frac{P_I \Delta t}{m_I c_{FB,I}}$$

(5-26)
where $\Delta T_i$ is the temperature change of the section, $P_i$ is the power dissipation in the section, $m_i$ is the mass of the section, and $c_{FB,i}$ is the specific heat of the firebrick. The temperature change was then used to reevaluate the resistivity value before the next time step, and desired charge rates were maintained by varying $V_{rms}$ to accommodate the changes in resistance.

### 5.3.2 Electrode Configuration Modeling

#### 5.3.2.1 Simple Stack Modeling

The simple stack (Figure 5.7) is modeled as one large firebrick resistor of uniform properties that undergoes uniform heating while charging, where $N_s = 1$. All voltage drop therefore occurs across one resistor of spatially uniform resistivity, and the power dissipated in the simple stack can be written:

$$P_{simple} = \frac{V_{rms}^2}{r_{FB} H_{FB} A_c}$$

(5-27)

The simple stack has no means of resistance control. During charge, $V_{rms}$ is constrained by the desired charge rate $P$, and varies corresponding to the changing resistance of the firebrick as it is heated.
5.3.2.2 Switch Stack Modeling: Series

![Diagram of series-operated switch stack](image)

Figure 5.8: Series-operated switch stack

Power dissipation in the series-operated switch stack configuration (Figure 5.8) may occur across one or more resistors in series during operation. Adding progressively more resistors in series gives the advantage of maintaining acceptable values of resistance on the circuit, which in the case of oxides such as titania will decrease exponentially as the system is heated. At the beginning of operation, where only one section is being charged, the power can be written:

\[
P_{\text{switch(1)}} = \frac{V_{\text{rms}}^2}{r_{FB,1} \frac{H_{FB}}{A_c}} N_s
\]

where \(N_s\) is the relative power advantage over the simple stack. As more resistors are added to the circuit, each will be at different temperatures, with different values of resistivity and
proportionally different voltage drops across each. For an arbitrary range of firebrick sections “n” through “m,” power dissipated in the $i$th section can be expressed as:

$$P_{\text{series}(i)} = \frac{V_{\text{rms}}^2 \cdot r_{FB,i}}{(r_{FB,n} + r_{FB,n+1} + \cdots + r_{FB,m})^2 \frac{H_{FB}}{A_c}} N_s$$

(5-29)

and the total power dissipated can be expressed as:

$$P_{\text{series}(n-m)} = \frac{V_{\text{rms}}^2}{(r_{FB,n} + r_{FB,n+1} + \cdots + r_{FB,m})^2 \frac{H_{FB}}{A_c}} N_s$$

(5-30)

During charge, resistance is regulated by incrementally adding unheated sections of firebrick to the circuit anytime $V_{\text{rms}}$ would be required to drop below the lowest allowable value in order to maintain desired power levels. Charging ceases when the system is at maximum charge or there are no more unheated sections to be added and voltage cannot be maintained.

**5.3.2.3 Switch Stack Modeling: Parallel**

![Figure 5.9: Parallel-operated switch stack](image)

- **Firebrick**
- **Electrode**
- **Current Path**
- **Voltage Source**
Power dissipation in the parallel-operated switch stack (Figure 5.9) occurs in all firebrick sections simultaneously. Parallel charging allows for a much faster charge rate for a relative voltage, or a much lower voltage required for a desired charge rate. The power dissipated to a single section is the same as the power dissipated as in the start of the series-operated switch stack. The total power dissipated in the parallel operation is equal to the sum of the dissipation power of each individual section, of which there are \( N_s \). Then the total charge power can be expressed:

\[
P_{\text{parallel(alt)}} = P_{\text{series(1)}} \times N_s = \frac{V_{\text{rms}}^2}{r_{FB} A_e} N_s^2
\]

(5-31)

where the relative power advantage is \( N_s^2 \) over the simple stack, and \( N_s \) over the series-operated switch stack. Parallel operation also holds the advantage of controlling resistance by switching sections of firebrick out of parallel and into series with one another, which can be used to accommodate the exponential decrease in resistivity of oxides such as titania. Combining sections in series has the same effect as reducing the number of sections, \( N_s \). This grants the ability to increase resistance by a factor of \( N_s^2 \), to the extreme case where \( N_s \) is reduced to 1, and \( P_{\text{parallel(alt)}} = P_{\text{simple}} \).

The parallel-operated switch stack begins charging in full parallel, with \( N_s \) number of firebrick sections of equal size, temperature and resistance. Resistance is regulated by switching parallel firebrick sections into series to increase the resistance of the circuit anytime the \( V_{\text{rms}} \) would be required to drop below the lowest allowable value in order to maintain desired power levels. Sections are recombined into a new number of equal resistance sections, in that \( N_s \) is always divided evenly (i.e. 8 parallel resistors are recombined into 4 parallel resistors of double resistance, then into 2 parallel resistors of quadruple resistance, etc.). Charging ceases when the system is at maximum charge or when resistors are fully combined and acceptable voltage cannot be maintained.
5.3.3 Limitations and Other Considerations

The idealized modeling used for DRH only serves to evaluate the performance characteristics and potential advantages of using firebrick as both the heating element and storage medium of FIRES. The modeling does not account for contact resistances between individual bricks or electrodes or non-uniformities in the brick properties. It also does not consider the effects of thermal expansion and aging that will occur in real systems, or skin effects that may cause preferential heating at the firebrick surfaces. Uneven heating is of greatest concern regarding the performance of oxide materials, whose exponentially decreasing resistivity may cause uncontrollable rapid heating and damage to areas of the brickwork. These effects remain to be studied in order to evaluate their influence on the viability of DRH of titania or other oxides. They are of significantly less concern with DRH of silicon carbide, whose resistivity changes are generally increasing and less dramatic over the temperature range of interest.

5.4 Heat Leakage Calculations

Heat leakage calculations were used to determine the thickness of insulation required for the desired storage duration. System geometry was approximated and heat conduction was modeled. Each is discussed. Chapter 6.3 contains the results of the heat leakage as a function of insulation thickness for different designs.

5.4.1 Geometry Model

With FIRES of a cylindrical geometry of a known Volume\textsubscript{FB}, H\textsubscript{FB}, D\textsubscript{FB}, air channel width a and firebrick wall half-width w, a true brickwork diameter D\textsubscript{true} can be calculated that accounts for the volume of the air channels:

\[
\frac{\pi D_{true}^2}{4}H_{FB} = \frac{\pi D_{FB}^2}{4 \times (F_{v,FB})}H_{FB}
\]

\[\text{(5-32)}\]

where \( F_{v,FB} \) is the volume fraction of firebrick in the total brickwork volume, which can be described by the ratio of the area of air in the characteristic cell divided by the entire area of the characteristic cell:
\[ F_{v,FB} = 1 - \frac{a^2}{(a + 2w)^2} \]  

(5-33)

The geometry to be insulated was taken as a cylinder of diameter \( D_{true} \) and height \( H_{FB} \), where the surfaces to be insulated are the top, bottom, and circumference.

### 5.4.2 Heat Transfer and Insulation Model

Heat leakage was calculated through one or two layers of insulation composed of one or two materials with peak temperature limits suitable for FIREs’ peak temperature. Heat leakage through the insulation was modeled as steady state and 1D:

\[
P_{\text{Leak}} = k_{\text{INS}} (2A_c) \frac{\Delta T_I}{w_{\text{INS}}} + k_{\text{INS}} 2\pi H_{FB} \frac{\Delta T_I}{\ln \left( \frac{D_{\text{inner},I} + 2w_{\text{INS},I}}{D_{\text{inner},I}} \right)} \]

(5-34)

\( P_{\text{Leak}} \) is the leakage rate of heat through the insulation, \( w_{\text{INS},I} \) is the thickness of the insulation layer, \( k_{\text{INS}} \) is the bulk average thermal conductivity of the insulation, \( \Delta T_I \) is the temperature difference across the insulation, \( D_{\text{inner},I} \) is the inner diameter of the cylindrical shell of insulation that wraps around the cylinder, and \( A_c \) is the cross sectional area of insulation through which heat flows, equal to the cross sectional area of the cylinder. Equation (5-34) is composed of two terms: conduction through the top and bottom walls of the cylinder, modeled as conduction through a slab, and conduction through the circumferential area of the cylinder. When modeling two layers of insulation, the inner layer of insulation has an inner diameter \( D_{\text{inner}} \) equal to \( D_{true} \); the outer layer of insulation has a \( D_{\text{inner}} \) equal to \( D_{true} + 2w_{\text{INS},1} \), where \( w_{\text{INS},1} \) is the insulation thickness of the inner layer. The total temperature difference across all layers of insulation \( \Delta T_{\text{total}} \) was taken as the difference between the peak temperature of the FIREs unit and a temperature safe for surrounding materials or open space; 50°C was considered low enough wall temperature for open air. When modeling two layers of insulation, the first layer of insulation was always designed with the appropriate thickness to produce a temperature drop \( \Delta T_1 \) such that the second layer of insulation would not experience a temperature above its peak operating temperature. The second layer would produce a temperature drop \( \Delta T_2 \) such that its outer
The temperature is 50°C. The best value of $k_{INS}$ available among firebrick insulation was used in each case.

The acceptable leakage rate of FIRES will depend on the anticipated charge and discharge cycle of the unit. Where units intend to fully charge and discharge on daily cycles, such as in areas with heavy solar energy penetration, heat loss reduction may be of relatively low priority, and a design with little insulation may be favored because the unit will typically spend few hours at a time storing high temperature energy. For comparatively larger units that expect to operate on longer cycles or irregular time periods, thicker insulation may be desirable to cut losses and ensure high quality energy has been retained after a week or more. The insulation thickness $w_{INS}$ is therefore selected based on the acceptable leakage rate $P_{Leak}$ for the given application. In each case insulation thickness is based on a tradeoff between the cost of lost energy and the cost of the insulation with two constraints: (1) safety for employees and (2) avoidance of damage to surrounding equipment.

5.4.3 Limitations and Other Considerations

The heat leakage calculations described only account for heat leakage through the insulation itself. Additional sources of heat loss include leakage through the electrodes and heater terminals that exit the firebrick. Heat loss through electrodes may be on the same order as heat loss through insulation or larger depending on the number of penetrations through the firebrick. Methods for reducing heat loss through penetrations, as previously discussed, include heat recovery by air-cooling anchors that inject airstreams along the heater terminals into the brickwork, or a baffle that forces the incoming airstream to run over the electrodes and insulation during discharge, preheating it as it enters the brickwork. This “dynamic insulation” holds the potential for ultra-low heat losses in systems that always discharge whenever FIRES contains heat, which would be true in the case of many industrial processes that operate with constant heat demand for periods of weeks or months.

Steady state 1D conduction should over-predict leakage through the walls because the internal wall is held at a constant temperature equal to the peak firebrick storage temperature, which in reality would cool down due to the thermal resistance of the brickwork itself (and the finite thermal mass contained within the unit assuming it is not being charged at the same time). Leakage near the cylinder edges is particularly over-predicted because the 1D approximations for slab conduction and cylindrical conduction are valid far from 2D boundaries. Designers may
choose to layer several types of insulation beyond one or two to improve performance and reduce required insulation thickness. The model results are approximate but suitable for conceptual design and preliminary performance analysis.

5.5 Conclusion

The models discussed in this chapter serve as tools to estimate the performance and relative advantages of different FIRES designs. They are generally simplified and yield only approximate results but are believed to offer a reasonable expectation of the capabilities of FIRES systems in terms of charge, discharge and heat retention.
6 Preliminary System Performance

6.1 Discharge Performance

The discharge performance of FIRES is dependent on multiple design parameters. The design parameters and performance characteristics of interest are identified. Results discussion begins with a base case of parameters that is used to feature general observations of FIRES’ behavior during discharge. Then each design parameter is varied to show its impact on performance, and the findings are summarized in regard to the performance characteristics that are achievable with FIRES units of different designs.

6.1.1 Discharge Design Parameters

In total there are eleven design parameters inputted to the discharge models for results. Each has different impacts on the discharge performance of FIRES that will be explored in terms of characteristics of interest. The design parameters are as follows:

- **Material:** The materials simulated were alumina, magnesia, silicon carbide, or titania. The bulk of the analysis conducted considers only alumina and silicon carbide. Alumina and magnesia are traditional firebrick materials. Silicon carbide and titania are of potential interest because they are conductive and thus create the option of the firebrick serving two functions: firebrick and resistance heater.

- **Pressure:** Both atmospheric pressure and 1000 kPa were simulated.

- **Air Inlet Temperature:** The temperature at which air enters the system. This will depend on the environment of the application, but was taken as 30°C in all atmospheric cases, and 670°C for FIRES coupled to a nuclear air-Brayton combined cycle.

- **Peak Temperature:** The maximum temperature to which the firebrick will be heated during operation. The peak temperature is the starting temperature of the firebrick in each discharge simulation. Peak temperatures of 1700°C or lower are considered, consistent with what is achievable by commercial heaters and ratings of insulation materials.

- **Minimum Temperature:** The estimated minimum temperature that the firebrick will reach during discharge, set slightly above the air inlet temperature.
• **Operating Temperature (of Application):** The temperature demanded by the application. The FIRES unit provides heat at the operating temperature and desired heat rate for as long as possible.

• **Storage Capacity \((Q_s)\):** The amount of heat that can be stored in FIRES. The desired capacity and peak and minimum firebrick temperatures are used to determine the required volume of firebrick.

• **Discharge Rate \((P_d)\):** The rate at which heat can nominally be removed from FIRES and delivered to the airstream.

• **Height-to-Diameter Ratio (HDR):** The height to diameter ratio of the solid volume of the firebrick cylinder before taking into account air channels.

• **Air channel width \((a)\):** The width of the square air channels. This dimension in combination with the firebrick wall half-width determines volume fraction of firebrick and the unit cell width.

• **Firebrick wall half-width \((w)\):** The width of the wall that makes up the square unit cell. This dimension in combination with the air channel width determines volume fraction of firebrick and the unit cell width.

### 6.1.2 Discharge Performance Characteristics

The discharge performance of FIRES can be evaluated in several ways, the merits of which depend on the application. The key performance characteristics of interest are as follows:

• **Nominal Discharge-Rate-to-Storage-Capacity Ratio (DQR):** The ratio of discharge rate to storage capacity describes the capability of the given FIRES unit to rapidly deplete its stored energy. Users will generally require a specific discharge rate that matches the heat demand of their industrial process or power cycle. Systems of larger DQR can provide this discharge rate with less storage capacity, such that the system may be more compact and less costly. Where FIRES’ nominal discharge rate \(P_d\) and storage capacity \(Q_s\) are measured in units of MW and MWh respectively, the unit of DQR is \(h^{-1}\), and represents the fraction of capacity depleted from FIRES per hour. The inverse of DQR is the nominal total discharge period in hours. In combination with the charge-rate-to-storage-capacity ratio (CQR), the DQR determines the nominal rate at which FIRES can take advantage of higher frequency fluctuations in electricity prices. The DQR is
emphasized as only a nominal value because in practice FIRES units will not necessarily discharge at their nominal rate throughout the discharge period. An “effective” DQR, or \( \text{DQR}_{\text{eff}} \), can be defined for a full discharge period of FIRES by simply taking the inverse of the time needed to fully deplete the unit.

- **Total Discharge Fraction at Constant Rate (TDF\(_p\))**: As FIRES cools the ability to effectively discharge heat to the airstream is reduced. This eventually causes FIRES’ discharge rate to drop below the nominal design value, at which point fossil fuel heat is added or the industrial process will experience a cool-down and ultimately cease. The total discharge fraction at constant rate TDF\(_p\) represents the fraction of FIRES’ total stored energy that can be discharged at the nominal discharge rate. A higher TDF\(_p\) means a relatively longer period of constant nominal discharge and less dependence on backup heat. If TDF\(_p\) is equal to 1 then nominal discharge rate is maintained throughout the discharge period, and DQR\(_{\text{eff}}\) is equal to DQR.

- **Volume Fraction of Firebrick (F\(_v,\text{FB}\))**: The volume fraction of firebrick F\(_v,\text{FB}\) determines the total size of the brickwork that is attributed to firebrick rather than air. F\(_v,\text{FB}\) is a function of the relative sizes of the air channel width and the half-width of the surrounding firebrick (previously denoted \(a\) and \(w\)) and influences the heat transfer rate and pressure losses in the brickwork. Equivalently, one can define the volume fraction of air, F\(_v,\text{air}\), as 1 - F\(_v,\text{FB}\). A comparatively large F\(_v,\text{FB}\) and small F\(_v,\text{air}\) is desirable since a greater air volume increases system size without adding energy capacity.

- **Delivered Fan Power (P\(_{\text{fan}}\))**: The delivered fan power P\(_{\text{fan}}\) represents the power delivered to the air by the blower system to overcome pressure losses through the brickwork. A lower P\(_{\text{fan}}\) value places lesser requirements on the blower system. The actual power consumed by the blower is equal to P\(_{\text{fan}}\) divided by the efficiency of the blower, which should be selected to match the volumetric flow rate and pressure loss of the system. In each case, fan power is constrained to never exceed 2% of the nominal discharge rate.

FIRES can be optimized according to the priorities of the application. The optimal DQR depends on the market, such that storage capacity is effectively used with respect to charge and discharge cycles. A FIRES unit that never fully discharges implies too low of a DQR (i.e. excessive storage capacity) and a FIRES unit that is frequently depleted before the charge cycle begins may benefit
from greater storage, assuming the charge rate and market support the full charge of the additional storage. Systems with fossil fuel backup may not value TDF\textsubscript{p}, whereas a large TDF\textsubscript{p} is crucial in systems where backup heat is not available so that steady operation is maintained for as long as possible. Applications with pressure vessels or other constraints on system size may value the reduction of F\text{v,air} and incur greater pressure losses that require more fan power. Simulations were focused on determining the performance that may be achieved in terms of each aspect with respect to the others.

6.1.3 **Discharge Simulation Results**

6.1.3.1 **Base Case**

A base set of parameters was chosen as inputs for discharge simulation that is representative of a low-tech FIRES unit that may operate with metallic heaters (1200°C) and comfortably provide heat for a steam supply system that could power ethanol production or other low temperature processes that do not require heat above 500°C. From this base case the design parameters were varied to explore their relative influences on system performance. For all subsequent cases it should be assumed that the parameters used are identical to the base case unless otherwise noted. Table 6.1 shows the base case. The results of the base case (case ID #9) can be seen in the following figures, and in Table 6.2. A full summary of the combined base case system with respect to charge, discharge and insulation performance can be found in Table 6.13.

**Table 6.1: Base case inputs of FIRES discharge simulation**

<table>
<thead>
<tr>
<th>Case ID#</th>
<th>Material</th>
<th>Pressure</th>
<th>Air Inlet Temperature</th>
<th>Minimum Firebrick Temperature (Nominal)</th>
<th>Application Operating Temperature</th>
<th>Peak Firebrick Temperature</th>
<th>Capacity</th>
<th>DQR</th>
<th>Height-to-Diameter Ratio</th>
<th>channel width</th>
<th>firebrick wall half-width</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>101.3</td>
<td>30</td>
<td>100</td>
<td>500</td>
<td>1200</td>
<td>250</td>
<td>0.2</td>
<td></td>
<td>5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Case 9 is an alumina system with capacity 250 MWh and a DQR of 0.2, i.e. a nominal discharge rate of 50 MW, and a nominal discharge time of 5 hours. Figure 6.1a shows the discharge rate of case 9 over time. It can be seen that discharge rate is maintained at the constant nominal value of 50 MW for the majority of the discharge period, approximately 275 minutes, or 4.6 hours. Over the course of this time the brickwork is gradually cooling down and flow rate through the brickwork is increasing to maintain constant heat transfer. The increase in flow rate represents the redirection of bypass flow through the brickwork by actuation of the dampers. The
total airflow from FIRES, which includes flow through the brickwork and the bypass, is constant in time, and always recombined at the brickwork exit before being sent to the application. Figure 6.1b and Figure 6.1c shows the exit temperature and the inlet and outlet velocity of the air passing through brickwork and over time, respectively. When examining the temperature curve it can be seen that the exit temperature of the brickwork is exactly equal to the operating temperature of the industrial process 500°C at 275 minutes and the inlet velocity to the channels reaches its maximum. This point in time represents the moment where the bypass damper is fully closed, and velocity through the brickwork becomes constant. This point is referred to as the zero bypass point.

The outlet velocity is significantly faster than the inlet velocity through most of the discharge period because of the large density difference between the channel inlet and outlet. This difference in density decreases as the brickwork cools and the outlet temperature approaches the inlet temperature. The firebrick materials considered are generally acknowledged for their excellent wear resistance, but channel velocity may be limited depending on the expected erosion of the firebrick walls over operation. Figure 6.1d shows the fan power required to overcome the pressure losses through the brickwork. Fan power generally increases with inlet velocity, and peaks in this case at 275 minutes. Although mass flow rate through the brickwork is constant beyond this point, power requirements decrease because the average airstream velocity along the channel decreases as the system cools, and the slower air experiences less pressure loss (Figure 6.1f). This behavior is also visible from the start of the discharge time through approximately 100 minutes. In this period the inlet and outlet velocities and outlet temperature are essentially constant, but the brickwork is nonetheless cooling such that the airstream average temperature, and therefore average velocity, along the channel is reduced, producing less pressure loss. This effect is overshadowed by the increasing flow at approximately 120 minutes.

The time evolution of temperature difference between the firebrick wall surface and centerline is shown in Figure 6.1e. Each curve from left to right represents a discretized portion of the channel at progressively further downstream locations. Large temperature gradients are developed rapidly at the start of discharge, and occur at the inlet where 30°C air is exposed to 1200°C firebrick. Firebrick at the inlet experiences a peak temperature difference of 100°C. The portion of firebrick just beyond the inlet experiences a peak of reduced magnitude (approximately 60°C) because the airstream has already been heated by the previous section.
Figure 6.1: Base Case (Case 9) discharge plots
a): Discharge rate versus time; b): Outlet temperature versus time. c): Inlet and outlet velocity versus time; d): Delivered fan power versus time; e): Temperature difference across the firebrick wall at different equally spaced channel locations versus time. Each line from left to right represents a channel position progressively further downstream of the channel inlet (e.g. thick blue line represents the channel inlet, and solid thin blue line represents the channel outlet); f): Pressure drop versus time.
Gradients also spike toward the end of the discharge period because flow rate is driven sharply upward to maintain constant discharge rate, which results in the peak temperature difference of 30°C seen at the channel outlet. Comparatively the bulk of the firebrick experiences more gradual temperature evolution and reduced gradients that peak near 20°C. The maximum and average peak temperature differences across the firebrick are of interest when considering the relative thermal shock experienced in different designs.

6.1.3.2 Effects of Peak and Application Operating Temperatures

The peak storage temperature of FIRES and application operating temperature were both varied to observe the relative performance advantages and disadvantages. FIRES peak temperatures of 1200°C, 1550°C, and 1700°C were evaluated at application operating temperatures of 500°C, 1100°C, and 1500°C. Eight cases were evaluated. The performance summary of all eight cases is in Table 6.2.

Figure 6.2 shows the discharge results of two cases overlaid with case 9. Cases 10 and 11 have peak firebrick temperatures of 1550°C and 1700°C respectively. The peak firebrick temperatures were chosen in line with the approximate performance temperatures of metallic heaters (1200°C), SiC heaters (1550°C), and MoSi₂ heaters (1700°C). The application operating temperature is 500°C for all three cases. Each unit is designed with the same parameters as case 9 (identical capacity, discharge rate, channel dimensions, HDR, etc.), but has reduced volume due to the added energy density granted by the larger high-to-low temperature swing during operations because of higher peak temperature.

With the exception of the different output temperatures, each unit exhibits the similar behavior. All three designs have TDFₚ greater than 0.9, such that more than 90% of capacity was discharged at the nominal discharge rate. The 1550°C and 1770°C peak temperature units maintain nominal discharge rates approximately 5 and 7 minutes longer than case 9, respectively, offering slight control and reliability advantage. This longer nominal discharge period coincides with greater peak pressure loss and required fan power, because the mass flow requirement is the same for all cases but the flow area is constricted for the smaller units. If the blower system capabilities were held constant and power were constrained to be no greater than the peak power of case 9, the higher temperature cases would have essentially the same TDFₚ as case 9.
Figure 6.2: Variation of peak temperature for FIRES units with 500°C application operating temperature
Case 9: peak temperature 1200°C (blue lines); Case 10: peak temperature 1550°C (green lines); and Case 11: 1700°C (red lines)

Cases identical to the previous three were run again but with the operating temperature increased from 500°C to 1100°C. Figure 6.3 shows the results. By increasing the desired operating temperature of the application FIRES reaches the zero bypass point sooner, corresponding exactly to the point in time where the output temperature of the brickwork is equal to the operating temperature of the application. The 1200°C case has TDF<sub>P</sub> of only 0.55, due to the limited ability of the system to provide heat above 1100°C. The 1550°C and 1700°C cases are able to maintain nominal discharge longer, with TDF<sub>P</sub> values of 0.72 and 0.75, respectively. In contrast to the previous cases with a 500°C operating temperature, the higher temperature units offer a significant advantage over the 1200°C system.
Figure 6.3: Variation of peak temperature for FIRES units with 1100°C operating temperature
Case 12: peak temperature 1200°C (blue lines); Case 13: peak temperature 1550°C (green lines); and case 14: peak temperature 1700°C (red lines)

Because only operating temperature was changed, in all plots of Figure 6.3 the results to the left of the zero bypass point are identical to the respective plots of Figure 6.2. The relationship of operating temperature, TDF$_p$ and fan power is made clearer by comparing cases that all have the same peak temperature, as shown in Figure 6.4. The three cases compared are all of the same brickwork design with peak temperature of 1550°C.
In all plots of Figure 6.4 each case is seen to follow the same curve until the point where its 
operating temperature is reached. The discharge rate of FIRES can be kept constant as long as 
the output of the brickwork is above the operating temperature of the application, and the air 
velocity, pressure losses, and fan power are not prohibitively high. In general, the most valuable 
information regarding the performance of a design, including its $T_{DF}$, peak pressure loss, peak 
fan power, and peak temperature differences is determined from before the zero bypass point. 
Therefore all essential discharge performance results can be known using the case of the lowest 
reasonable operating temperature. For example the key results of cases 13 (1100°C) and 14 
(1500°C) are known solely from case 10 (500°C). The one result of interest not obtainable from 
the lowest operating temperature case is $DQR_{eff}$, which requires the total duration of discharge. 
The total duration of discharge of a given case will always fall between cases of lower and 
higher operating temperatures and may therefore be approximated from other cases.
One result of particular interest is the case of the 1550°C unit with an operating temperature of 1500°C, which was able to achieve a TDF_p of 0.45. That is, despite only a 50°C difference between peak temperature and the operating temperature, nearly half (45%) of FIRES’ heat was provided at 1500°C. Comparatively, the 1700°C unit was able to achieve a TDF_p of 0.55 with a 200°C difference in peak and operating temperatures. More results can be found in Table 6.2.

Table 6.2: Summary of discharge results for systems of different peak temperatures and different application operating temperatures

<table>
<thead>
<tr>
<th>Operating Temperature</th>
<th>°C</th>
<th>500</th>
<th>1100</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Temperature</td>
<td>°C</td>
<td>1200</td>
<td>1550</td>
<td>1700</td>
</tr>
<tr>
<td>Volume</td>
<td>m³</td>
<td>233</td>
<td>172</td>
<td>154</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>18</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Diameter</td>
<td>m</td>
<td>4.1</td>
<td>3.7</td>
<td>3.6</td>
</tr>
<tr>
<td>TDF_p</td>
<td>-</td>
<td>0.92</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Duration of TDF_p</td>
<td>h</td>
<td>4.60</td>
<td>4.69</td>
<td>4.72</td>
</tr>
<tr>
<td>Energy Factor</td>
<td>-</td>
<td>1.05</td>
<td>1.04</td>
<td>1.03</td>
</tr>
<tr>
<td>Total Duration</td>
<td>h</td>
<td>6.13</td>
<td>5.87</td>
<td>5.81</td>
</tr>
<tr>
<td>DQR</td>
<td>l/h</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Peak Total Pressure Loss</td>
<td>kPa</td>
<td>7.80</td>
<td>9.49</td>
<td>9.53</td>
</tr>
<tr>
<td>Peak Blower Power</td>
<td>kW</td>
<td>636</td>
<td>752</td>
<td>747</td>
</tr>
<tr>
<td>Firebrick ΔT Max</td>
<td>°C</td>
<td>94</td>
<td>114</td>
<td>113</td>
</tr>
<tr>
<td>Firebrick ΔT Average</td>
<td>°C</td>
<td>23</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>Case ID#</td>
<td>-</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

All units were of 250 MWh capacity and 0.2 DQR, and all design parameters were taken as the base case, case 9. System volumes include firebrick and air channels.

### 6.1.3.3 Effects of Nominal Discharge-to-Storage-Capacity Ratio (DQR)

The DQR was varied for systems with peak operating temperature 1200°C and 1550°C. The results are shown in Figure 6.5 and Figure 6.6 and summarized in Table 6.3.
Figure 6.5: Variation of DQR for FIRES units with 1200°C peak temperature and 500°C operating temperature

Case 17: 0.1 (green); Case 9: 0.2 (blue); Case 18: 0.3 (red); Case 19: 0.4 (pink).

Values of 0.1, 0.2, 0.3, and 0.4 were used for DQR, where 0.2 is the base case. TDFₚ of each case is 0.93, 0.92, 0.88, and 0.81, respectively, showing a decrease in reliability as DQR rises. In the cases of 0.3 and 0.4 DQR, there is an additional effect constraining the discharge performance, which is the peak allowable fan power. All simulations were constrained to never exceed fan power equal to 2% of the nominal discharge rate. As DQR increases from 0.1 to 0.4 it can be seen that pressure losses and required fan power increase dramatically, because an increase in DQR means a proportional increase in flow rate desired by the application. The allowed peak fan power also increases proportionally to DQR since it is constrained as a percentage, but major pressure losses increase approximately by the square of the mass flow rate, and fan power increases by the cube of the mass flow rate. The fan power of the 0.3 and 0.4 cases reach 1500 kW and 2000 kW at approximately 180 minutes and 120 minutes, respectively. This means that the point where nominal discharge rate is lost is not the zero bypass point, but
instead the point of maximum fan power. Beyond this point, fan power remains constant even as pressure losses decrease because whenever fan power is available more of the bypass air is driven through the brickwork to produce the maximum possible discharge rate. In the 0.3 case, the zero bypass point occurs at approximately 250 minutes, where fan power can be seen to reduce below the maximum. In the 0.4 case, zero bypass never occurs even after the unit is fully depleted of heat, indicating that the combination of brickwork and blower is essentially incapable of handling the full flow rate of the application. Very similar results can be seen with a peak temperature of 1550°C, shown in Figure 6.6:

![Discharge Power vs Time](image)

![Output Temperature vs Time](image)

![Pressure Loss vs Time](image)

![Fan Power vs Time](image)

**Figure 6.6: Variation of DQR for FIRES units with 1550°C peak temperature and 500°C operating temperature**

Case 40: 0.1 (green); Case 10: 0.2 (blue); Case 41: 0.3 (red); Case 42: 0.4 (pink)
The one behavioral difference between the 1200°C and 1550°C scenarios is that zero bypass is never reached in either the 0.3 or 0.4 DQR cases. This result is a product of the higher DQR and the effects of more compact high temperature systems previously discussed. Despite the limitation of fan power the TDF\textsubscript{p} remains at 0.9 or higher for DQR of 0.3 or lower, and falls to 0.84 for a DQR of 0.4, showing comparatively higher values in TDF\textsubscript{p} than the 1200°C cases.

Although the analysis so far may suggest that these designs are impractical for DQR above 0.2, it should be kept in mind that the curves considered are simulated with an operating temperature of 500°C. Higher temperature applications would demand less mass flow rate and would have performance characteristics found to the left of the maximum fan power point seen in Figure 6.5 and Figure 6.6. For comparison, Table 6.3 summarizes the results of the discussed cases and four additional cases of the 1550°C peak temperature system with 1100°C operating temperature. Compared to the 500°C case, an 1100°C operating temperature reduces fan power by a factor of 2 or greater in all cases.

In general, most applications are expected to operate on daily cycles or longer depending on the wind or solar penetration of an area, such that discharge may occur over the period of a night (8 to 12 hours), or days. These values correspond to a DQR of 0.125 or less. The DQR performance results suggest that FIRES is not limited to use in daily cycles, and may be capable of effectively capturing and discharging cheap electricity on hourly cycles for flexible response to changes in renewable generation.
Table 6.3: Summary of discharge results for systems operated at different DQR and different operating temperatures

<table>
<thead>
<tr>
<th>Peak Temperature °C</th>
<th>1200</th>
<th>1550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume m³</td>
<td>233</td>
<td>172</td>
</tr>
<tr>
<td>Height m</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Diameter m</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Operating Temperature °C</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>DQR 1/h</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>TDFp</td>
<td>0.93</td>
<td>0.92</td>
</tr>
<tr>
<td>Duration of TDFp h</td>
<td>9.30</td>
<td>4.60</td>
</tr>
<tr>
<td>Energy Factor</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Total Duration h</td>
<td>12.11</td>
<td>6.13</td>
</tr>
<tr>
<td>DQR_off 1/h</td>
<td>0.08</td>
<td>0.16</td>
</tr>
<tr>
<td>Peak Total Pressure Loss kPa</td>
<td>2.07</td>
<td>7.80</td>
</tr>
<tr>
<td>Peak Blower Power kW</td>
<td>85</td>
<td>636</td>
</tr>
<tr>
<td>Firebrick ΔT Max °C</td>
<td>49</td>
<td>94</td>
</tr>
<tr>
<td>Firebrick ΔT Average °C</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>Case ID#</td>
<td>17</td>
<td>9</td>
</tr>
</tbody>
</table>

All other design parameters were taken as the base case, case 9

6.1.3.4 Effects of Height-to-Diameter Ratio (HDR)

The results of base case parameters (FIRES temperature range from 100°C to 1200°C, application operating temperature of 500°C) with HDR values of 2, 3, 5, and 7 are shown in Figure 6.7.
An increase in HDR from 2 to 7 for the base case parameters is shown to slightly increase $TDF_p$ and significantly increase pressure drop and fan power. The increase in pressure drop and fan power arises from the simultaneous constriction of flow area and lengthening of flow path as HDR is increased. The case with HDR of 7 experiences a period of maximum allowable fan power (1000 kW) for approximately 50 minutes before reaching the zero bypass point. Comparatively HDRs of 2 and 3 reach only a small fraction of the maximum power of 130 kW and 263 kW respectively. The higher HDR yields little advantage at low operating temperatures compared to small HDR, but appears to improve $TDF_p$ significantly compared to HDRs of 2 and 3 at higher operating temperatures such as 1100°C by inspection of the temperature results. The results of each case are summarized in Table 6.4.
Table 6.4: Summary of discharge results for systems designed with different HDR

<table>
<thead>
<tr>
<th>HDR</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>10</td>
<td>13</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>5.4</td>
<td>4.8</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>TDFp</td>
<td>0.85</td>
<td>0.89</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Duration of TDFp (h)</td>
<td>4.29</td>
<td>4.48</td>
<td>4.60</td>
<td>4.64</td>
</tr>
<tr>
<td>Energy Factor</td>
<td>1.04</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Total Duration (h)</td>
<td>6.46</td>
<td>6.27</td>
<td>6.13</td>
<td>6.06</td>
</tr>
<tr>
<td>DQR\textsubscript{eff} (l/h)</td>
<td>0.15</td>
<td>0.16</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>Peak Total Pressure Loss (kPa)</td>
<td>1.59</td>
<td>3.22</td>
<td>7.80</td>
<td>12.79</td>
</tr>
<tr>
<td>Peak Blower Power (kW)</td>
<td>130</td>
<td>263</td>
<td>636</td>
<td>1002</td>
</tr>
<tr>
<td>Firebrick \Delta T Max (°C)</td>
<td>55</td>
<td>70</td>
<td>94</td>
<td>113</td>
</tr>
<tr>
<td>Firebrick \Delta T Average (°C)</td>
<td>17</td>
<td>20</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Case ID#</td>
<td>43</td>
<td>20</td>
<td>9</td>
<td>21</td>
</tr>
</tbody>
</table>

Fires temperature range 100°C to 1200°C, application operating temperature of 500°C. All other design parameters were taken as the base case, case 9.

6.1.3.5 Effects of System Capacity

System capacity was varied between 150, 250 and 500 MWh of storage while keeping DQR constant among cases. The results can be seen in Figure 6.8.

As the system capacity is increased so do both TDF\textsubscript{p} and required fan power. The increase in fan power is significant and causes the 500 MWh system to experience a period of maximum allowable fan power (2000 kW) for 50 minutes before the zero bypass point. The difference in behavior of a larger system compared to that of a smaller system is attributable to the HDR that is held constant among the three cases, which results in an effective constriction of flow area and lengthening of flow path as capacity is increased. When increasing capacity from 250 MWh to 500 MWh one can imagine two 250 MWh systems operating in parallel, which would yield identical temperature and pressure curves and exactly double the values of the discharge rate and fan power observed from a single 250 MWh system. In such a case the height...
of the equivalent 500 MWh system should remain the same as the 250 MWh system, and the
diameter would be taken as $\sqrt{2}$ the diameter of the 250 MWh system to match the area of two
250 MWh systems, such that the HDR of the larger unit is $\frac{1}{\sqrt{2}}$ of the smaller unit. Generalizing
this relationship, holding all other parameters constant, two systems of different capacity will
behave identically if:

$$\sqrt{Q_s} HDR_1 = \sqrt{Q_s} HDR_2$$

(6-1)

where $Q_s$ is the storage capacity of the subscripted system. Considering that a HDR of 5
multiplied by $\sqrt{2}$ is 7.07, the above relation states that the 500 MWh system with a HDR of 5
(case 23) will behave equivalently to a 250 MWh system with a HDR of 7 (case 21). These cases are plotted together in Figure 6.9, alongside case 9 for reference.

As expected, the temperature and pressure plots of cases 21 and 23 are identical, and the discharge rate and fan power differ by a factor of two, exactly the difference of mass flow rates in the two systems. This direct relationship between HDR and capacity helps to generalize performance results. It also means that as systems grow in capacity units will be faced with undesirable pressure losses unless they are designed with smaller HDR, which will influence containment design. The practical implication is that the height is set to meet a specific set of performance requirements and the diameter is set to obtain the desired capacity—with adjustments for the cost of insulation and other engineering constraints.
6.1.3.6 Effects of Cell Size

Cell width was varied between 0.2, 0.3, 0.4, and 0.6 m while maintaining firebrick volume fraction $F_{v,FB}$ at the constant base case value of 0.75. Figure 6.10 shows the results.

Figure 6.10: Variation of cell width for FIRES (with constrained $F_{v,FB}$) with temperature range 100°C to 1200°C, application operating temperature of 500°C
Case 9: 0.2 m (blue); Case 34: 0.3 m (pink); Case 32: 0.4 m (green); Case 33: 0.6 m (red).

A smaller cell width benefits heat transfer in the channel by virtue of the increased surface area, increased convective heat transfer coefficient, and the reduced thermal resistance of the thinner walls. The increased surface area causes an increase in pressure drop, but the improved heat transfer demands less flow rate, such that although the smallest cell width has the highest pressure drop throughout operation, its required power is generally less throughout operation than that of the cells of larger width, even as each reach their zero bypass points earlier. The results show significantly improved $TDF_p$ in smaller cell widths compared to larger
cell widths. Cell width in practice will be limited by what relative firebrick wall thickness is practically achievable. The full results are summarized in Table 6.5.

Table 6.5: Summary of discharge results for systems designed with different cell width

<table>
<thead>
<tr>
<th>FIRES Discharge Results Summary: Cell Width Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Width</td>
</tr>
<tr>
<td>Channel Width</td>
</tr>
<tr>
<td>Firebrick half-width</td>
</tr>
<tr>
<td>TDFp</td>
</tr>
<tr>
<td>Duration of TDFp</td>
</tr>
<tr>
<td>Energy Factor</td>
</tr>
<tr>
<td>Total Duration</td>
</tr>
<tr>
<td>DQR_{eff}</td>
</tr>
<tr>
<td>Peak Total Pressure</td>
</tr>
<tr>
<td>Peak Blower Power</td>
</tr>
<tr>
<td>Firebrick ΔT Max</td>
</tr>
<tr>
<td>Firebrick ΔT Average</td>
</tr>
<tr>
<td>Case ID#</td>
</tr>
</tbody>
</table>

Temperature range 100°C to 1200°C, application operating temperature of 500°C All other design parameters were taken as the base case, case 9.

6.1.3.7 Effects of Volume Fraction of Firebrick

Volume fraction of firebrick F_{v,FB} was varied from approximately 0.44 to 0.86. The results are shown in Figure 6.11.
As $F_{v,FB}$ is increased the relative flow area of air is decreased, causing higher flow rate per channel, driving up pressure losses and convective heat transfer coefficient. Because thermal resistance of the firebrick wall is also increased and surface area available for heat transfer decreases, the heat transfer advantage of excessively high $F_{v,FB}$ becomes outweighed by impractically high pressure losses. Reasonable values are generally found to be between 0.7 and 0.8, but may be higher depending on the specific operating points of the application. Results are summarized in Table 6.6.
Table 6.6: Summary of discharge results for systems designed with different volume fraction of firebrick

<table>
<thead>
<tr>
<th>FIRES Discharge Results Summary: Volume Fraction Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Fraction of Firebrick</td>
</tr>
<tr>
<td>Channel Width m</td>
</tr>
<tr>
<td>Firebrick half-width m</td>
</tr>
<tr>
<td>TDFp</td>
</tr>
<tr>
<td>Duration of TDFp h</td>
</tr>
<tr>
<td>Energy Factor</td>
</tr>
<tr>
<td>Total Duration h</td>
</tr>
<tr>
<td>DQR$_{off}$ l/h</td>
</tr>
<tr>
<td>Peak Total Pressure Loss kPa</td>
</tr>
<tr>
<td>Peak Blower Power kW</td>
</tr>
<tr>
<td>Firebrick $\Delta T$ Max $^\circ$C</td>
</tr>
<tr>
<td>Firebrick $\Delta T$ Average $^\circ$C</td>
</tr>
<tr>
<td>Case ID#</td>
</tr>
</tbody>
</table>

Temperature range 100°C to 1200°C, application operating temperature of 500°C. All other design parameters were taken as the base case, case 9.

6.1.3.8 High Pressure System Results: FIRES coupled with FHR and NACC

Eight FIRES designs were simulated for coupling to the FHR. The parameters of the cases considered are shown in Table 6.7.
Because design points of the application are known, the pressure, discharge rate, air inlet temperature, operating temperature, and nominal minimum temperature were kept constant between cases. HDR, cell width, and peak temperature were varied, while volume fraction of firebrick was kept constant. Results for a peak operating temperature of 1700°C and 1500°C are shown in Figure 6.12 and Figure 6.13, respectively. The summary of results for all can be found in Table 6.8.

Results of FIRES coupled with FHR at 1700°C peak temperature show that, depending on the parameters, $T_{DF_p}$ between 0.78 and 0.93 may be achieved. This is dependent mainly on cell width, which has already been shown to considerably improve performance in atmospheric systems. Increasing the HDR from 3 to 5 very slightly improves $T_{DF_p}$ but with a relatively large disadvantage in required fan power, as can be seen when comparing cases 5 and 7 as well as case 1 and 3. The advantage of HDR is more appreciable in systems that have close peak and operating temperatures, which is not true of FIRES coupled with FHR because higher peak storage temperatures (1500°C or higher) are desirable for reducing volume of the pressure vessel, and the operating temperature of the cycle is expected to be only 1065°C. This may change if a higher temperature turbine is used.
Several noteworthy differences can be seen in the high pressure systems compared to the low pressure systems examined. Despite the much larger capacity and discharge rate and comparable DQR (.142), the high pressure systems have pressure losses and fan power on the same order as the low pressure systems. This is owed to the much higher density of air at 1000 kPa compared to that of atmospheric air, which results in reduced channel velocities and volumetric flow, requiring significantly reduced power by the blower. The case with smaller cell width and HDR of 5 only requires near 700 kW of delivered fan power, which is less than 20% of the 2% constraint. The higher density also improves the heat transfer performance of air.
Case 2: HDR = 3, cell width = 0.4 (blue); Case 4: HDR = 5, cell width = 0.4 (green); Case 6: HDR = 3, cell width = 0.2 (red); Case 8: HDR = 5, cell width = 0.2 (pink).

Figure 6.13: Variation of HDR and cell width for FIRES coupled with FHR with peak temperature of 1500°C. The systems with peak temperature of 1500°C show similar results to the 1700°C, where the larger HDR and smaller cell width were found to be the best at maintaining nominal discharge. TDF$_p$ varies from 0.73 to 0.91, indicating that the control advantage of 1700°C over 1500°C is relatively small. However the volume of the 1700°C unit is 20% smaller, offering the advantage of reduced materials and pressure vessel size. More results can be found in Table 6.8.

One caveat is relevant to these high pressure systems. The pressure vessel design may impose constraints on the width to diameter ratio and other features of FIRES. This was not investigated herein.
6.2 Charge Performance

Charge performance was evaluated with respect to one representative case of charging via metallic resistance heaters and several configurations of direct resistance heating (DRH) of each of the candidate storage materials: alumina, magnesia, titania and silicon carbide. The key design parameters and charge performance characteristics are identified and discussed. Results discussion explores performance as a function of the option space, and concludes with general observations of the behavior of each candidate material and configuration.
6.2.1 Charge Design Parameters

In total there are seven design parameters inputted to the DRH models for results. Each has different impacts on the charge performance of FIRES that will be explored in terms of characteristics of interest. The design parameters are as follows:

- **Material**: The materials simulated were alumina, magnesia, silicon carbide, or titania.

- **Peak Temperature**: The maximum temperature to which the firebrick will be heated during operation. Firebrick sections are considered fully charged when they reach peak temperature. Peak temperatures of 1700°C or lower are considered, consistent with what is achievable by commercial heaters and ratings of insulation materials.

- **Minimum Temperature**: The estimated minimum temperature that the firebrick will reach during discharge, set slightly above the air inlet temperature. The minimum firebrick temperature is the starting temperature of all firebrick sections during charge simulation.

- **Storage Capacity (Qs)**: The amount of heat that can be stored in FIRES. The desired capacity and peak and minimum firebrick temperatures are used to determine the required volume of firebrick.

- **Charge Rate (Pc)**: The rate at which heat is delivered to the firebrick.

- **Height-to-Diameter Ratio (HDR)**: The height to diameter ratio of the solid volume of the firebrick cylinder before taking into account air channels.

- **Number of firebrick sections (Ns)**: The number of firebrick sections that are available to be individually charged in series or parallel, separated by electrodes.

6.2.2 Charge Performance Characteristics

The charge performance of FIRES is evaluated in three ways:

- **Charge-Rate-to-Storage-Capacity Ratio (CQR)**: The ratio of charge rate and storage capacity describes the capability of the given FIRES unit to rapidly accumulate energy and reach full capacity of storage. Where FIRES’ charge rate $P_c$ and storage capacity $Q_s$ are measured in units of MW$_e$ and MWh respectively, the unit of CQR is h$^{-1}$, and represents the fraction of capacity accumulated in FIRES per hour (assuming the system does not simultaneously discharge). The inverse of CQR is the total charge period in...
hours, assuming constant charge. In combination with the nominal discharge-rate-to-
storage-capacity ratio (DQR), the CQR determines the nominal rate at which FIRES can
take advantage of higher frequency fluctuations in electricity prices, by permitting the
rapid charging of FIRES during periods where electricity prices reach their lowest point.
In systems with simultaneous charge and discharge it is necessary that charge rate exceed
discharge rate so that heat may be provided to both the application and the firebrick for
storage. In such cases it is practical to consider a CQR_{net}, equal to CQR – DQR, which is
the nominal accumulated portion of capacity per hour when also discharging at the
nominal rate.

- **Maximum Required Voltage (V_{max}):** The maximum voltage determines in part the
  sophistication of the power supply. A lower V_{max} is generally desirable because electrical
  insulation involving the operation of the unit is simpler, but higher values of V_{max} in class
  with other industrial power applications are considered feasible. If V_{max} can be matched
  with the line voltage at the application site and voltage control can be met without tap
  changing, the power supply may be simplified by removing the need for a transformer.\(^6\)

- **High-to-Low Voltage Ratio (VR):** In order to maintain constant charge rate the voltage
  will be increased or decreased to respond to changes in resistivity of the storage material
  as it is heated. The ratio of the high and low voltage determines the requirements of the
  power supply with respect to transformer taps and thyristor firing. A smaller VR is
  therefore desirable because it requires a generally less sophisticated power supply.

### 6.2.3 Charge Simulation Results

#### 6.2.3.1 Resistance Heater Calculations

For near-term deployment of FIRES, resistance heaters will be used to charge FIRES
rather than DRH. This is off-the-shelf technology. The major technical limitation is the allowable
peak temperature. A single characteristic case was considered with respect to the use of metallic
heaters in FIRES to determine the practicality of achieving relatively fast charge rates with
metallic heaters, both in terms of the number of heaters required. The parameters of the unit are
shown in Table 6.9.

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\(^6\) This assumes the intermediate connection to the broader transmission system, if there is one, can handle the
additional power transmission required by FIRES.
The temperature through the firebrick walls were simulated with a constant heat flux, representative of the power coming from metallic heater wires strung along the length of each channel. Radiative resistance was considered negligible compared to conduction resistance, and it was assumed the heaters were controlled to maintain the proper temperature difference between the firebrick surface and the heater surface to deliver constant power. The case considered has a peak FIRES temperature of 1200°C, in class with the capabilities of metallic heaters, which have peak operating temperatures of 1300°C or higher in the case of Kanthal heaters, the highest among them being Kanthal APM™ at 1425°C [28]. The goals of the simulation were to determine the temperature difference across the firebrick, and calculate the fraction of energy stored in the system after the wall surface reaches the peak FIRES temperature of 1200°C. Figure 6.14 shows the results of the simulation.

<table>
<thead>
<tr>
<th>Equivalent Discharge Case ID#</th>
<th>Material</th>
<th>Pressure</th>
<th>Air Inlet Temperature (Nominal)</th>
<th>Minimum Operating Temperature</th>
<th>Peak Temperature</th>
<th>Capacity</th>
<th>CQR</th>
<th>Height-to-Diameter Ratio</th>
<th>Channel Width</th>
<th>Firebrick Wall Half-Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Al₂O₃</td>
<td>101.3</td>
<td>30</td>
<td>100</td>
<td>500</td>
<td>1200</td>
<td>250</td>
<td>0.3</td>
<td>5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

In order to achieve a CQR of 0.3 (75 MW charge rate) a temperature difference of 20°C was developed across the thickness of the firebrick wall, in the first 3 minutes of operation. If desired the rate at which the temperature difference is established may be reduced by gradually ramping...
up the heaters over time in order to reduce thermal shock. At the end of the charge period, the temperature profile shows the 20°C difference through the wall thickness, with the centerline of the firebrick wall reaching 1180°C. The end state represents a system charge percentage of approximately 98.8%, indicating that the slightly cooler portion of firebrick on the inner wall does not represent a significant portion of energy.

The necessary amount of heater wire was estimated considering Kanthal APM™ with a conservative value of surface load over the temperature range. For the largest standard stock wire (1 cm diameter) and at an estimated 40 kW/m² of surface loading constant throughout operation, the heating required may be provided with approximately ten wires per channel, equal to 58,000 m long (ten wires for 323 channels of 18 meters each) and 33.4 metric tons, representing approximately 3.6% the mass of the alumina firebrick. This is a feasible amount of wire, but may be reduced considerably if (1) the diameter is reduced so that surface area to volume ratio of wire is increased, and (2) the surface loading is maintained at a higher value. However both of these modifications decrease the life span of the heaters, which may vary by an order of magnitude or more depending on the wire diameter and operating conditions. The optimal tradeoff between diameter, surface load and required wire length needs further consideration. In any case, these results are for a CQR of 0.3, which corresponds to a charge period of only 3.33 hours. This is a significantly larger CQR than that required by a daily cycle of charge and discharge, which is expected to be the most practical cycle for many applications due to the behavior of electricity prices with respect to solar energy penetration. The results therefore support the expectation that metallic heaters can be used to effectively heat FIRES with charge rates on the order of daily cycles or faster.

There are several caveats associated with such calculations. First is the allowable temperature drops across the firebrick. Second, if the peak temperatures for the firebrick are significantly below the temperature limits of the heater wire, higher power levels for the heater wire are allowable.

6.2.3.2 Overview of DRH

The DRH is an advance high-performance option that allows FIRES to operate at very high temperatures. That high temperature capability may be the largest technical benefit of such a system.
DRH calculations considered silicon carbide, titania, alumina, and magnesia with the three different charging configurations previously discussed: the simple stack, the switch stack operated in series, and the switch stack operated in parallel. The simple stack consists of one large section of firebrick, the resistance of which depends only on the storage material, volume, and HDR. The charge rate delivered is simply proportional to the square of the voltage. However each candidate material experiences changes in resistivity as they are heated, such that RMS voltage must be varied proportional to the square root of resistance if charge rate is to remain constant. Therefore maintaining constant power requires that the high-to-low voltage ratio VR be equal to the square root of the high-to-low resistance ratio over the temperature range. Table 6.10 compares the behavior of the candidate materials and the resulting requirements of the power supply. The general parameters considered are representative of a FIRES unit that may be coupled with the FHR, with a capacity of 1500 MWh, charge rate of 450 MW (CQR of 0.3), HDR of 3, and a peak and minimum temperature of 1700°C and 700°C, respectively. One case with a minimum temperature of 100°C is also considered.

For the same temperature ranges, all four candidates have approximately the same system size, with dimensions of approximately 24 meters tall and 8 meters wide. However the peak voltage and VR of each material varies dramatically due to their different resistivity behaviors. In the simple stack configuration ($N_s = 1$), alumina and magnesia exceed practical peak voltage requirements by an order of magnitude or more, each requiring thousands of kilovolts (hundreds of thousands in the case of magnesia) to achieve a charge rate of 450 MW. Comparatively, titania requires only 121 kV to achieve 450 MW, which is in class with the operating voltage of transmission power lines. All three oxides vary in resistance by several orders of magnitude over the temperature range, the square root of which is the voltage ratio required to maintain constant charge rate. This is because each oxide experiences an exponential decrease in resistivity with temperature. Resistance of magnesia changes by five orders magnitude from 700°C to 1700°C, which would require a VR of approximately 800 to provide constant charge rate. Alumina and titania require a voltage ratio of 25 and 21 respectively, which is generally out of class with that required by resistance heaters, but on the same order of the VR capable of being produced by transformers such as those used for electric arc furnaces, which are capable of transmitting power on the scale of 100s of megawatts [45].
Silicon carbide is far more electrically conductive than the oxides, requiring less than 10 kilovolts to charge with 450 MW in both designs. Moreover, its resistivity varies nearly linearly with temperature rather than exponentially, changing by only a factor of 5 over the temperature range from 100°C to 1700°C. This requires a VR of approximately 2.3, dramatically reducing the required capabilities of the power supply. Comparatively MoSi$_2$ heaters experience a factor of 10 increase in resistance [30], corresponding to a voltage increase of 3.2. It is also the only practical option for achieving DRH at temperatures below 600°C, due to the exponential growth of resistivities of the oxides at lower temperatures. These attributes of silicon carbide would be expected since it is already used as a material for resistance heaters. Figure 6.15 shows the

<table>
<thead>
<tr>
<th>Material</th>
<th>Al$_2$O$_3$</th>
<th>MgO</th>
<th>TiO$_2$</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume ($m^3$)</td>
<td>1051</td>
<td>1136</td>
<td>1326</td>
<td>1328</td>
</tr>
<tr>
<td>Diameter ($m$)</td>
<td>7.6</td>
<td>7.8</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>Height ($m$)</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Peak Temperature ($°C$)</td>
<td>1700</td>
<td>1700</td>
<td>1700</td>
<td>1700</td>
</tr>
<tr>
<td>Minimum Temperature ($°C$)</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
</tbody>
</table>

The design parameters shown are representative of a FIRES unit that may be coupled with the FHR. System dimensions and volume include firebrick and air volume without insulation.
behavior of system resistance and voltage drop and temperature in time while maintaining the constant charge rate of 450 MW over the charge period.

![Graph showing Voltage vs Time](image1)

![Graph showing Temperature vs Time](image2)

![Graph showing Resistance vs Time](image3)

**Figure 6.15**: Charge results of silicon carbide simple stack unit of 1500 MWh, HDR 3, constant charge rate of 450 MW, temperature range of 100°C to 1700°C.

a): Voltage versus time; b): Temperature versus time; c): Resistance versus time.

With the assumption that the brickwork can be developed to produce manageable contact resistance on the same order of the bricks, very large charge rates in silicon carbide can be produced in a simple stack configuration with relatively low voltages and common control options. If, hypothetically, contact resistances were to increase overall resistance by an order of magnitude (i.e. factor of 10), the resulting increase in required voltage would be the square root of this (3.16), with no direct effect on the required VR. Effects on VR may however be introduced by thermal expansion and shifting of bricks, which may change the contact resistance
over the heating period. Both of these effects, while not investigated in this study, may be partially addressed by the switch stack configuration, which both reduces peak required voltage and grants control of circuit resistance by splitting the brickwork into several sections, allowing for the heating of only portions of the firebrick at a time or multiple sections of firebrick in parallel. The benefits of the switch stack may make a silicon carbide system more reliable and make the oxide systems more viable. Series and parallel operation of a switch stack are discussed in the following sections.

6.2.3.3 Switch Stack: Series

As previously described the switch stack splits the firebrick into sections by including intermediate electrodes in the brickwork. Where FIRES is split into \( N_s \) portions of equal height stacked on top of one another, one may charge a single section of firebrick, which has resistance of only \( 1/N_s \) compared to the resistance of the whole stack, because it has the same cross section but only has a height of \( 1/N_s \) the height of the whole stack. This reduces the voltage required to produce the desired charge rate by the square root of \( 1/N_s \). Of the candidate materials discussed only silicon carbide and titania are considered viable with switch stack configurations operated in series, because even with high \( N_s \) both alumina and magnesia require voltages significantly higher than transmission line voltage (1061 kV and 23211 kV respectively for \( N_s \) of 16 and HDR of 3, Table 6.10). The value of \( N_s \) will be chosen based on what number gives adequate charge characteristics. the practical limitation on \( N_s \) is the thickness of the sections (i.e. sections of only a few centimeters are impractically thin for construction), and the cost of electrode materials required to separate each section, which may be made from metals able to withstand the operating temperature, such as titanium or tungsten, or firebrick of a higher conductivity than the storage material—including potentially highly doped SiC. The number of electrodes introduced to the firebrick beyond the mandatory ones on each extremity is equal to \( N_s - 1 \).

Figure 6.16 shows the voltage required to charge the first unit of firebrick in a titania system with the same design parameters shown in Table 6.10 with the desired charge rate of 450 MW in a 1500 MWh titania system with different values of \( N_s \) and HDR.
Figure 6.16: Required maximum voltage for different values of $N_s$ and HDR in a titania series-operated switch stack.

1500 MWh capacity, 450 MW charge rate, 700°C-1700°C temperature range.

An $N_s$ of 1 is equal to the simple stack, which for titania required 121 kV to charge with an HDR of 3. By splitting the brickwork into 4 sections, voltage is reduced by half, to only 60 kV, and by three quarters with 16 sections, bringing the voltage to only 30 kV. HDR directly influences the maximum required voltage by changing the ratio of length to cross-sectional area of the cylinder. This ratio changes by a factor of 4 when changing HDR from 3 to 1, such that voltage reduces to 60 kV.

A more generalized map of $V_{\text{max}} N_s$ and HDR may be produced that pertains to all capacities and CQRs (i.e. charge rates) of FIRES by acknowledging two relationships. First, the CQR is proportional to the square root of the required voltage, such that, for two identical systems:

$$\frac{V_{\text{max},1}}{\sqrt{CQR_1}} = \frac{V_{\text{max},2}}{\sqrt{CQR_2}} = V^*$$

(6-2)
The second relationship involves system capacity and HDR. Consider two identical systems with capacities of 250 MWh and CQRs of 0.2, operating in parallel. Just as the independent systems have equal height and double the cross sectional area for double the electricity (but still CQR of 0.2), combining these systems into one 500 MWh that behaves identically would require the height and cross sectional area of the larger system to be equal to the smaller ones. This yields a shorter HDR that is reduced by a factor $\frac{1}{\sqrt{2}}$ compared to the smaller units. It is understood then that two systems behave the same, i.e. require the same maximum voltage for a given CQR, if:

$$\sqrt{Q_{s1}}HDR_1 = \sqrt{Q_{s2}}HDR_2 = HDR^*$$

(6-3)

A demonstration of these relations can be seen in Figure 6.17, which plots different maximum required voltage versus HDR for systems of different capacities and CQRs. Although all cases have different All cases can be seen to collapse to the same curve when $V^*$ and $HDR^*$ are plotted, showing the generalized behavior of a system with $N_s$ of 4. With this understanding, the results shown in Figure 6.16 that were explicitly for a 1500 MWh system of 450 MW charge rate can be generalized to systems of any capacity and charge rate by instead considering the values $V^*$ and $HDR^*$. The results are valid for all titania units with a temperature range from 700°C to 1700°C.

![Figure 6.17: Generalization of maximum voltage and HDR for different charge rates and capacities.](image)

a): The required voltage as a function of HDR for systems of 500 MWh and 1500 MWh and CQRs of 0.2 and 0.3; b): The same cases plotted with values $V^*$ and $HDR^*$ (curves collapse to one).
If FIRES were to be charged by fully heating one section of firebrick and then the next until the entire system were at peak temperature, the VR required for a steady controlled charge rate would be equal to that of the simple stack, because each individual firebrick section still experiences the same resistance change while being heated. However if a system were designed with a high enough number of firebrick sections \( N_s \), it can be almost completely charged with only a fraction of the VR. This is desirable because a smaller VR reduces the requirements of the power supply. This is accomplished by adding another firebrick section to the circuit each time the resistance of the circuit drops below the acceptable value. Figure 6.18 shows how the switch stack operated in series may be used to charge a titania FIRES unit 4 firebrick sections and a VR of 10, rather than the VR of 21 that would normally be required to heat the system to 1700°C.

![Graphs](image.png)

Figure 6.18: Charging of a titania switch stack operated in series: 1500 MWh capacity, 450 MW charge rate, HDR of 3, \( N_s \) of 4, VR of 10.

a): Voltage versus time; b): total resistance versus time; c): temperature of consecutively heated firebrick sections versus time; d): resistance of consecutively heated firebrick sections versus time.
It can be seen in Figure 6.18c that at the start of charge only the first firebrick section is being heated (blue line). This continues until the voltage of the circuit drops from 60 kV at the start of charge to only 6 kV (seen in Figure 6.18a) at approximately 30 minutes, constrained by the ratio of 10 between high and low voltages. Correspondingly, the resistance of the heated firebrick section drops by a factor of 100, from 8 ohm to 0.08 ohm (seen in Figure 6.18d and Figure 6.18b). At this point the second resistor is added to the circuit (green line), which increases the resistance back up 8.08 ohm, and the voltage back up to 60 kV. Heat is now split between the two firebrick sections proportional to their resistance, such that the colder section is heated more. When their combined resistance drops to 0.08 ohm again (factor of 100) and the voltage drops to 6 kV (factor of 10), the third section is added, and the cycle is repeated, until there are no more sections of firebrick remaining. At approximately 170 minutes the first firebrick section reaches the peak temperature of 1700°C, at which point it is removed from the circuit. Charge ends at 180 minutes, with the four sections at 1700°C, 1700°C, 1600°C, and 1400°C, respectively. This represents approximately 92% of the nominal storage capacity of the system. By charging sections sequentially from the firebrick air outlet to the firebrick air inlet, a favorable temperature gradient can be achieved that increases the effectiveness of heat exchange during discharge relative to a uniformly heated sections of the same partial capacity. Comparatively, the simple stack of the same unit with a VR of 10 would only be able to charge to the first point where the voltage dropped to one-tenth the starting voltage. This corresponds to only 55% of the nominal storage capacity, and is stored at only 1250°C. Figure 6.19 shows the fraction of charge achieved for different voltage ratios in a series-operated titania switch stack operated from 700°C to 1700°C with different values of Ns. The results depend only on the behavior of the resistivity of the material over the temperature range, and are independent of system size or geometry.
Figure 6.19: Fraction of charge achieved for different voltage ratios and numbers of firebrick sections in a series-operated titania switch stack operated from 700°C to 1700°C

Results are independent of system size and geometry.

Although the switch stack operated in series with a lower VR cannot generally heat the entire system to the uniform peak temperature, enough sections allows the unit to achieve an energy fraction of greater than 90% while reducing the maximum voltage and VR required by the power supply. This is essentially a system of lesser storage capacity. The simple stack design may therefore be configured to potentially trade a small portion of system capacity for some simplification of the power supply, each dependent on the value of Ns, which is limited by the practicality of section size and cost of electrodes. However this is not necessary if the VR is simply taken as the nominal VR of the material; 21 in the case of titania over the range of 700°C to 1700°C.

The key advantage of the series-operated switch stack over the other configurations is the temperature gradient created during charge, which promotes effective discharge when only at partial charge. That is, a system with a gradient from 1200°C to 1700°C can produce air at 1700°C for some time, but a system uniformly heated to 1450°C can only produce air of 1450°C.
This may be particularly valuable in FIRES units that frequently charge during short periods of intermittent renewable penetration, such that the system often reaches only partial charge, or where the customer has a large incentive to be delivered only very high-temperature heat.

6.2.3.4 Switch Stack: Parallel

The switch stack may also be operated in parallel, where instead of beginning the charge cycle by heating only one section all sections are charged at once throughout the cycle. Each section of firebrick experiences the full voltage drop of the circuit simultaneously, such that the power generated is multiplied by the factor $N_s$ compared to that of the series-operated switch stack. This means that operating in parallel reduces the required maximum voltage by another factor of the square root of $N_s$ when compared to operating in series, such that voltage is now inversely proportional to $N_s$. Figure 6.20 and Figure 6.21 each map the effects of HDR and $N_s$ on the required maximum voltage for parallel operation in titania and alumina switch stacks of 1500 MWh capacity and 450 MW charge rate.

![Figure 6.20: Required maximum voltage for different values of $N_s$ and HDR in a parallel-operated switch stack (titania)](image)

1500 MWh capacity, 450 MW charge rate, 700°C-1700°C temperature range.
In the case of titania the voltages required are generally 30 kV or less for \( N_s \) of 4 or less, and can reach values of less than 10 kV for higher \( N_s \) of 12 or higher. In the case of alumina voltages may be reduced to within the range of transmission power lines, making it potentially feasible in systems of lower HDR and lower power, but still a generally less attractive candidate for DRH than titania or silicon carbide.

Resistance may be adjusted in the parallel-operated switch stack by switching sets of resistors out of parallel and into series with one another instead. Switching is done in such a fashion that keeps all resistances equal, so that preferential heating does not occur (i.e. 8 parallel resistors are recombined into 4 parallel resistors of double resistance, then into 2 parallel resistors of quadruple resistance, etc.). By switching in this way, the parallel-operated switch stack can vary its own resistance by a factor \( N_s^2 \). Figure 6.22 shows the charge behavior of a titania switch stack operated in parallel, with identical parameters to the ones used before: 1500 MWh capacity, 450 MW charge rate.
At the start of charge, the system has all 4 resistors heated simultaneously in parallel forming four parallel flow paths for current. The maximum voltage is only 30 kV rather than the 60 kV required for the series-operated switch stack, because the parallel resistors reduce the resistivity by a factor of 4 from that of their individual resistances. As the system is heated, all sections are heated together at the same rate. At approximately 25 minutes the system resistance reaches one quarter of the original resistance due to the drop in resistivity with increasing temperature. At this point the 4 firebrick sections that were operating as four parallel flow paths for current are switched to two parallel paths, each with 2 firebrick sections. The circuit resistance increases by a factor of 4, and the voltage by a factor of 2, each up to their starting values. At 50 minutes the firebrick sections are reorganized again into one flow path, again increasing the resistance by a factor 4, to accommodate the resistivity change with temperature. After this period, no more sections may be switched into series from parallel, and the voltage must be controlled to
maintain power, dropping to approximately 6 kV at the end of the charge period. The final VR required to charge the system to full capacity at the constant rate is approximately 5, rather than 21. This results from the factor of $N_s^2$ by which resistance was changed over the course of operation, the square root of which relates to voltage. Then the VR of 21 typically required to fully charge titania from 700°C to 1700°C is reduced to $\frac{VR}{N_s}$, in this case 21 divided by 4. Because the minimum change in resistance from this mode of operation will always be a factor of 4, the minimum VR of parallel operation is 2, which is well within typical requirements of commercial heaters today. The parallel-operated switch stack is therefore advantageous over the series-operated switch stack both in terms of maximum required voltage and VR, and requires only $N_s$ of 4 or 8 to grant dramatic advantage in each. Its only disadvantage relative to the series-operated switch stack is the uniform heating of the firebrick that is less valuable at partial charge.

6.2.3.5 Conclusions of DRH Simulations

The results of DRH calculations show that silicon carbide is a capable candidate for DRH because of its relatively low resistance and small VR. A simple stack of silicon carbide may be charged with high CQR using only a few kilovolts, or a switch stack may be used to reduce voltages below 1 kV or increase charge rates near 1, i.e. charge periods of only 1-2 hours to fill storage capacity. This implies that FIRES units that charge with DRH of silicon carbide can rapidly respond to changes in the electricity market. Although contact resistances and effects of thermal expansion on resistivity in the brickwork are not yet accounted for, the capabilities of silicon carbide independent of these factors is a good starting point for addressing them and achieving practical CQRs. Silicon carbide also allows the option of doping the material to change its electrical characteristics.

Titania is a promising alternative to silicon carbide for applications with air inlet temperatures near 700°C such as power cycles, and generally requires 10s of kilovolts, which may require a more sophisticated power supply and electrical insulation compared to that of silicon carbide. The exponential decrease in resistivity is best accommodated by the parallel-operated switch stack, which may reduce requirements of the power supply.

Compared to a single heating zone, series resistance heaters have a major advantage. The exit firebrick is heated first so can provide high-temperature heat even if FIRES

---

7 In systems with $N_s$ that is not a power of 2, the reorganization of the switch stack from full parallel to full series will result in a VR equal to the largest prime number that is a divisor of $N_s$, i.e. $N_s = 12$ has a minimum VR of 3.
is only partly charged. For some specific applications such as coupling to gas turbines, this may be a preferred option. partly charged FIRES. The cost is that need a more complex electrode system in FIRES.

6.2.4. Other Configurations

The above designs assume that resistance heating is within the brickworks. There is the option of heating air outside the brickworks and circulating hot air through the brickworks. This simplifies heater design but adds the constraints and costs associated with circulating hot air from the heating system to the brickworks and back to the heating system. It may also limit the rate of heat input into FIRES. This set of design options was not investigated.

6.3 Insulation Performance

Insulation performance of FIRES is evaluated for some characteristic cases and basic insulation configurations. The design parameters and performance characteristics of interest are identified. Results discussion begins with a starting case of parameters that is used to feature general observations of FIRES’ insulation performance for different insulation thicknesses. Then system size and peak temperature are varied to show the relative effects on performance, and the findings are summarized in regard to the performance characteristics that are achievable with FIRES units of different designs.

6.3.1 Insulation Design Parameters

There are eight main design parameters that determine insulation performance. The design parameters are as follows:

- **Peak Temperature**: The maximum temperature to which the firebrick will be heated during operation. The peak temperature determines the insulation type. Peak temperatures of 1700°C or lower are considered, consistent with what is achievable by commercial heaters and ratings of insulation materials.

- **Storage Capacity (Qₛ)**: The amount of heat that can be stored in FIRES. Heat leakage is considered as a percentage of storage capacity.

- **Volume of Firebrick**: The total volume of firebrick (excluding air channels). Total volume and dimensions are calculated in combination with HDR and Fᵥ,FB.
• **Height-to-Diameter Ratio (HDR):** The height to diameter ratio of the solid volume of the firebrick cylinder before taking into account air channels. HDR describes the nominal cylindrical dimensions of a volume of firebrick, which is modified to the true dimensions by $F_{v,FB}$.

• **Volume Fraction of Firebrick ($F_{v, FB}$):** The volume fraction of firebrick $F_{v, FB}$ determines the total size of the brickwork that is attributed to firebrick rather than air. Combined with the volume and HDR of firebrick, the true system dimensions are known.

• **Insulation Type:** The material used to insulate FIRES. Type of insulation is determined from the peak temperature of FIRES. In each case the material with the lowest thermal conductivity that also satisfies the peak temperature condition was used. One or two layers of different insulation types were used.

• **Outer Insulation Temperature:** The temperature at which heat is rejected to the surroundings, set at 50°C.

• **Insulation Thickness:** The combined thickness of the insulating layer. Thickness was varied to produce different leakage rates.

### 6.3.2 Insulation Performance Characteristics

Discussed below are three characteristics of interest when evaluating insulation performance:

• **Leakage Rate:** The leakage rate of heat from the system. Leakage rate is described in three equivalent ways: kilowatts, percent capacity leakage per day, and days of “high quality” storage available. High quality storage days are defined as the number of days where 90+% of capacity remains, i.e. the number of days before 10% capacity is lost.

• **Percent Volume Increase:** The percent by which the system volume increases due to the insulation. A smaller volume is generally desirable to satisfy space constraints or reduce the size and cost of a surrounding pressure vessel in high pressure applications.

• **Percent Capacity of Insulation:** The approximate energy absorbed by the insulation as a percentage of the storage capacity of the system. This is the energy held by the insulation when it has reached steady state conduction, i.e. the conditions assumed when calculating heat leakage rate. As FIRES is heated to full capacity, it will lose a portion to heating the insulation at a rate higher than the nominal heat leakage rate before steady state is
achieved. Therefore a low capacity of insulation is desirable, such that it does not absorb a significant percent of FIRES’ capacity every time it is charged.

Because a decrease in leakage rate is accompanied by a greater volume and thermal capacity of insulation, FIRES units will be designed by determining the lowest practically achievable leakage rate with respect to charge and discharge cycles, space constraints of the application and insulation cost.

6.3.3 Insulation Results

Insulation calculations examined systems of different capacities and peak temperatures. The parameters of different cases are shown in Table 6.11.

Table 6.11: Design parameters for insulation performance calculations

<table>
<thead>
<tr>
<th>Insulation Performance Calculation: Case Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Volume Fraction of Firebrick</td>
</tr>
<tr>
<td>Minimum Temperature (°C)</td>
</tr>
<tr>
<td>Outer Insulation Temperature (°C)</td>
</tr>
<tr>
<td>Capacity (MWh)</td>
</tr>
<tr>
<td>Peak Temperature (°C)</td>
</tr>
<tr>
<td>Volume (m³)</td>
</tr>
<tr>
<td>Height (m)</td>
</tr>
<tr>
<td>Diameter (m)</td>
</tr>
</tbody>
</table>

**Insulation Properties:**

<table>
<thead>
<tr>
<th>Name</th>
<th>Temperature Limit (°C)</th>
<th>Thermal Conductivity (W/mK) @ 600°C - 800°C</th>
<th>@ Bulk Temperature (°C)</th>
<th>Case ID#</th>
</tr>
</thead>
<tbody>
<tr>
<td>JM 23</td>
<td>1260</td>
<td>0.14</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>JM 30</td>
<td>1650</td>
<td>0.4</td>
<td>800</td>
<td>2</td>
</tr>
<tr>
<td>JM 32</td>
<td>1760</td>
<td>0.53</td>
<td>1000</td>
<td>3</td>
</tr>
<tr>
<td>JM 23</td>
<td>1260</td>
<td>0.14</td>
<td>600</td>
<td>4</td>
</tr>
<tr>
<td>JM 30 ; JM 23</td>
<td>1650 ; 1260</td>
<td>0.14 ; 0.14</td>
<td>600 ; 1000</td>
<td>5</td>
</tr>
<tr>
<td>JM 23 ; JM 32</td>
<td>1260 ; 1260</td>
<td>0.6 ; 0.14</td>
<td>1400 ; 600</td>
<td>6</td>
</tr>
</tbody>
</table>

Dimensions are true dimensions of the brickwork (firebrick + air) before insulation is added. Insulation products and data from Morgan Thermal Ceramics [20].
Calculations assumed an outer wall temperature of insulation of 50°C. For peak temperatures of 1200°C, 1550°C, and 1700°C, the thermal conductivity of insulation was taken as the value reported for the mean temperatures of 600°C, 800°C, and 1000°C, respectively. A HDR of 5 was used in all cases. It was assumed that the effective thermal conductivity of the firebrick system was much larger than the insulation resulted in a uniform temperature across the firebrick with no temperature drop within the firebrick. Figure 6.23 shows the results for case 1.

![Graphs showing relationships between heat loss, insulation thickness, and storage days.](image)

**Figure 6.23:** Relationships of heat loss, volume increase and insulation heat capacity as a function of insulation thickness: Case 1 (250 MWh, 1200°C)

Results are for a 250 MWh system of alumina with peak temperature of 1200°C, minimum temperature of 100°C, and volume fraction of firebrick of 0.75. a): Days of high quality storage (90+% storage) and heat leakage rate; b): Heat loss percent per day and system volume percent increase from insulation; c): Heat loss percent per day and insulation thermal capacity as percent of system capacity.
The insulation performance showcased by case 1 is that of the base case examined in discharge (discharge case 9). An insulation thickness of approximately 9 cm results in 520 kW of leakage. This represents 5% leakage per day (or 2 high quality storage days), with a 3.1% volume increase, and only 0.23% steady state thermal capacity. Systems with space constraints, particularly if the firebrick operating inside a pressure vessel coupled to a gas turbine, that run on short cycles may choose relatively thin insulation. For thicknesses that are much smaller than FIRES’ diameter, conduction through the walls is similar to that of a plane slab, such that leakage is approximately inversely proportional to insulation thickness. One may therefore halve the leakage rate from 5% per day to 2.5% per day (260 kW, 4 storage days) by doubling the insulation (18 cm), which also approximately doubles the percent volume increase (6.6%) and thermal capacity (0.49%). This linear relationship diminishes for greater thicknesses where the radial change in area is no longer negligible. The lowest leakage case considered, which leaks only 0.5% per day (52 kW, 20 storage days), requires thickness of 103 cm. The insulation volume and thermal capacity also increase to 49% and 3.6% respectively at 103 cm.

Systems with larger volume are more effectively insulated because of the reduced volume to surface area ratio. Figure 6.24 shows the results of two systems with identical design parameters to case 1 but with 150 MWh and 500 MWh of storage, respectively. Compared to the 500 MWh system, the 150 MWh system requires greater thickness for the same number of storage days. 5% leakage per day (312 kW, 2 days) requires 10 cm of insulation compared to just 7 cm for the 500 MWh system (1042 kW, 2 days). This is because the 150 MWh system has more surface area per unit capacity. The reduced surface to volume ratio of larger units makes them generally preferable for longer storage periods. While the 150 MWh system nearly doubles in volume (84%) to achieve 20 quality storage days, the 500 MWh can achieve 20 quality storage days with only a 25% volume increase. These scaling factors imply both efficiency and lower capital costs advantages for larger systems.
Figure 6.24: Relationships of heat loss, volume increase and insulation heat capacity as a function of insulation thickness: Case 4 (150 MWh, 1200°C) and Case 5 (500 MWh, 1200°C) Case 4 (150 MWh, left) and Case 5 (500 MWh, right). Each system has a peak temperature of 1200°C, minimum temperature of 100°C, and volume fraction of 0.75. a,b): Days of high quality storage and heat leakage rate; c,d): Heat loss percent per day and system volume percent increase from insulation; e,f): Heat loss percent per day and insulation thermal capacity as percent of system capacity.
One design parameter that directly influences the ratio of surface area and volume is the HDR, which has minimized surface area when HDR equals 1. Comparatively a HDR of 5 has approximately 25% more surface area per unit volume. However the HDR referred to up to this point has been the ratio of the height and diameter of the firebrick volume without air channels. The HDR of the system including air channels is equal to the HDR without air channels multiplied by the square root of the volume fraction of firebrick $F_{v,FB}$, and is equal to 4.33. This corresponds to 21% more surface area than a HDR of 1. However the HDR will primarily be selected to achieve desirable discharge and charge performance.

Higher temperature units generally require proportionally more insulation for several reasons. First, heat leakage is driven higher proportional to the system temperature. Second, they are more energy dense, such that they have a higher surface area to volume ratio. Third, insulators designed for higher temperatures are significantly more conductive than low temperature insulators, requiring greater thickness. Figure 6.25 shows results of cases 2 and 3, with peak temperatures of 1550°C and 1700°C respectively.

The 1550°C and 1700°C systems require 28 cm and 39 cm to achieve just 2 days of storage, compared to that of 9 cm required by the 1200°C system of the same capacity. This corresponds to a volume increase of 12% and 18% respectively, compared to just 3.1% by the 1200°C system. At 5 days of storage both the 1550°C and 1700°C units match or surpass the total volume of 1200°C system with the same number of storage days, with volumes of 258 m³ (1550°C), 258 m³ (1200°C), and 283 m³ (1700°C). The required volume of insulation for more storage days appears increasingly impractical, resulting in several hundreds percent volume gain under the given conditions. However the insulation requirement reduces dramatically with the inclusion of a second layer of insulation that has significantly lower thermal conductivity than the first. Parameters used in cases 6 and 7 were identical to those used in cases 2 and 3, but insulation was instead designed with two layers. The inner layer consists of a material with a high temperature rating (JM 30 for 1550°C and JM 32 for 1700°C) and was designed to produce a temperature drop to 1200°C. The outer layer consists of JM 23, with a thickness designed to produce a temperature drop to 50°C. Figure 6.26 shows the results for two layers of insulation for units of the same peak temperature and capacity, 250 MWh at 1550°C and 1700°C.
Figure 6.25: Relationships of heat loss, volume increase and insulation heat capacity as a function of insulation thickness: Case 2 (250 MWh, 1550°C) and Case 3 (250 MWh, 1700°C)

Case 2 (1550°C, left) and Case 3 (1700°C, right). Each system has capacity of 250 MWh, minimum temperature of 100°C, and volume fraction of 0.75. a,b): Days of high quality storage and heat leakage rate; c,d): Heat loss percent per day and system volume percent increase from insulation; e,f): Heat loss percent per day and insulation thermal capacity as percent of system capacity.
Figure 6.26: Relationships of heat loss, volume increase and insulation heat capacity as a function of insulation thickness, with high and low temperature insulators: Case 6 (250 MWh, 1550°C) and Case 7 (250 MWh, 1700°C)

Case 6 (1550°C, left) and Case 7 (1700°C, right). Each system has capacity of 250 MWh, minimum temperature of 100°C, and volume fraction of 0.75. a,b): Days of high quality storage and heat leakage rate; c,d): Heat loss percent per day and system volume percent increase from insulation; e,f): Heat loss percent per day and insulation thermal capacity as percent of system capacity.
With the extra layer of insulation, the thickness, volume increase, and thermal capacity of insulation all reduce dramatically. This is due to the much lower thermal conductivity of JM 23 (0.14 W/mK) compared to JM 30 (0.41 W/mK) or JM 32 (0.60 W/mK), as well as its lower density and specific heat capacity. 2 days of storage requires only 14 cm and 17 cm of insulation from the 1550°C and 1700°C units respectively, approximately half the thickness required with one layer of insulation. For both systems the same volume of insulation that granted 5 days of storage using one layer instead grants approximately 10 days of storage with two layers. In all cases, the ultimate insulation thickness of FIRES is an economic tradeoff depending upon the cost of lost energy. Results from all cases are summarized in Table 6.12.

Table 6.12: Summary of insulation performance results, for 5%, 2.5%, and 1.25% loss per day

<table>
<thead>
<tr>
<th>Insulation Performance Results Summary</th>
<th>5% Loss Per Day (2 Storage Days)</th>
<th>2.5% Loss Per Day (4 Storage Days)</th>
<th>1.25% Loss Per Day (8 Storage Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case ID#</td>
<td>- 1 2 3 4 5 6 7</td>
<td>- 1 2 3 4 5 6 7</td>
<td>- 1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>Capacity MWh</td>
<td>150 250 500</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Peak Temperature °C</td>
<td>1200 1550 1700</td>
<td>1200 1550 1700</td>
<td>1200 1550 1700</td>
</tr>
<tr>
<td>Uninsulated Volume m³</td>
<td>232 171 154</td>
<td>139 464 171</td>
<td>139 464 171</td>
</tr>
<tr>
<td>Height m</td>
<td>18 16 15</td>
<td>15 22 16</td>
<td>15 22 16</td>
</tr>
<tr>
<td>Uninsulated Diameter m</td>
<td>4.1 3.7 3.6</td>
<td>3.4 5.1 3.7</td>
<td>3.4 5.1 3.7</td>
</tr>
<tr>
<td>Insulation Type</td>
<td>JM 23 JM 30 JM 32</td>
<td>JM 23 JM 32 JM 32</td>
<td>JM 23 JM 32 JM 32</td>
</tr>
<tr>
<td>Leakage Rate kW</td>
<td>521 521 521</td>
<td>521 521 521</td>
<td>521 521 521</td>
</tr>
<tr>
<td>Volume Increase %</td>
<td>3.1 11.8 17.7</td>
<td>4.5 1.9 5.5</td>
<td>4.5 1.9 5.5</td>
</tr>
<tr>
<td>Thermal Capacity %</td>
<td>0.23 1.89 3.44</td>
<td>0.34 0.15 0.88</td>
<td>0.34 0.15 0.88</td>
</tr>
<tr>
<td>Combined Volume m³</td>
<td>239 192 181</td>
<td>146 473 181</td>
<td>146 473 181</td>
</tr>
<tr>
<td>Insulation Thickness m</td>
<td>0.09 0.28 0.39</td>
<td>0.10 0.07 0.06</td>
<td>0.13 0.07 0.13</td>
</tr>
<tr>
<td>5% Loss Per Day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation Thickness m</td>
<td>0.18 0.59 0.84</td>
<td>0.22 0.14 0.13</td>
<td>0.15 0.26 0.15</td>
</tr>
<tr>
<td>Leakage Rate kW</td>
<td>260 260 260</td>
<td>156 521 260</td>
<td>260</td>
</tr>
<tr>
<td>Volume Increase %</td>
<td>6.6 27.8 44.8</td>
<td>9.6 4.0 11.9</td>
<td>9.6 4.0 11.9</td>
</tr>
<tr>
<td>Thermal Capacity %</td>
<td>0.49 4.45 8.68</td>
<td>0.72 0.30 1.85</td>
<td>0.72 0.30 1.85</td>
</tr>
<tr>
<td>Combined Volume m³</td>
<td>247 219 223</td>
<td>153 483 192</td>
<td>153 483 192</td>
</tr>
<tr>
<td>2.5% Loss Per Day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation Thickness m</td>
<td>0.37 1.33 2.00</td>
<td>0.45 0.29 0.27</td>
<td>0.34 0.55 0.35</td>
</tr>
<tr>
<td>Leakage Rate kW</td>
<td>130 130 130</td>
<td>78 280 130</td>
<td>130</td>
</tr>
<tr>
<td>Volume Increase %</td>
<td>14.5 78.3 148.3</td>
<td>22.0 8.5 27.9</td>
<td>22.0 8.5 27.9</td>
</tr>
<tr>
<td>Thermal Capacity %</td>
<td>1.08 12.56 28.80</td>
<td>1.64 0.63 4.10</td>
<td>1.64 0.63 4.10</td>
</tr>
<tr>
<td>Combined Volume m³</td>
<td>266 306 382</td>
<td>170 504 219</td>
<td>170 504 219</td>
</tr>
</tbody>
</table>

Insulation thickness of cases 6 and 7 are of the higher temperature insulation (left) and lower temperature insulation (right). Refer to Table 6.11 for case design parameters.

As discussed previously, separate from the system insulation are heat losses through penetrations into FIRES—particularly for electrodes of the resistance heating elements (metallic, SiC, MoSi₂, or DRH). The electrodes must have high electrical conductivity, which usually implies high thermal conductivity. Although not quantified in this study, these losses can be reduced by directing airflow into FIRES along the electrodes or heater conductors to provide cooling to the component, thereby recovering the heat. A baffle may also be used to direct the
incoming air of FIRES around the outside of the insulation or between layers to recover heat loss during discharge.

For whatever leakage rate that is designed, the adjacent spaces and structures to FIRES’ insulation must be appropriately cooled so that safe temperatures are maintained. This includes the foundation structure of FIRES, which may be designed with air channels to allow for forced or natural convection for cooling.

6.4 Conclusion

Table 6.13 summarizes the design parameters and performance characteristics of the base case FIRES unit with 0.2 DQR, 0.3 CQR, and 4 days of high quality insulation days. Preliminary performance evaluation of FIRES shows that there is a great deal of flexibility in the technology for charging and discharging at various rates and storing heat for short or long periods of time. While charge and discharge cycles on the order of one to three days are expected to be the most practical in most markets, FIRES is potentially capable of operating on more rapid cycles, with charge and discharge periods of 5 hours or less each, or on slower cycles, with commercially available insulation providing a week or more of high quality storage time with approximately 20% volume increase. This flexibility suggests that FIRES may be a technology capable of addressing a wide spectrum of energy problems.

Charge performance results show that charging with commercially available resistance heaters such as metallic heaters can be reasonably achieved for a CQR of 0.3 (75 MW, 3.33 hours charge time) in an alumina system of 250 MWh capacity. Direct resistance heating of silicon carbide and titania brickworks show promise for higher temperature charge systems that may avoid the cost of heaters. In particular the parallel-operated switch stack grants a high level of flexibility in terms of required maximum voltage and high-to-low voltage ratio. The main questions that remain to be answered concern the properties of bulk silicon carbide bricks compared to that of silicon carbide used in resistance heaters today, the magnitude of contact resistance achievable in the brickwork, the effects of thermal expansion on the resistance of the brickwork, and the threat of uneven conductivity in a switch stack of titania, which has positive feedback for heating.

Discharge rates can be achieved comfortably for DQR values of 0.1 and 0.2, or for values as high as 0.3 or 0.4 in applications that have higher operating temperatures. The TDF generally ranges from 90+% in systems with substantially peak temperatures than operating temperatures.
Table 6.13: Design Parameters and Performance Characteristics for Combined Base Case FIRES Unit of 250 MWh, Charge Rate of 75 MW, and Discharge Rate of 50 MW, (2.5% Leakage per day)

<table>
<thead>
<tr>
<th>Combined Base Case Design Parameters and Performance Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Temperature</td>
</tr>
<tr>
<td>Minimum Temperature</td>
</tr>
<tr>
<td>Application Operating Temperature</td>
</tr>
<tr>
<td>CQR</td>
</tr>
<tr>
<td>DQR</td>
</tr>
<tr>
<td>Uninsulated Volume</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Uninsulated Diameter</td>
</tr>
<tr>
<td>Insulation Thickness (Insulation Type JM 23)</td>
</tr>
<tr>
<td>Combined Diameter</td>
</tr>
<tr>
<td>Combined Volume</td>
</tr>
<tr>
<td>Volume Fraction of Firebrick</td>
</tr>
<tr>
<td>Channel Width</td>
</tr>
<tr>
<td>Firebrick half-width</td>
</tr>
</tbody>
</table>

to ~50% for systems that have only a 50°C or 100°C difference between peak and application operating temperatures. TDF<sub>p</sub> is slightly reduced as a function of DQR but is not significantly worse in the cases.

On average insulation calculations showed that two days of high quality storage may be provided by approximately 10 cm of insulation, and a volume increase (i.e. volume of the insulation required as a percentage of the system with insulation) of 10% or less. This may generally be increased to 4 days of storage with a volume increase of approximately 20% or less, depending on system capacity and operating temperature.
7 Preliminary Economic Evaluation

7.1 Cost Estimates

Cost of FIRES is estimated based on prices of the major components. The pricing of residential heating storage systems is examined and taken as a baseline price, then assumptions regarding the cost estimates of each major FIRES component are described, and a total cost estimate for a characteristic FIRES design of near term deployment is suggested.

7.1.1 Baseline: Residential Heating Storage Systems

As mentioned previously, a smaller low temperature variant of FIRES is used for electric home heating. The technology became popular in Britain and other European countries in the 1960s as a way of time-shifting electricity demand to reduce electricity grid requirements and make more efficient use of excess electricity overnight by offering this electricity at a discount. By 1973 there were 150,000 MWh of firebrick heat storage capacity in Britain and Germany [46]. This technology contains the same basic systems as FIRES, including firebrick, a blower and damper system, and metallic heaters similar to the ones that will be used in the first deployment of FIRES, but operates at lower temperatures and on the scale kilowatt-hours rather than megawatt-hours. Its price therefore serves as a baseline for FIRES, where economies of scale would be expected to improve the cost competitiveness.

The US Department of Energy long-term price goal for energy storage technology is $150/kWh. The FIRES goal is near $5/kWh. Domestic firebrick heater retail prices were typically found to be $25-100/kWh. The cheapest individual heater was the Elnur® ER SH24M (storage capacity 24 kWh), sold in Britain for the equivalent of $16/kWh (at a conversion rate of $1.51/£) when five or more units are bought [47]. The largest domestic firebrick storage heaters are central heating systems with storage capacities of ~250 kWh. In 2013 VCharge® installed 15 MWh of firebrick heat storage across 200 homes in eastern Pennsylvania at a cost of $15/kWh. These prices compare to $350/kWh for the Tesla Powerwall home battery storage system (10 kWh energy storage). As would be expected, economies of scale can be seen at work when examining the pricing of electric firebrick heaters with respect to their energy storage capacity. Table 7.1 shows the cost and technical specifications of a range of heaters produced by Steffes®.
and sold in Massachusetts. Prices drop from $100/kWh to $25/kWh when buying a “large” 240 kWh system.

Table 7.1: Performance and price characteristics of home heating storage systems (Steffes©) [48]

<table>
<thead>
<tr>
<th>Storage capacity (kWh)</th>
<th>Charging Input (kW)</th>
<th>Max Heat Output (kW)</th>
<th>CQR (1/h)</th>
<th>DQR (1/h)</th>
<th>Retail Price ($/kWh)</th>
<th>Price per Unit Storage ($/kWh)</th>
<th>Internal Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5</td>
<td>3.6</td>
<td>-</td>
<td>0.27</td>
<td>-</td>
<td>1500</td>
<td><strong>111.11</strong></td>
<td>700</td>
</tr>
<tr>
<td>40</td>
<td>10.8</td>
<td>-</td>
<td>0.27</td>
<td>-</td>
<td>3000</td>
<td><strong>75</strong></td>
<td>700</td>
</tr>
<tr>
<td>120</td>
<td>24.8</td>
<td>23.9</td>
<td>0.21</td>
<td>0.20</td>
<td>3500</td>
<td><strong>29.17</strong></td>
<td>700</td>
</tr>
<tr>
<td>240</td>
<td>45.6</td>
<td>38.5</td>
<td>0.19</td>
<td>0.16</td>
<td>6000</td>
<td><strong>25</strong></td>
<td>700</td>
</tr>
</tbody>
</table>

The case of domestic electric heating units is promising to FIRES for two reasons. First, the heaters are already an order of magnitude cheaper than the DOE long-term target, despite their small scale. When scaled up to the size and peak temperature of FIRES (100s MWh, 1200°C-1700°C) the cost will fall still further. Second, the costs presented are retail prices, which include manufacturers’ and retailers’ markups. These factors suggest that the FIRES target of $5/kWh is feasible as a long-term goal.

### 7.1.2 Firebrick

As previously discussed the firebrick candidates considered range from approximately $600 per ton to $100 per ton based on the cheapest sales prices from online vendors. This corresponds to approximately $0.40/kWh for alumina and magnesia firebrick, which will be used in the first deployment of FIRES with metallic heaters. Actual prices may be lower due to the large tonnage of FIRES (930 tons for 250 MWh alumina unit with temperature range 100°C to 1200°C) compared to the minimum orders (1 ton or several kilograms) from the vendors considered. Because the insulation is generally made from alumina and silica, the cost of insulation price was also estimated using the firebrick cost.
Table 4.2: Estimated energy density and cost per unit storage capacity for different candidate materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical</th>
<th>Energy Density (ΔT = 1000°C)</th>
<th>Estimated Material Cost (Sale Price)</th>
<th>Estimated Energy Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>MWh/m³</td>
<td>$/ton</td>
<td>$/kWh</td>
</tr>
<tr>
<td>Titania</td>
<td>TiO₂</td>
<td>0.84</td>
<td>600</td>
<td>3.04</td>
</tr>
<tr>
<td>Alumina</td>
<td>Al₂O₃</td>
<td>0.93</td>
<td>100</td>
<td>0.43</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>SiC</td>
<td>0.66</td>
<td>300</td>
<td>1.44</td>
</tr>
<tr>
<td>Magnesia</td>
<td>MgO</td>
<td>0.96</td>
<td>100</td>
<td>0.37</td>
</tr>
<tr>
<td>Silica</td>
<td>SiO₂</td>
<td>0.58</td>
<td>150</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Sale prices from alibaba.com [23,24,25,26,27].

7.1.3 Steel Vessel

The cost of the steel containment vessel that holds the brickwork and insulation is dependent on the size of the system. Figure 7.1 shows cost estimates of a steel drum vessel as a function of volume and pressure rating from a report 2002 by the National Energy Technology Laboratory (NETL) [49]

![Figure 7.1: Cost estimates of steel drum vessel for different volumes and pressures](image)

1st quarter 1998 dollars, 650°F (343°C) design temperature. From National Energy Technology Laboratory (NETL) [49]
The results of the NETL cost study show that a vessel of 283 m$^3$ (75,000 gallons) costs approximately $75,000 for a 100 kPa (15 psig) vessel, or $150,000 for a 1000 kPa (150 psig) vessel. This is approximately $112,500 and $225,000 in 2016 dollars\(^8\), and corresponds to $398/m$^3$ and 796/m$^3$ respectively. A vessel of this size could hold a 250 MWh FIRES unit with temperature range of 100°C to 1200°C and a firebrick volume fraction of 0.75 (232 m$^3$) and enough insulation for 4 days of quality storage (247 m$^3$ combined) while leaving space for air plenums. Since the vessel is designed for 343°C some insulation may be moved outside the vessel to reduce vessel size and cost. The lower pressure vessel under this configuration has a cost per unit energy of $0.45/kWh. For most applications a vessel designed for 100 kPa will not be required, and actual containment cost may be less.

7.1.4 Blower

The blower cost estimate is done with the assumption that an additional blower would be bought and incorporated into the air handling system already in place at the industrial site. There are other options for addressing the flow requirements of FIRES, dependent on the system in place, which as a perquisite already handles the flow rate of the application. If the pressure loss through FIRES is small compared to the pressure losses of the rest of the industrial process then the original system may be capable of handling the pressure losses of FIRES such that no additional blower is required or the added blower may be smaller than otherwise. Alternatively rather than adding an additional blower others may be upgraded.

The cost of the blower depends on the pressure rise and volumetric flow rate requirements of the application. For identical FIRES units the required fan power increases by the cube of the flow rate. If one considers a 250 MWh FIRES unit with temperature range from 100°C to 1200°C, application operating temperature of 500°C, and a firebrick volume fraction of 0.75, peak fan power is 85 kW if operated with a DQR of 0.1, or 636 kW if operated with a DQR of 0.2 (i.e. factor of $2^3$ increase). These values of required fan power correspond to approximate values of pressure and flow rate: 2 kPa and 40 m$^3$/s for a DQR of 0.1, and 8 kPa and 80 m$^3$/s for a DQR of 0.2. Centrifugal blowers on the order of 100s of kilowatts and 10s of cubic meters per second were found to cost around $40/kW [51], or approximately $3400 in the case of

\(^8\) Calculated using the annual average price indices for fabricated structural metal products from the Bureau of Labor Statistics: 142.5 in 1998, 212.7 in 2016 [50]
0.1 DQR, and $25400 in the case of 0.2 DQR. The fan cost per unit discharge rate of FIRES and
fan cost per unit energy of FIRES is estimated as $0.50/kW and $0.10/kWh for a DQR of 0.2
with 500°C operating temperature. Required fan power will also be reduced if operating
temperature of the applications is higher than 500°C because the required flow rate will be
reduced.

7.1.5 Metallic Heaters

Kanthal APM™ is expected to be the metallic heater of choice for FIRES due to its
unmatched operating temperatures (1425°C) and longer life compared to other heaters under
identical conditions. The minimum sales price for Kanthal APM wire was found to be $3/kg,
with a minimum purchase size of only 5 kg. Achieving a CQR of 0.3 in a 250 MWh unit (75
MW charge rate) with a temperature range of 100°C to 1200°C with 1 cm diameter wire (the
thickest option) at an average surface loading of 40 kW/m² was found to require 33.4 tons of
wire. The price of this wire is approximately $100,000, or $1.33/kW, and $0.40/kWh,
respectively. Thick wires and lower surface loading grant longer life to wires, which may be on
the order of 10000 hours, or only 100s-1000s of hours⁹. But thicker wires also have lower energy
density, and therefore require a greater upfront investment for the desired power. Buying wire by
the ton versus the kilogram would be expected to substantially lower costs.

7.1.6 Transformer

The need for a transformer depends on the required voltage of the resistance heating
configuration, the line voltage available at the industrial site, and the ability of the electrical
system in place to handle the additional power transmission required by FIRES. If the kVA
rating of the equipment in place is capable of handling the extra load of charging FIRES, and the
voltage required by the heaters can be matched to the existing line voltage of the industrial site,
and the voltage control of tap changing is not necessary, the transformer can be avoided. It is
most possible to achieve this with metallic heaters, because they can be combined in parallel or
series as needed and require no tap changing due to the relatively constant resistance over their
temperature range and lifetime. It may also be possible with DRH configurations that have many
options for changing and controlling resistance of the circuit, such as the parallel-operated switch
stack.

⁹ Creep rupture strength tests show 4mm wire reaching 10000 hours of life at 1400°C [28]
Transformer cost depends on the kVA rating and the sophistication of the transformer, including the number of windings, and on-load or off-circuit tap changing capabilities. Estimates consider a step down transformer from a common transmission voltage of 110 kV to different values ranging from 6.3 kV to 11 kV. Triple winding step down transformers with on-load tap changing abilities ranging from 6.3-63 MVA were found to have a price range from $130,000 to $200,000 [52]. Transformers of higher kVA ratings therefore have a lower cost per kilowatt than those of lower kVA ratings. On the scale of 10s of megawatts, the price of a relatively sophisticated transformer is found as approximately $3.20/kW. For a FIRES unit of 250 MWh with a desired CQR of 0.3, or 75 MW, the estimated price of a relatively complex transformer is $240,000, or $0.96/kWh. This price may be less for lesser complexity and larger systems.

7.1.7 Cost Estimate Summary

Table 7.2 shows the estimated cost of all major components of the characteristic FIRES unit discussed throughout the majority of this report, as well as the key combined performance characteristics of charge, discharge, and heat loss. It is assumed in this case that a transformer is required to accommodate FIRES’ charge system.

The costs of all major components based on the estimates discussed sum to $586,700, which on a per-unit-energy basis comes to $2.35/kWh. Additional costs not accounted for in this result are construction and installation costs and less significant hardware, such as the ductwork and electrical cables required to interface with the industrial site. It also does not include the cost of modifications to the furnace and burner system that will be specific to the application. It is expected that such costs would be low for a new furnace or kiln but could be very significant for an existing industrial facility. However the result of $2.35/kWh accentuates the cheap cost of components required for heat storage compared to other technologies. The transformer represents the largest single expense at $0.94/kWh, which may be avoidable at industrial sites with grid connections capable of handling additional 10s of megawatts. This would reduce the price to only $1.41/kWh. Firebrick is very cheap relative to other components, such that larger heat storage capacity may be an often attractive option even when the marginal value of capacity and storage days becomes small. Where a 250 MWh FIRES unit of $5/kWh would cost $1,250,000, there remains over half this amount ($663,000) to pay for the remaining expenses of construction and installation to the industrial site. There is a considerable learning curve to the efficient deployment of any new technology that is associated with experience in design, construction and
### Table 7.2: Cost Estimates for Characteristic FIRES Unit of 250 MWh, Charge Rate of 75 MW, and Discharge Rate of 50 MW, (2.5% Leakage per day)

<table>
<thead>
<tr>
<th>Components</th>
<th>Cost</th>
<th>Cost Per Unit Charge</th>
<th>Cost Per Unit Discharge</th>
<th>Cost Per Unit Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$</td>
<td>$/kW</td>
<td>$/kW</td>
<td>$/kWh</td>
</tr>
<tr>
<td>Firebrick</td>
<td>100000</td>
<td>1.33</td>
<td>2.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Insulation</td>
<td>8800</td>
<td>0.12</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>Transformer</td>
<td>240000</td>
<td>3.20</td>
<td>4.80</td>
<td>0.96</td>
</tr>
<tr>
<td>Blower</td>
<td>25400</td>
<td>0.34</td>
<td>0.51</td>
<td>0.10</td>
</tr>
<tr>
<td>Containment Vessel</td>
<td>112500</td>
<td>1.50</td>
<td>2.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Metallic Heater Wire</td>
<td>100000</td>
<td>1.33</td>
<td>2.00</td>
<td>0.40</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>586700</strong></td>
<td><strong>7.82</strong></td>
<td><strong>11.73</strong></td>
<td><strong>2.35</strong></td>
</tr>
</tbody>
</table>

#### Combined Base Case Design Parameters and Peformance Characteristics

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Temperature</td>
<td>°C</td>
<td>1200</td>
<td>Capacity</td>
<td>MWh</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>°C</td>
<td>100</td>
<td>Charge Rate</td>
<td>MW</td>
</tr>
<tr>
<td>Application Operating Temperature</td>
<td>°C</td>
<td>500</td>
<td>Discharge Rate</td>
<td>MW</td>
</tr>
<tr>
<td>CQR</td>
<td>1/h</td>
<td>0.3</td>
<td>TDFp</td>
<td>-</td>
</tr>
<tr>
<td>DQR</td>
<td>1/h</td>
<td>0.2</td>
<td>Duration of TDFp</td>
<td>h</td>
</tr>
<tr>
<td>Uninsulated Volume</td>
<td>m³</td>
<td>233</td>
<td>Total Duration</td>
<td>h</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>18</td>
<td>DQR eff</td>
<td>1/h</td>
</tr>
<tr>
<td>Uninsulated Diameter</td>
<td>m</td>
<td>4.1</td>
<td>Peak Total Pressure Loss</td>
<td>kPa</td>
</tr>
<tr>
<td>Insulation Thickness (Insulation Type JM 23)</td>
<td>m</td>
<td>0.18</td>
<td>Insulation Volume (%) Increase</td>
<td>%</td>
</tr>
<tr>
<td>Combined Diameter</td>
<td>m</td>
<td>4.4</td>
<td>Peak Blower Power</td>
<td>kW</td>
</tr>
<tr>
<td>Combined Volume</td>
<td>m³</td>
<td>248</td>
<td>Firebrick ΔT Max</td>
<td>°C</td>
</tr>
<tr>
<td>Volume Fraction of Firebrick</td>
<td>-</td>
<td>0.75</td>
<td>Firebrick ΔT Average</td>
<td>°C</td>
</tr>
<tr>
<td>Channel Width</td>
<td>m</td>
<td>0.1</td>
<td>Nominal Heat Leakage Rate</td>
<td>% / day</td>
</tr>
<tr>
<td>Firebrick half-width</td>
<td>m</td>
<td>0.05</td>
<td>High Quality Storage Days</td>
<td>Days</td>
</tr>
</tbody>
</table>

Design parameters are of discharge case 9, insulation case 1, and the characteristic charge case with metallic heaters.

150
operation of the technology. Early FIRES units will be at the beginning of the learning process, and will have a high installed cost. However the relative simplicity of the industrial heat supply version of FIRES demands only common and generic construction techniques; firebrick regenerator construction and metallic heater installations are commonplace in industry. The case is therefore strong that the installed cost of FIRES is on the order of dollars per kilowatt-hour, with the long-term goal of $5/kWh potentially being attainable.

7.2 Market Performance

The economic performance of FIRES in a market of high renewable penetration (Northwestern Iowa) is considered. The market characteristics of Iowa are described and candidate industrial users are identified, then different schemes of analyzing FIRES’ operating profit are discussed. A baseline case of profitability is set by considering a case of no storage, equivalent to the operation of resistance heaters, and then the results of different profit optimization schemes subject to different levels of insight of the future market prices are compared.

7.2.1 Western Iowa Energy Markets

The first demonstrations of FIRES will be carried out in regions known to have both substantial heat-demanding industrial activity and electricity that is cheaper than the equivalent fuel during a significant fraction of the year. The state of Iowa in the Midwestern United States has been identified as such a region.

Iowa is located within the territory of the Midcontinent Independent System Operator (MISO), which also serves much of Illinois, Indiana, Michigan, Wisconsin, Minnesota, North Dakota, Arkansas, and Louisiana [53]. Iowa’s electricity demand is served primarily by coal-fired generation, with small amounts of nuclear and natural gas generation and a significant and fast-growing amount of wind. 27% of Iowa’s electricity was supplied by wind in 2013 [54].

Nearly half of Iowa’s total energy is consumed by industry [54]. In particular, Iowa has more ethanol production capacity than any other state [54]. Ethanol production normally requires a substantial amount of natural gas, primarily for the production of steam. This has a low operating temperature requirement that can be comfortably met by a FIRES unit of 1200°C.

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10 Special thanks to Daniel Curtis for help with the market assessment of Iowa
Ethanol production continues to grow in Iowa, with a large new plant being opened as recently as September 2014 in northwestern Iowa and with at least two others under construction [54].

Electricity prices for northwestern Iowa are reported at the grid node designated MEC.PPWIND (compiled from [5-8]). The distribution of wholesale electricity prices at MEC.PPWIND across 2013 and 2014 is shown in Figure 7.2.

![Day-Ahead Hourly Electricity Price Distribution at Iowa MEC.PPWIND node, 2013–2014](image)

**Figure 7.2: Distribution of wholesale electricity prices in Iowa**  
(The price of a unit of natural gas heat shown for reference [57])

The mean day-ahead wholesale price of electricity at MEC.PPWIND in Iowa was $24.58 across 2013 and 2014. The price of electricity is negative about 5% of the time in each year, and the price is lower than the equivalent heating value of natural gas approximately 57% of the time across those two years. The ability to take advantage of this electricity as a heating source in place of natural gas would be profitable to ethanol plants and other industrial users of northwestern Iowa. Such market conditions make northwestern Iowa a promising setting for an early demonstration of a FIRES system operating at ambient pressure and relatively low temperature.

### 7.2.2 FIRES Revenue in Western Iowa

An initial estimation of the potential revenue of an early demonstration, ambient pressure, low temperature, industrial heat supply FIRES system has been performed with the following assumptions:

- Ramp rates are ignored.
- The industrial customer demands heat at all times.
The industrial customer already has a natural gas burner installed as their standard heat supply system. The FIRES system supplements this burner by providing hot air at incrementally lower cost when available.

The FIRES system operates in one of four states during all hours:

- Buying electricity and heating the firebrick stack at full input power while discharging heat to the customer at full output power.
- Buying electricity and heating the firebrick stack at sufficient input power to exactly maintain the quantity of stored heat while discharging heat to the customer at full output power. (i.e. heat input equals heat output, no storage change)
- Discharging stored heat to the customer at full output power.
- Standing by inactive, because electricity is too expensive to buy and there is no stored heat available to discharge.

The optimum strategy to maximize revenue involves complex market and FIRES design tradeoffs. If one has limited storage capacity and a period of low price electricity is predicted, one wants to buy the electricity when the price is at a minimum—not necessarily when it just falls below the price of natural gas. However, the heaters have limited capacity as do transmission lines. Three approaches were used to determine when to charge, each representing progressively more foresight of the market conditions. They are as follows:

- **The Simple Strategy:** Charge whenever the price of electricity falls below that of natural gas.

- **24 Hour Optimization:** With knowledge of the hourly day-ahead electricity market prices, optimize the revenue of FIRES operation by always storing the cheapest electricity possible. This is most indicative of practical FIRES operation, because day-ahead electricity markets are attainable knowledge.

- **2 Year Optimization:** With knowledge of the hourly electricity prices for 2 years, optimize the revenue of FIRES operation by always storing the cheapest electricity possible. This case explores the limit of profitability of a given FIRES system over the 2 year period with perfect foresight of the market.
In the simplest case for consideration, the FIRES system is reduced to a simple pass-through system with equal electric input power and thermal output power (i.e. an electric heater). In such a case, the storage capacity of the firebrick itself is not relevant, and all three operating strategies simplify to the simple strategy, where FIRES will provide heat at 1 MW whenever electricity is cheaper than natural gas. A FIRES system would not actually be built in this way, but this case provides a revenue baseline to compare with systems that have storage capacity; if this were the best possible case, or adding storage offered negligible improvement, Iowa ethanol producers would do best to install electric heaters next to their gas burners with no storage capacity. Table 7.3 shows the result of this case with no storage.

### Table 7.3: Simplest FIRES System Financial Results

<table>
<thead>
<tr>
<th>FIRES System Parameters</th>
<th>Financial Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max input power</td>
<td>1 MWe</td>
</tr>
<tr>
<td>Energy capacity</td>
<td>n.a.</td>
</tr>
<tr>
<td>Max output power</td>
<td>1 MWt</td>
</tr>
<tr>
<td>Heat Sales Revenue</td>
<td>$122,000 / yr</td>
</tr>
<tr>
<td>Electricity Purchase Cost</td>
<td>$65,800 / yr</td>
</tr>
<tr>
<td>Operating Income</td>
<td>$56,500 / yr</td>
</tr>
</tbody>
</table>

In the case with no storage FIRES supplied heat 57% of the time, and earned an operating income of $56,500/year; that is, $56,500 was saved by using 1 MW of electricity as heat rather than 1 MW of natural gas whenever the price was favorable. Comparatively, a characteristic case of 10 MWh storage capacity, 2 MW charge rate (CQR of 0.2), and 1 MW discharge rate (DQR of 0.1) was simulated for profitability with each of the three operating schemes. Results for the case with a maximum heater power of 2 MW are shown in Table 7.4. Compared to the baseline case, the FIRES unit with storage earned $72,300, $84,284 and $89,477 for the cases with no insight (simple strategy), 24 hour insight, and 2 year insight, respectively. The addition of storage produces a sizable advantage over no storage, earning 50% more operating income with the 24 hour optimization approach. 24 hour insight was found to have an advantage of 17% over the simple strategy. Comparatively, 2 year optimization granted only 6% more operating income than that of 24 hour optimization, indicating that knowledge of the day-ahead market is relatively effective at maximizing profits for systems with CQR of 0.2 and DQR of 0.1. It would be
expected that this 6% advantage would diminish further in markets influenced by solar generation rather than wind, because solar power has the same cycle period as the day-ahead market.

Table 7.4: 2 MWₑ FIRES system financial results

<table>
<thead>
<tr>
<th>FIRES System Parameters</th>
<th>Simple Strategy</th>
<th>Optimized (24 hrs)</th>
<th>Optimized (2 yr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max input power 2 MWe</td>
<td>Revenue ($/yr)</td>
<td>$172,700</td>
<td>$166,682</td>
</tr>
<tr>
<td>Energy capacity 10 MWhₜ</td>
<td>Cost ($/yr)</td>
<td>$100,400</td>
<td>$82,399</td>
</tr>
<tr>
<td>Max output power 1 M Witt</td>
<td>Operating Income ($/yr)</td>
<td>$72,300</td>
<td>$84,284 (+17%)</td>
</tr>
</tbody>
</table>

7.2.3 Comments Regarding Regulatory Structure

FIRES economics depends upon ISO rules and tax policies, which determine the price at which electricity can be bought by FIRES. The market assessment of Iowa assumes that FIRES can purchase electricity at the deregulated wholesale market price, rather than the price at which the utility sells to consumers. If it can be purchased at the deregulated market rate, the economics are highly favorable; however, the state public utilities commission (PUC) determines the electricity rate structure. From the perspective of the ISO and the electricity generators, there are large incentives for FIRES to be on the electricity grid that suggest a favorable regulatory structure is achievable—treated similar to a pumped hydro facility or batteries. Grid reliability can be improved by controlling the charge rate of FIRES in quick response to mismatches in supply and demand, which may be controlled remotely by the ISO as needed in agreement with the industrial user. Towards the goal of reducing carbon emissions, FIRES improves the economics of nuclear, wind and solar relative to fossil fuel plants. Agreements must be made that result in a favorable regulatory structure in order for FIRES to purchase electricity at the wholesale price and experience favorable economics. Separate from this are tax policies including production tax credits for renewables. This suggests that if FIRES is associated with a solar or wind system, it could be considered part of that system and eligible for a production tax credit. This and many other issues must be resolved.

All of this emphasizes that FIRES is a new element in the electric grid enabled by the changing markets with the large-scale introduction of low-marginal-cost non-fossil-fuel electric
generators. It has the potential to change the bottom of the electric market from a market controlled by the marginal price of electricity to a market controlled by the price of fossil fuels—a major change in the basic structure of the electricity markets.

7.3 Conclusion

Markets exist today where FIRES may bridge the electricity and heating markets for the benefit of each, and the cost estimates of FIRES indicate relatively fast payback and profitability in a favorable regulatory market where electricity may be purchased at the wholesale price. The results of even sub-optimal operation make a compelling case for employing FIRES in Iowa ethanol plants. Where the 10 MWh system earned $84,000 profit per year, it would pay for itself in the first year at a price of $5/kWh, or certainly in the first three to five years at typical domestic home heating system prices of $15-25/kWh.
8 Summary of Findings and Future Work

8.1 Summary of Findings

Electricity price collapse caused by increases in renewable energy penetration is damaging the economic competitiveness of solar, wind, and nuclear power. The current electrical energy storage options are too expensive to be deployed in sufficient quantity to prevent the price collapse. Heat storage charged via electrical resistance heating enables the sale of electricity to the heating market at the price of the competing fossil fuel, thereby preventing electricity price collapse. Heat storage also holds the potential to be used for electricity production. With the considerations of the large potential of heat storage relative to the current options of electricity storage in improving the economics of a low-carbon grid, the new heat storage concept of firebrick-resistance heated energy storage (FIRES) was developed.

There is a wide variety of applications that FIRES may be coupled with for advantages of improved economics, increased flexibility, and reduced environmental impact. Some candidate industries that may benefit from the coupling of FIRES with their kilns or furnaces include steel, glass, cement, and different low and high temperature chemical process plants (biofuels including ethanol, refineries, general chemicals). In the long term, FIRES’ heat addition to power cycles is a promising avenue for efficient roundtrip storage of electricity using the very cheap heat storage methods that FIRES employs, especially as cycle efficiency continues to improve from advances in turbine technology. In the context of energy storage systems, FIRES has several unique characteristics.

- **Hot Air Product.** Our society is based on burning fossil fuels to produce hot air. With very limited exceptions our entire industrial system starts with hot air. FIRES produces hot air that directly couples to that system.

- **Unlimited Storage Capacity When Coupled to Industry.** Most storage systems (batteries, hydro pumped storage, etc.) have limited storage capacity. If the firebrick is at peak temperatures but the price of electricity is below that of fossil fuels, the FIRES resistance heaters continue to provide hot air to the industrial processes and thus effectively an unlimited capacity to use low-price electricity.
• Large scale. The industrial heat market is larger than the production of electricity. It is the only market of sufficient scale to consume all “excess electricity” and thus set a minimum price for electricity to the benefit of low-carbon nuclear, wind and solar systems.

The design space for FIRES was explored with respect to storage materials, charging systems, discharge systems and containment. Each system has options of varying complexity, which generally increase with the temperatures, pressure and size of the application.

Table 4.6: Design configurations of different capabilities with varying complexity and readiness

<table>
<thead>
<tr>
<th>Readiness Term</th>
<th>Design Configurations of Increasing Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short (Today)</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Materials</td>
<td>Al_2O_3, MgO</td>
</tr>
<tr>
<td>Heating Element</td>
<td>Metallic Heaters</td>
</tr>
<tr>
<td>Containment</td>
<td>Insulated Steel</td>
</tr>
<tr>
<td>Temperatures</td>
<td>Ambient - 1200°C</td>
</tr>
<tr>
<td>Pressures</td>
<td>Atmospheric</td>
</tr>
</tbody>
</table>

The simplest FIRES designs consist of materials and technology that are well established within industrial heating systems: magnesia or alumina bricks coupled with metallic heaters that reach maximum temperatures of approximately 1200°C, and a low pressure insulated steel containment. Such designs will be the first deployment of FIRES. Intermediate designs include units of higher temperatures, but low pressures. Units of greater temperatures may be developed that use SiC or MoSi_2 heaters or direct resistance heating (DRH) of firebrick, and units of higher pressure may use advanced insulation systems or active cooling of the pressure vessel.

Preliminary performance evaluation showed that ratios of charge rate to storage capacity (CQR) and nominal discharge rate to storage capacity (DQR) as high as 0.3 and 0.2 may be reasonably achieved, respectively, and 90+% heat retention is possible for several days with reasonable insulation requirements. Such performance characteristics suggest that FIRES is a technology capable of comfortably operating on daily cycles or multi-day cycles, with great flexibility in design. Systems on the order of hundreds of megawatt-hours of storage with these
charge and discharge characteristics were estimated to have a component cost of approximately $2.35/kWh, indicating that the technology is likely deployable with a price on the order of dollars per kilowatt-hour, with a long term goal of approximately $5/kWh expected to be achievable.

Table 7.2: Cost Estimates for Characteristic FIRES Unit of 250 MWh, Charge Rate of 75 MW and Discharge Rate of 50 MWt (2.5% Leakage per day)

<table>
<thead>
<tr>
<th>Components</th>
<th>Cost</th>
<th>Cost Per Unit Charge</th>
<th>Cost Per Unit Discharge</th>
<th>Cost Per Unit Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firebrick</td>
<td>100000</td>
<td>1.33</td>
<td>2.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Insulation</td>
<td>8800</td>
<td>0.12</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>Transformer</td>
<td>240000</td>
<td>3.20</td>
<td>4.80</td>
<td>0.96</td>
</tr>
<tr>
<td>Blower</td>
<td>25400</td>
<td>0.34</td>
<td>0.51</td>
<td>0.10</td>
</tr>
<tr>
<td>Containment Vessel</td>
<td>112500</td>
<td>1.50</td>
<td>2.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Metallic Heater Wire</td>
<td>100000</td>
<td>1.33</td>
<td>2.00</td>
<td>0.40</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>586700</strong></td>
<td><strong>7.82</strong></td>
<td><strong>11.73</strong></td>
<td><strong>2.35</strong></td>
</tr>
</tbody>
</table>

Combined Base Case Design Parameters and Performance Characteristics

<table>
<thead>
<tr>
<th>Peak Temperature (°C)</th>
<th>1200</th>
<th>Capacity (MWh)</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Temperature (°C)</td>
<td>100</td>
<td>Charge Rate (MW)</td>
<td>75</td>
</tr>
<tr>
<td>Application Operating Temperature (°C)</td>
<td>500</td>
<td>Discharge Rate (MW)</td>
<td>50</td>
</tr>
<tr>
<td>CQR (1/h)</td>
<td>0.3</td>
<td>TDFp</td>
<td>-</td>
</tr>
<tr>
<td>DQR (1/h)</td>
<td>0.2</td>
<td>Duration of TDFp</td>
<td>h</td>
</tr>
<tr>
<td>Uninsulated Volume (m³)</td>
<td>233</td>
<td>Total Duration</td>
<td>h</td>
</tr>
<tr>
<td>Height (m)</td>
<td>18</td>
<td>DQR_{eff} (1/h)</td>
<td>0.16</td>
</tr>
<tr>
<td>Uninsulated Diameter (m)</td>
<td>4.1</td>
<td>Peak Total Pressure Loss (kPa)</td>
<td>7.80</td>
</tr>
<tr>
<td>Insulation Thickness (Insulation Type JM 23) (m)</td>
<td>0.18</td>
<td>Insulation Volume (% Increase)</td>
<td>%</td>
</tr>
<tr>
<td>Combined Diameter (m)</td>
<td>4.4</td>
<td>Peak Blower Power (kW)</td>
<td>636</td>
</tr>
<tr>
<td>Combined Volume (m³)</td>
<td>248</td>
<td>Firebrick ΔT Max (°C)</td>
<td>94</td>
</tr>
<tr>
<td>Volume Fraction of Firebrick</td>
<td>-</td>
<td>Firebrick ΔT Average (°C)</td>
<td>23</td>
</tr>
<tr>
<td>Channel Width (m)</td>
<td>0.1</td>
<td>Nominal Heat Leakage Rate (% / day)</td>
<td>2.5</td>
</tr>
<tr>
<td>Firebrick half-width (m)</td>
<td>0.05</td>
<td>High Quality Storage Days (Days)</td>
<td>4</td>
</tr>
</tbody>
</table>

Design parameters are of discharge case 9, insulation case 1, and the characteristic charge case with metallic heaters.
8.2 Future Work

Technology for low temperature systems is ready today. Detailed design work for the specific sizing and integration of FIRES with existing industrial sites in economically favorable markets is the next step. Designs may be optimized according to the specific application parameters by using performance modeling techniques (i.e. finite element or finite volume software packages) more rigorous than that used in this study, which are only approximations of the expected performance of actual systems. An appropriate regulatory structure must be established that treats the storage capabilities offered by FIRES similar to pumped hydro facilities or batteries. This requires discussions between the utility, generators and industry in each market where FIRES is deployed. Higher temperature FIRES units that may use SiC or MoSi$_2$ heaters require development regarding heater configurations and operating points that minimize the frequency of costly heater replacements. The lifetime of heaters for the given environment, cycling, charge rate and desired peak temperature of an application will determine if they are practical.

The most advanced version of FIRES, units that use DRH of firebrick, requires the most development. Development of brickworks heated via DRH will require experimentation that investigates performance and controllability over many heating and cooling cycles with respect to contact resistance, thermal expansion, aging, and non-uniform conductivity. Brickworks heated by DRH, if successfully developed, are expected to offer the best performance for FIRES that couple with power cycles for peak electricity production.
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