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Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Reactor Operations

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ABSTRACT

Electricity markets are changing rapidly because of (1) the addition of wind and solar and (2) the goal of a low-carbon electricity grid. These changes result in times of high electricity prices and very low or negative electricity prices. California has seen its first month where more than 20% of the time (mid-day) the wholesale price of electricity was zero or negative. This creates large incentives for coupling heat storage to advanced reactors to enable variable electricity and industrial-heat output (maximize revenue) while the reactor operates at base load (minimize cost).

Recent studies have examined coupling various types of heat storage to Rankine and Brayton power cycles. However, there has been little examination of heat-storage options between (1) the reactor and (2) the power-conversion system or industrial customer. Heat-storage systems can be incorporated into sodium, helium-, and salt-cooled reactors. Salt-cooled reactors include the fluoride-salt-cooled high-temperature reactor (FHR) with its solid fuel and clean coolant and the molten salt reactor (MSR) with its fuel dissolved in the salt. For sodium and salt reactors, it is assumed that a heat-storage system would be in the secondary loop between the reactor and power cycle. For helium-cooled reactors, heat storage can be in the primary or secondary loop.

This report is a first look at the rational and the heat storage options for deploying gigawatt-watt hour heat-storage systems with GenIV reactors. Economics and safety are the primary selection criteria. The leading heat-storage candidate for sodium-cooled systems (a low-pressure secondary system with small temperature drop across the reactor core) is steel in large tanks with the sodium flowing through channels to move heat in and out of storage. The design minimizes sodium volume in the storage and, thus, the risks and costs associated with sodium. For helium systems (high-pressure with large temperature drop across the core), the leading heat storage options are (1) varying the temperature of the reactor core, (2) steel or alumina firebrick in a secondary pressure vessel and (3) nitrate or hot-rock/firebrick at atmospheric pressure. For salt systems (low pressure, high temperatures, and small temperature drop across the reactor core) the leading heat-storage systems are secondary salts. In each case, options are identified and questions to be addressed are identified.

In some cases there is a strong coupling between the heat-storage technology and the power cycle. The leading sodium heat-storage technology may imply changes in the power cycle. High-temperature salt systems couple efficiency to Brayton power cycles that may create large incentives for the heat storage to remain within the power cycle rather than in any intermediate heat transfer loop.

ACKNOWLEDGEMENTS

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CONTENTS

FIGURES

TABLES

ACRONYMS

ACAS	adiabatic compressed air storage system
CSP	concentrating solar plant
FHR	fluoride-salt-cooled high-temperature reactor
FIRES	firebrick resistance-heated energy storage
Gen IV	next-generation nuclear reactors
GTHTR300C	Gas Turbine High-Temperature Reactor
HTGR	high-temperature gas-cooled reactor
HTTR	High-Temperature Test Reactor
JAEA	Japanese Atomic Energy Agency
LWR	light-water reactor
T-B-T	Tianjin, Beijing, and Tangsha
TES	thermal energy storage
VHTR	very-high-temperature reactor

Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Reactor Operations

1. INTRODUCTION

This report is a first look at the rational and heat-storage options for deploying gigawatt-watt hour heat-storage systems with GenIV reactors. Economics and safety are the primary selection criteria. Electricity markets are changing. Those changes will alter the requirements for nuclear power plants. We discuss herein (Chapter 1) the market changes. Chapter 2 discusses the new requirements these impose on reactor stations to meet those requirements. Chapters 3 through 5 describe technology options for heat storage in the secondary loops of high-temperature gas-cooled reactors (HTGRs), salt-cooled reactors, and sodium fast reactors to meet these requirements.

The goal of the heat-storage system is to enable variable electricity to the grid while the reactor operates at base load. Sending variable electricity to the grid (1) maximizes revenue while minimizing cost and (2) enables nuclear energy to replace fossil fuels in the role of providing variable electricity to the grid. A heat-storage system has three components, each with specific functions.

- *Heat storage*. At times of low electricity demand, some heat is sent to the power cycle to operate at low power levels while the remaining heat is sent to storage. Operating the power cycle at minimum power levels at times of low electricity demand allows rapid return to full power. For smaller plants, there is an option of shutting down the power system at times of low electricity demand. At times of high electricity demand, heat from both the reactor and storage goes to the power cycle to produce electricity at a rate greater than the base-load capacity of the reactor.
- *Power cycle*. The power cycle can produce variable electricity including peak electricity at a rate greater than the base-load rating of the nuclear power plant. Without this extra power-cycle capacity, there would be no way to use stored heat.
- *Assured peak-generating capacity*. Heat storage cannot provide assured peak power capability because heat storage can be depleted. To provide assured peak generating capacity, a combustion heater is added that can provide heat to storage or the power cycle. This allows the system to provide peak electricity above the base-load capacity of the nuclear plant, even when heat storage is depleted. The combustion heater is seldom used because, most of the time, heat storage provides heat for peak electricity production.

The economics are based on two factors. The heat-storage system is less expensive than meeting variable electricity loads with a nuclear reactor operating at part load. The capital costs of heat-storage systems cost are measured in hundreds of dollars per kW(e), versus thousands of dollars for the same unit provided by nuclear power plants. Second, the assured peak generating capacity provided by the auxiliary heater is less expensive than buying a gas turbine for added assured peak electricity-generation capacity—the alternative assured generating capacity used to backup electricity storage systems such as batteries and hydro-pumped storage.

Historically, the market for nuclear power plants has been base-load electricity. The traditional electricity grid has a mixture of electrical generating technologies [EIA 2016, NREL 2018]. Nuclear plants have high capital and low operating costs. Fossil plants have low capital and high operating (fuel) costs. The economic mode of operation to minimize total electricity costs is to operate the nuclear plants at base-load (full power), with fossil plants providing variable electricity to match electricity production with demand. The electricity grid is changing rapidly in Europe, the United States, Japan, and China for two reasons: (1) wind and solar have been added at large-scale and (2) nations have set a goal of creating a low-carbon grid. We examine the impacts of each of these changes. Those changes create the incentives for adding heat storage to future nuclear reactors.

1.1 Market Impacts of Large-Scale Wind and Solar

Because of advances in technology, the levelized cost of electricity from wind and solar is low in areas with good wind or solar conditions (Table 1-1). Because of their low operating and maintenance costs, in a free market these plants bid lower prices to sell electricity than other plants. This changes electricity markets. Fossil fuel generating plants no longer set the minimum price of electricity.

Table 1-1. Levelized cost of electricity for new plants (Lazard 2017) in \$/MWe, unsubsidized cost and in parenthesis cost after U.S. federal tax subsidies.

Technology	Range of Levelized Cost of Electricity: \$/MWh: Unsubsidized (Subsidized)
Solar PV: Rooftop Residential	187–319 (145–240)
Solar PV: Crystalline Utility Scale	46–53 (37–42)
Solar PV: Thin Film Utility	43–48 (35–38)
Solar Thermal Tower with Storage	98–181 (79–140)
Wind	30–60 (14–52)
Natural Gas Peaking	156–210
Natural Gas Combined Cycle	42–78
Nuclear	112–183

However, wind and solar only produce electricity at times of wind and solar inputs—they cannot produce electricity to match electricity demand. This results in very different market dynamics. Figure 1-1 (left) shows wholesale electricity prices in parts of California on a spring day in 2012 and 2017. In 2012, the California electricity market was dominated by fossil-fuel generating units. The minimum price of electricity was set by the price of fossil fuels. If the electricity price went below the cost of the fossil fuels, power plants shut down. Over a period of five years, large numbers of photovoltaic (PV) systems were installed that collapsed prices on days with good solar conditions and low electricity demand when PV could meet most of the electrical load. The first month occurred during which the wholesale price of electricity was zero or below zero (negative pricing) more than 20% of the time—i.e., during the mid-day. This also resulted in higher prices near sunrise and sunset when electricity demand goes up, but PV can't provide electricity to meet demand.

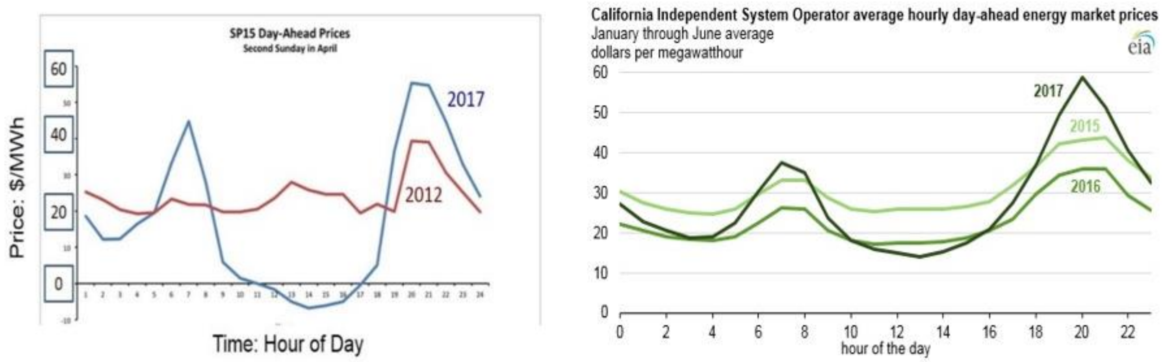

Figure 1-1. Price impact of adding solar pholtovoltaics (1) between 2012 and 2017 on a spring day in California and (2) averaged over six months for different years [California ISO 2017, California ISO 2018, EIA 2018].

The average wholesale prices for electricity in California for the first six months of each year are also shown in Figure 1-1 (right) for the last several years. The price collapse is increasing at times of high solar output, and wholesale electricity prices are increasing at other times.

Revenue collapse limits the use of solar even if there are large decreases in solar capital costs [MIT 2015] and large subsidies. A recent study [Sivaram 2018] examined the growth of solar in six European countries (Germany, Spain, Greece, etc.) where there were large government efforts to support deployment of solar. In each country solar initially grew rapidly, but leveled off before providing 8% of total electricity production. Price collapse made it uneconomical to add solar, even with large subsidies, because each added PV system drove down the revenue of all other existing PV systems. There was no value producing more electricity when there was excess electricity on the market. At the same time, the price of electricity increased at times of low wind and solar because other plants must start up and shut down to provide electricity at these times.

The same effect occurs with wind. Studies have quantified this effect in the European market [Hirth 2013, Hirth 2015]. If wind grows from providing 0% to accounting for 30% of all electricity, the average yearly price for wind electricity in the market would drop from 73 €/MWh(e) (at the advent of the first wind farm) to 18€/MWh(e) (when 30% of all electricity is generated by wind power). There would be 1000 hours per year when wind could provide the total electricity demand, the price of electricity would be near zero, and 28% of all wind energy would be sold in the market for prices near zero. A similar effect would be seen in an electricity grid with only nuclear plants competing with each other. At times of low electricity demand, the price would be driven to very low levels. This does not occur in markets dominated by fossil-fuel generating plants because the minimum price is set by the cost of fuel. That is, when electricity prices go below fuel prices, the plants shut down.

Markets limit the large-scale use of wind and solar. To increase the use of wind and solar, governments have chosen to subsidize these energy sources. In such markets the large-scale use of wind and solar results in electricity price increases to consumers and/or taxpayers. In areas of good solar and wind conditions, the levelized cost of electricity is very low (Table 1-1); however, the actual cost is low only if wind and solar systems operate at full capacity, producing electricity sold for a price greater than cost. If wind and solar operate at half capacity (because there is excess electricity on the grid), the electricity costs are twice as large per MWh. Price collapse indicates the value of electricity at a particular time has gone to zero or less than zero. Many hours of negatively priced electricity can only happen if subsidies of some type are available for electricity producers. There is a second cost. Wind and solar do not provide assured generating capacity. Other electric generators must be built to provide electricity at times of no sun or wind.

In most parts of the world, subsidies come from electricity customers as surcharges to their electricity bills, resulting in higher retail electricity prices as wholesale prices decline. In some countries, the taxpayer pays for the subsidies. In the U.S., there are both federal subsidies, paid by taxpayer, and state subsidies (direct or portfolio standards) that are paid by the ratepayer. Table 1-1 shows the actual and subsidized cost of different sources of energy based on U.S. federal tax subsidies—this does not include state and local subsidies.

On a large scale, these effects can be seen in comparing electricity prices and carbon dioxide emissions of multiple countries with different policies, as shown in Table 1-2. Denmark and Germany have made major commitments to wind and solar, with coincident price collapse. They have expanded wind and solar using subsidies, with resultant increases in electricity prices. Each country has its own story. Sweden has lower-cost electricity and low carbon emissions because nearly half the power is from nuclear, and the other half is generated by hydroelectric dams that enable base-load electricity from nuclear plants with dispatchable electricity from dams. France has less hydroelectricity, with a larger fraction of electricity from nuclear, with some of those nuclear plants doing load following. Denmark depends upon hydroelectricity from Norway to provide variable electricity and, thus, has been able to have wind and solar provide more than half their electricity, but at a high cost. Germany burns fossil fuels for variable electricity.

Table 1-2. Impacts of renewables in different countries.

Country	Sweden	France	Denmark	Germany
Carbon Dioxide Emissions (g CO_2/kWh)	11	46	174	450
Electricity Price (Cents/kWh)	20	22	41	40
Intermittent Renewables (%)	10	5	51	18
Dispatchable* Low-Carbon Electricity (%)	88	88	15	25

* Nuclear, hydroelectric, biomass and geothermal

Denmark and Germany export a significant fraction of wind and solar; thus, the percentage of electricity from intermittent renewables when calculated by production divided by national consumption is higher than when calculated by intermittent power produced by renewables consumed in the country, divided by total electricity consumed. Addressing price collapse with exports depends upon neighboring countries not installing large amounts of wind or solar capacity. For many national governments where the subsidies are in the form of assured electricity prices for renewables, price collapse results in large increases in subsidy costs because subsidies apply to both new and existing wind and solar facilities.

The addition of non-dispatchable generators (e.g., wind and solar) fundamentally changes the market, producing large swings in electricity prices. These electricity markets would benefit from a nuclear reactor with heat storage so that (1) more electricity is sent to the grid when prices are high with a demand for more electricity, (2) less electricity is sent to the grid when prices are low or negative, and (3) the heat-storage system can buy low-price electricity and convert that electricity into stored heat for later use. This last capability can set a minimum price for electricity near that of natural gas. In such a system, nuclear energy with heat storage would become the economic enabling technology for the larger-scale use of wind and solar by creating a market for low-price electricity and help set a minimum price of electricity above zero. The very low cost of heat storage versus electricity storage (e.g., batteries or pumped hydropower) implies the ability to consume massive amounts of low price electricity and thus minimize price collapse.

Without storage, the addition of wind and solar creates the ideal economic environment for natural gas turbines that have low capital cost, higher operating cost and can quickly be ramped up and down in power. For countries with access to lower-cost natural gas, such as the United States, this becomes the preferred option where wind and solar are used to reduce natural-gas consumption.

1.2 Impacts of the Goal of a Low-Carbon Grid

To better understand the challenges of a low-carbon economy and its impact on the potential requirements for advanced nuclear reactors, we asked this question: *What would be the optimum mix of technologies to minimize total cost of electricity for different constraints on carbon dioxide emissions per unit of electricity produced using existing and near-term technologies?* It is an alternative approach to understand the requirements for nuclear reactors in a low-carbon electrical grid. Such modeling shows how nuclear plants would be operated in a low-carbon economy and thus reveals the requirements for future reactors in such a world.

This question has been addressed in the MIT study *Future of Nuclear Energy in a Carbon Constrained World*. [Petti 2018] and follow-on studies at MIT [Forsberg 2018]. We summarize some results from the MIT study.[a] The study used GenX [Sepulveda 2016, Jenkins 2017, Sepulveda 2018], a power system decision-support tool, to explore the optimal electricity generation mix based on minimizing the total average cost of electricity generation for a set of pre-specified scenarios. Each scenario is characterized by a carbon-emission limit, a year-long hourly demand profile, year-long hourly availability profiles for solar and wind resources, and a set of investment and operational costs that model different systems under different carbon-emission targets. The optimization is based on an economic criterion because energy is about 8% of the global gross national product. Large increases in energy costs imply large decreases in global standards of living.

The energy technologies included energy production technologies (natural gas, coal, fossil fuels with carbon sequestration, nuclear (from light-water reactors [LWRs]), wind, solar) and storage technologies (hydro and batteries). All of the technologies chosen are commercial technologies. LWRs could operate at part load but did not have heat storage. This analysis did not evaluate advanced technologies that have not yet been deployed.

The study considered electricity futures with and without nuclear energy for several areas of the world including (1) Texas, United States; (2) New England, United States; (3) Tianjin, Beijing, and Tangshan (T-B-T), China; (4) Zhejiang, China; (5) the United Kingdom and (6) France. This includes electricity grids with excellent (Texas) and poor (New England) solar and wind resources. It includes countries with high (U.S.) and low (China) capital costs for nuclear power plants. Five different levels of carbon constraints were considered measured in carbon dioxide released per kilowatt-hour (gCO_2/kWh) of electricity produced: 500, 100, 50, 10 and 1 g CO_2/kWh. The average U.S. electric sector carbon emissions are near 500 g CO_2/kWh with higher carbon dioxide emissions in China.

Figure 1-2 shows average electricity costs for the six regions at reduced carbon dioxide emissions and including all technologies. Figure 1-3 shows average electricity costs for the six locations if nuclear is excluded from the generating mix.

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[a] Parts of this section are excerpted from Petti 2018.

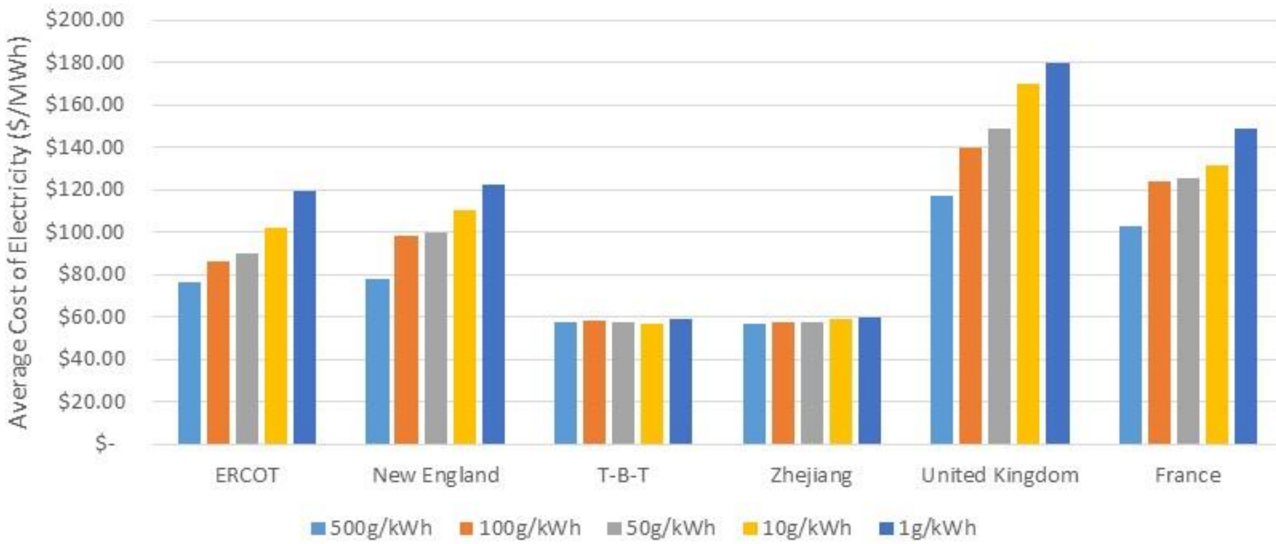

Figure 1-2. Average cost of electricity (all technologies allowed) versus carbon dioxide constraint

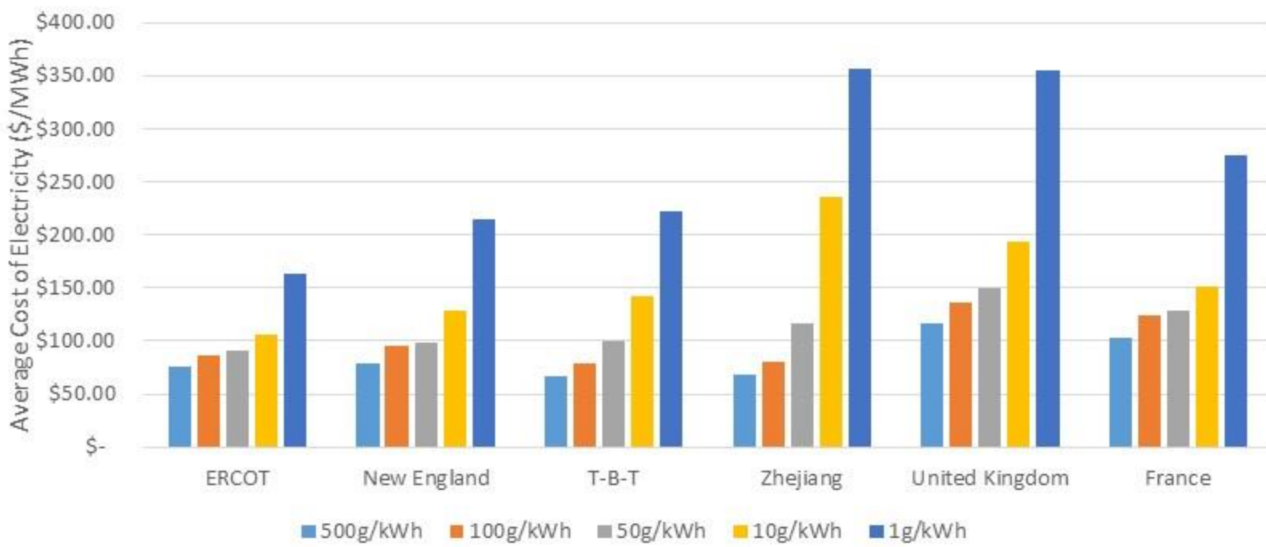

Figure 1-3. Average cost of electricity for non-nuclear scenarios versus carbon dioxide constraint

In western countries going from 500 g CO_2/kWh to 1 g CO_2/kWh in scenarios that included the option of building nuclear plants, electricity costs increased (Texas: $76.32 to 119.10/MWh, New England: $78.21 to 122.36/MWh, France: $102.85 to 148.64/MWh, and United Kingdom: $117.03 to 172.71/MWh). With no restrictions on carbon dioxide, natural gas is the preferred fuel with addition of nuclear electricity increasingly preferred as carbon constraints become more limiting. If nuclear energy is not allowed, much larger increases in electricity costs occur as the carbon-emission limits go from 500 to 1 g CO_2/kWh (Texas: $76.52 to 162.99/MWh, New England: $78.23 to 214.09/MWh), France: $103.29 to 274.55/MWh, and United Kingdom: $116.38 to 355.05/MWh). Note that the vertical axis (cost of electricity) is twice is high in the no-nuclear case (i.e., Figure 1-3) as in the nuclear case (Figure 1-2). In a carbon-constrained world, electricity costs for locations such as Texas with excellent wind and solar resources are lower than locations such as New England with poor wind and solar resources. Because Texas has very-low-cost natural gas, it is the preferred fuel until carbon dioxide constraints limit its use.

There were only small changes in electricity costs in China with tighter restrictions on carbon dioxide emissions because the low capital cost of nuclear power plants makes nuclear power the preferred electricity-generating technology from high to low emissions of carbon dioxide (T-B-T: $57.83 to 59.30/MWh and Zhejiang: $56.97 to 59.62/MWh). Except for China, the optimum mix of generating technologies changes dramatically as carbon constraints become more restrictive. In Western countries, there are large increases in electricity costs to reduce carbon dioxide emissions if nuclear energy is not available. In the context of heat storage, several conclusions can be drawn from such analysis:

- Electricity costs increase with tighter restrictions on carbon dioxide emissions because of the mismatch between electricity production and demand. A low-carbon grid with existing technologies results in expensive electricity. To assure electricity supplies when needed (i.e., sufficient generating capacity) the system requires expensive batteries, overbuilding of wind and solar to reduce storage costs, and nuclear plants operating at part load. That is because with tighter carbon constraints, the use of low-capital-cost, high-operating-cost fossil-fuel electric generating plants is reduced. Note that this analysis did not include nuclear reactors with heat storage—only the existing option of operating nuclear plants at part load.
- Nuclear plants operate with variable output. As carbon constraints increase, nuclear reactors increasingly take on the role of providing variable electricity to the grid—not base-load reactor operation. They partly replace the role of fossil-fuel power-generating systems.

Figure 1-4 and Figure 1-5 show how nuclear reactors would be operated in such a world under different carbon emission constraints respectively for the Texas and New England electricity grids. The model assumes no transmission constraints or import-exports of electricity from each region. It is a greenfield model—what one would build in the absence of existing power generators. Data in the two figures below are only shown for lower carbon dioxide emission constraints. If there are only limited constraints on carbon dioxide emissions, natural gas is the low-cost method to generate electricity, and no nuclear plants are built in the United States. Most electricity is generated by natural gas in such scenarios.

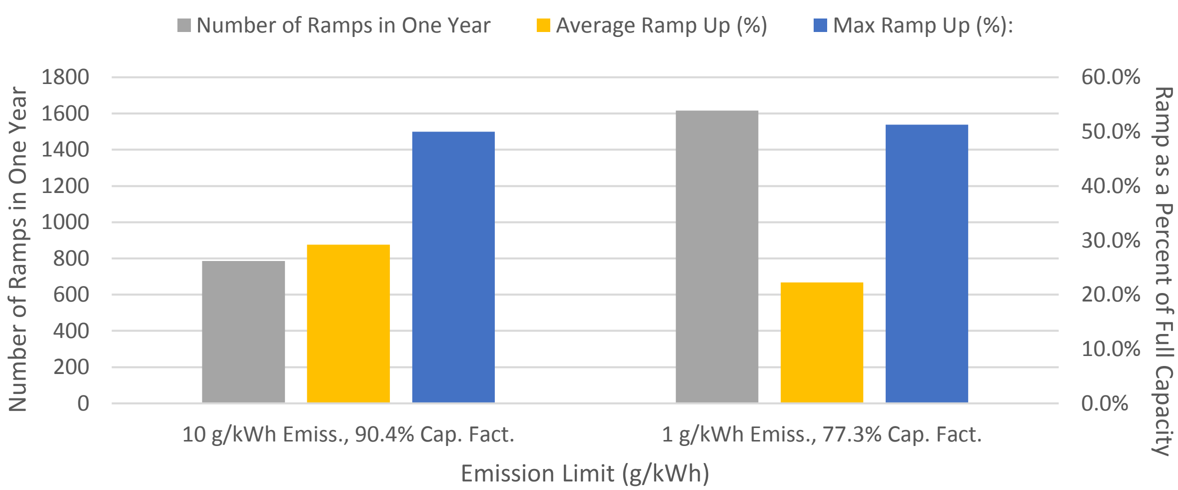

Figure 1-4. Texas ERCOT: Characterization of nuclear plant operations over a year.

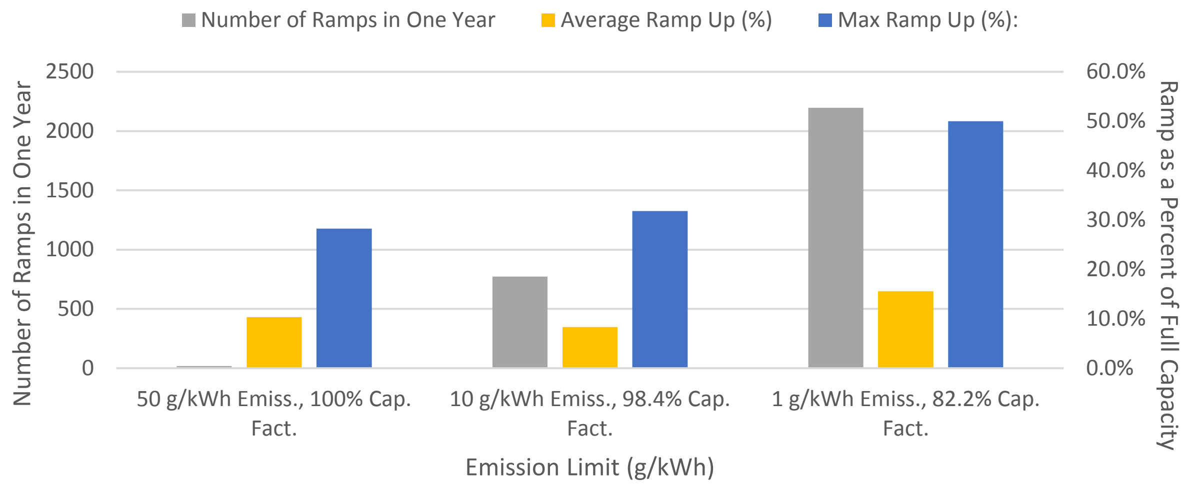

Figure 1-5. New England: Characterization of nuclear plant operations over a year.

There are several conclusions that can be drawn from such analysis:

- *Number of ramps per year*. The model optimizes the system for each hour of the year—8760 hours. The number of ramps per year is the number of times the power level changes in a year. The number of ramps per year increases as the carbon constraints become more severe; that is, the nuclear plants do more load following and spend less time operating at base load. With tight carbon constraints, reactors are changing their power levels more than a thousand of times per year.
- *Average ramp up.* This is the average increase in power when the power level increases. This may occur over one or many hours. It ends when the next change in power level decreases power levels.
- *Maximum ramp up*. This is the largest increase in power over a year in any ramping event that could occur in an hour or over many hours. In this case, the maximum ramping event is near 50% of full power.

There is one other observation. In all very-low-carbon futures, nuclear energy provides a large fraction of the total electricity, but typically 20% of the generating capacity is non-nuclear with very low capacity factors—everything from batteries to gas turbines that operate very few hours per year. This generating capacity is built because it is cheaper than building added nuclear power plants with lower capacity factors. In a low-carbon world, generating capacity (not kWh) is the expensive limiting factor.

Going to a low-carbon grid with existing nuclear power systems implies that the reactors will partly replace fossil plants for producing dispatchable electricity. The reactors are not used for base-load electricity production. The most economic reactor is the reactor that can provide variable electricity to the grid and heat to industry with assured peak electricity generating capacity at the lowest cost.

1.3 Other Considerations

There are other implications from such analysis.

- *Reactor operations*. Without heat storage, reactors in a low-carbon world operate in a load-following mode. Load following is easy for a boiling water reactor and somewhat more difficult for a pressurized water reactor. There may be significant operational costs for operating higher-temperature reactors with variable load and temperatures over time. Heat storage moves the power transients from the reactor core to the power cycle and heat-storage system.

- *Economics*. The economic reactor is not necessarily the reactor with the lowest levelized cost because reactors are not operated in that mode. The most economic advanced reactor is the reactor that produces variable electricity to the grid with heat storage. The integration of heat storage into the reactor and its power cycle may determine which reactor is most economic.

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2. FUNCTIONAL SYSTEM REQUIREMENTS FOR GENIV REACTORS IN A LOW-CARBON WORLD: ROLE OF HEAT STORAGE

2.1 Functional Requirements

Nuclear reactors are capital intensive, with low operating costs; thus, the reactor should be operated at full capacity to minimize production cost. But the electricity grid needs variable electricity. Figure 2-1 shows the proposed system for variable electricity to the grid and heat to industry with assured peak generating capacity from a base-load nuclear plant. It is what enables a base-load nuclear plant to replace a fossil-fuel plant for production of variable electricity to the grid. This is a system design applicable to any type of nuclear reactor, but the performance is dependent upon the temperatures over which the reactor delivers heat. Thus, the choice of future reactors may be determined by how they perform within this system.

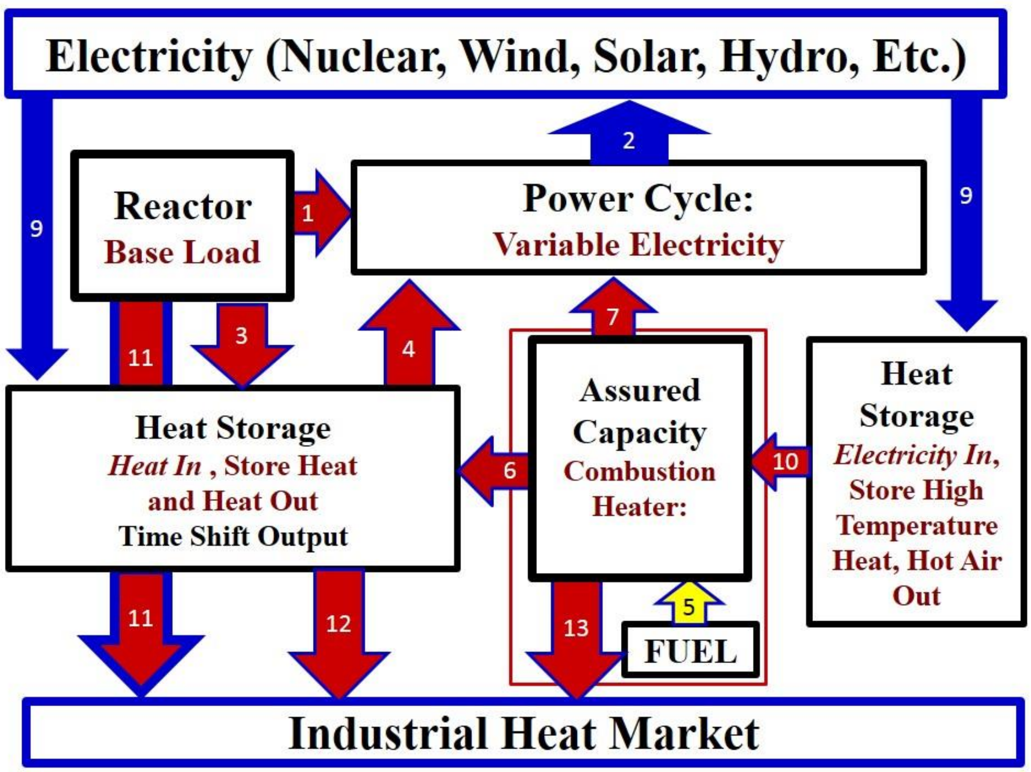

Figure 2-1. Reactor system with dispatchable electricity to the grid.

The top-level goal is to minimize total societal energy cost with variable electricity and optional heat to industry with nuclear, solar, and wind facilities operating at full capacity. For any particular market, only some components may be built. The system description below includes examples for both light-water (the best understood system) and next generation (Gen IV) reactors.

2.1.1 Heat storage

The reactor operates at base-load (its most economic mode of operation) with variable electricity [2] to the grid with the option of heat to industrial customers [11] (numbers in brackets [] refer to energy flows in Figure 2-1). The electricity grid may include wind or solar production facilities. When there is excess electricity production (low prices), some of the heat from the reactor is diverted to heat storage [3]. Sufficient heat is sent to the power cycle [1] to operate at minimum electrical output. By operating the power cycle at minimum load, the power cycle can quickly return to full base-load power by sending all heat from the reactor to the power cycle. When additional electricity is needed (in periods of high electricity prices), all heat from the reactor [1] is sent to the power cycle, and additional heat from storage [4] is sent to the power cycle to produce added peak electricity.

If the reactor were a 1000 MWe LWR that produced steam with a single turbine, the minimum electricity output might be as low as 300 MWe, with a peak power capability of 1300 MWe. In a GenIV reactor with other storage and power cycle options, the range of power output could be much larger.

Energy storage can be used to operate nuclear, wind, and solar at full capacity (lowest cost) with variable electricity to the grid. Wind and solar photovoltaic produce electricity; thus, there is the option to include electricity storage in the system in the form of batteries, hydroelectric pumped storage, or other technologies. Nuclear reactors produce heat that is converted to electricity; thus, there is the option of using heat storage. The cost of electricity storage systems (batteries, pumped hydroelectric) is much higher than thermal (heat) storage systems. In the United States, U.S. Department of Energy goals are $150/kWh of electricity storage for batteries, with the associated electronics doubling costs. In contrast, the DOE heat-storage goal for concentrated solar power systems is $15/kWh. Heat storage at the gigawatt-hour scale is now used with some concentrated solar-power systems to enable those systems to sell electricity at times of higher prices. It is the low-cost energy-storage option.

2.1.2 Assured peak electricity generating capacity

Heat-storage systems can become depleted by high electricity demand. At such times, electricity production could be limited to base-load production from the reactor operating at full power. To assure the capability of peak electricity production at all times, a combustion heater (natural gas, oil, biofuels, hydrogen, etc. [5]) can provide heat to the storage system [6] or directly to the power cycle [7]. Where to add heat will depend upon the specific system design.

For an LWR, the combustion heater is a water-tube boiler that provides saturated steam that matches LWR steam conditions. The cost of assured peaking capacity is small. Beginning with a 1000 MWe LWR and adding a storage system to produce an additional 200 MWe of peak power capacity, extra power-cycle equipment (an added turbine, generator, electrical switchgear, condenser, or cooling tower capacity) is required to produce the added 200 MWe of peak power capacity. To provide 200 MWe of added assured generating capacity even if storage is depleted, a water-tube boiler only needs to provide the heat for that peak 200 MWe capacity. For an LWR with 33% efficiency, that would be 600 MWt of saturated steam. Because heat storage usually provides peak capacity, the boiler will likely be operated for fewer than 100 hours per year with very low annual fuel consumption. In a low-carbon system, biofuels, or hydrogen could be used rather than oil or natural gas. Capital costs [Forsberg 2018a] for such a boiler are estimated at $100–300/kWe, substantially less than the cost of a simple gas turbine ($600/kWe) to provide assured electricity generating capacity. For GenIV reactors, the type of combustion heater depends upon the choice of power cycle or heat-storage system. The important characteristic is that the cost of a combustion heater for assured peak generating capacity is much lower than a gas turbine, the traditional technology for assured peak electricity production. Storage with assured peaking capacity creates a new class of storage that can partly replace traditional generating capacity.

2.1.3 Converting excess low-price electricity to stored heat

If there is excess electricity production from wind and solar, options exist to convert that excess electricity from the reactor power cycle and the electricity grid into stored high-temperature heat, rather than curtailing wind or solar resources. The first option is to add electric resistance heaters to the heat-storage systems—an option that works with some, but not all types of heat storage. For LWRs, the second option is to add hot-rock or firebrick resistance-heated energy storage (FIRES) [Forsberg July 2017a] to convert excess electricity [9] into high-temperature stored heat in the form of hot rock or hot firebrick. When there is a demand for peak electricity, cold air is blown through voids in the crushed rock or channels in the hot firebrick to produce hot air [10] that goes to the combustion boiler to produce steam. The type of system to convert low-price electricity into high-temperature stored heat for different reactors depends upon the power cycle and is discussed in the next several chapters.

When converting low-price electricity to heat to electricity, the nuclear reactor is effectively competing with all other storage technologies: batteries, hydroelectric pumped storage, etc. There are three factors that determine the relative economic advantage of the different storage technologies.

- *Capital costs*. In all cases heat storage costs less than storing electricity (batteries, hydroelectric pumped storage, etc.). Furthermore, the cost of converting heat to electricity is lower than other options because of the economics of scale associated with nuclear plants.
- *Assured electricity generation capacity*. With heat storage, there is assured generating capacity if the heat-storage system is depleted by times of high demand or low wind or solar output by use of an auxiliary combustion furnace. The cost of such a furnace is less than the cost of a stand-alone gas turbine (i.e., the competing technology) to produce assured peak generating capacity.
- *Efficiency*. The round-trip electricity to heat storage to electricity strongly depends upon the storage system and reactor type. Converting electricity to stored heat efficiency is near 100%; but converting stored heat to electricity depends upon the power cycle. At one extreme are LWRs, with round trip efficiencies between 20 and 35%. That is acceptable if the alternative is curtailed wind or solar. GenIV reactors that operate at higher temperatures have higher heat to electricity efficiencies.

2.1.4 Industrial heat market

The above system enables highly reliable heat to industry. Heat from the reactor [11], heat storage [12] and the combustion heater [13] can provide low-cost industrial heat, generated at times of low electricity prices. Industrial processes have very high requirements for reliability (99.9%) of steam supplies. Assessments of those requirements [Herd 2010, Herd 2012] where high-temperature gas-cooled reactors provide the heat often lead to a requirement for "extra" reactors or other equipment to assure steam supplies. The above system design, with heat storage and assured heat production with auxiliary combustor, can help meet these requirements while minimizing the number of reactors required to achieve specific reliability goals.

Heat storage enables coupling the electricity market with the industrial heat market to store low-price energy when available from the electricity market for later use by the heat market. Coupling the electricity and industrial heat markets should lower total costs.

2.2 Economics of Options for Variable Electricity

Variable electricity demand using nuclear energy can be met in at least three different ways: (1) operate reactor at part load, (2) add heat storage for variable electricity from a base-load reactor, and (3) develop hybrid energy systems that produce two products, e.g., variable electricity and a second product such as hydrogen. What are the relative economics?

U.S. capital costs for nuclear power plants are estimated at $5500/kW of electricity. The DOE heat storage goal is $15/kWh(t). The thermal-to-electricity efficiency depending upon the reactor type will be between 30 and 50%. This implies that heat storage costs per kWh electric will be under $50/kwh(e). If storing eight hours of electricity (during a solar-induced price collapse), this is $400/kWe. The cost breakdown of nuclear plants in Figure 2-2 indicates that the turbine-generator equipment cost is somewhere near 5% of total costs. If the turbine-generator for peak electricity production is oversized above base load, this represents a small cost. A separate turbine-generator for peak power production is a small cost relative to reactor costs. Such analysis indicates that in approaching DOE heat-storage goals, a reactor with heat storage for variable electric production will be much more economical than oversizing a reactor and operating it at part load.

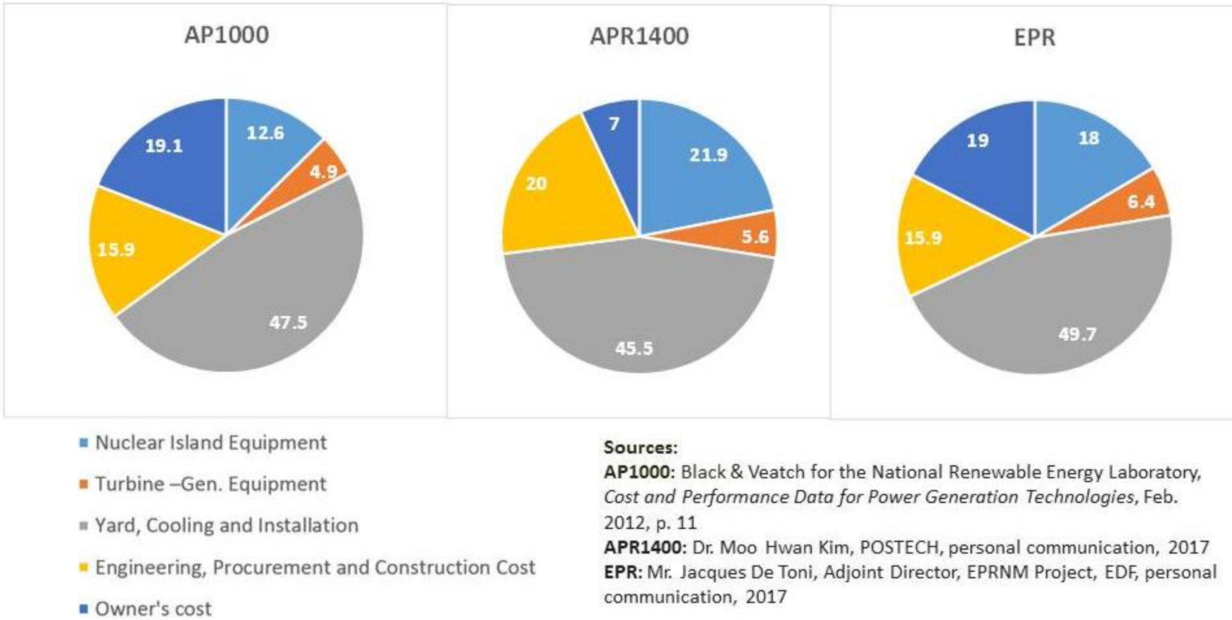

Figure 2-2. Capital cost breakdown for several advanced light-water reactors (Petti 2018).

The other set of options involves hybrid energy that produces variable electricity and a second product, such as hydrogen, while the reactor operates at base-load. This is a longer-term option that is not discussed in this report.

Recent studies for the United States [Petti 2018] indicate that there is little difference in the capital costs of different advanced reactors. In a low-carbon electricity grid, the most economic reactor becomes the reactor with heat-storage system, with the capabilities described above at the lowest cost. Heat-storage economics partly drives the choice of nuclear reactor. The economics of the storage systems strongly favors reactors that deliver higher-temperate heat—Generation IV reactors—for the following reasons:

- *Low-cost heat storage*. Heat storage costs are measured in dollars per kilowatt hour ($/kWh). Different heat-storage technologies require heat input at different temperatures. Most storage systems have losses in efficiency through heat exchangers and other mechanisms; those losses are proportionally greater in low-temperature than high-temperature systems. For sensible heat-storage systems (hot rock, liquid salts, etc.), the heat capacity per unit volume of the storage material depends upon the temperature swing from hot to cold. If that temperature swing in storage is doubled, heat-storage costs are reduced by a factor of two. High input temperatures enable larger temperature swings in the storage material with lower-cost storage.
- *Efficiency in converting stored heat from the reactor into electricity*. The efficiency of converting stored heat to electricity depends upon the power cycle and the temperature of the stored heat. Higher temperatures increase efficiency. For LWRs, the efficiency of converting stored heat into electricity will be between 20 to 30% depending upon the storage technology. For GenIV reactors, this heat-to-electricity efficiency may be above 40%. The amount of heat that would need to be stored may be reduced by a factor of two if the heat-to-electricity efficiency is twice as high. The cost of electricity using stored heat is reduced for high-temperature heat storage because of this efficiency effect.
- *Efficiency in converting auxiliary heat into electricity*. If heat storage is depleted, auxiliary combustion heaters can provide very-high-temperature heat for assured electricity generation. When converting excess low-price electricity from the grid into stored heat, this heat can be stored at high temperatures.

2.3 Technology Pathways

There are three technological pathways for heat storage:

- *Heat Storage in Steam Cycles.* There is ongoing work by universities, vendors, and utilities to incorporate heat storage with assured peak electricity-generating capacity into LWR steam cycles [Forsberg 2017b, Forsberg 2018a, Forsberg 2018b]. The same systems apply to Gen IV reactors, except that one is using high-temperature rather than saturated steam. Higher-temperature heat storage implies higher efficiencies in converting stored heat to electricity . The changes in the electricity markets in the last several years make this option potentially competitive today with LWRs; consequently, several utilities have begun plant-specific engineering studies as the first step for adding heat storage to existing reactors.
- *Brayton Power Cycles***.** Generation IV reactors can couple to Brayton power cycles [Forsberg 2018a, Forsberg 2018c] with the option of efficient peak electricity production via a thermodynamic topping cycle using an auxiliary combustion fuel such as natural gas, biofuels or, ultimately, hydrogen or high-temperature stored heat. Thermodynamic topping cycles for nuclear reactors are not new. In the 1960s, the Indian Point I pressurized water reactor was built in the United States. Saturated steam from this reactor, nearly 300°C, was sent to an oil-fired superheater to raise the steam temperature to about 550°C—a topping cycle. At that time, this was the most efficient power plant in converting incremental heat from oil into electricity. Brayton power cycles exist where the reactor provides lower-temperature heat, and a second heat source provides higher-temperature heat. These power cycles include various internal heat-storage systems.
- *Heat Storage in Secondary Loop.* There is the option of including heat storage in the secondary loop between the reactor and the power system—the subject of this report.

There are large incentives to examine heat storage in secondary loops to enable base-load reactors to operate with variable electricity to the grid:

- *Minimum change in reactor and power cycle*. If heat storage is in the intermediate loop of a GenIV reactor, it minimizes changes elsewhere in the plant.
- *Coupling with concentrated solar thermal power systems*. The concentrated solar power community has adopted heat storage as a requirement for commercial viability because of solar-induced revenue collapse on days with good solar conditions. In some systems, heat is stored at the gigawatt-hour scale to enable electricity sales as the sun sets. It is not economically viable to sell most of the electricity when the sun is shining. For solar-power towers, the competing heat-transfer fluids are salts, sodium, and gases; these are either the same as or similar to fluids used in GenIV reactors.

The next three chapters examine heat storage options for HTGRs, salt-cooled reactors and sodium reactors.

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3. SODIUM SYSTEM HEAT STORAGE OPTIONS

Sodium has excellent heat-transfer characteristics. As a consequence, it is used or proposed to be used in three types of power systems (Forsberg 2018a).

- *Sodium fast reactors*. These nuclear systems use sodium as the coolant in the reactor core and in the intermediate loop that transfers heat from the reactor to the power cycle. Sodium fast reactors have peak coolant temperatures typically between 500 and 550°C. There is a 50 to 100°C temperature drop across the reactor core.
- *Molten salt reactors*. There are three classes of molten salt reactors (MSRs): fluoride-salt-cooled high-temperature reactors [FHRs] with solid fuel and clean salts [Andreades 2016], molten-salt reactors with fuel dissolved in the salt [Dolan, 2017], and salt-cooled fusion machines [Sorbom 2016]. Salt reactors have peak temperatures between 600 and 700°C, with 50 to 100°C temperature rise across the reactor core. The first molten-salt reactor was built for the Aircraft Nuclear Propulsion Program in the 1950s, with a sodium intermediate loop to transfer heat from the reactor to aircraft jet engines—partly because sodium enabled design of very efficient sodium-to-air heat exchangers within the jet engine. Today there is an interest in coupling salt reactors to nuclear air-Brayton combined cycle power systems that have high efficiency and the ability to rapidly vary power levels [Andreades 2014, Forsberg 2016, Fathi 2018]. For such systems, sodium is one candidate for the intermediate loop between reactor and power cycle.
- *Concentrated Solar Power Systems* [Wetzel 2014, Mehos 2017]. Most existing concentrated solar power systems use nitrate salts, hot oil, or water and nitrate salts, hot oil or steam accumulators for heat storage. There is a rapidly growing interest in using sodium for the next generation of solar-power towers at operating temperatures that exceed 700°C. The temperature drop across a concentrated solar-power system may be several hundred degrees C. Nitrate salts decompose as they approach 600°C and, thus, a new liquid coolant is required to go to higher temperatures with higher heat-to-electrical efficiencies and potentially lower costs. The major coolant options for such high temperature systems are sodium, chloride salts, and gases—each with different challenges.

Sodium heat storage has been coupled to solar power towers. In the 1980s the International Energy Agency/Small Solar Power Systems facility in Almeria, Spain had a 5 MWh heat-storage system that consisted of hot and cold tanks of sodium, with a heat storage capacity of 5 MWh.

3.1 Sodium Reactor and Solar-power Tower Boundary Conditions

Different sodium systems have different operating ranges. Sodium fast reactors typically have peak temperatures below 550°C, with less than a 100°C cold-to-hot temperature variation. Existing sodium concentrated solar-power towers have peak temperatures that vary widely, but remain below 550°C. Advanced high-temperature solar power towers would have peak sodium temperatures above 750°C. Sodium in the intermediate loop of a salt-cooled reactor would likely have temperatures in the 600–700°C range, with less than 100°C variation across the reactor core.

Sodium is highly reactive with air, water, and many other materials. The scale of heat storage associated with nuclear reactors will likely be an order of magnitude larger than associated with solar-power towers; this creates greater concern about fire and the absolute total inventory of sodium in the system. The potential for radioactive contamination in the storage system if a heat exchanger fails at a nuclear reactor is not a major safety concern, but an economic one. Chemical reactivity likely rules out sodium use with nitrate salts—the traditional heat storage fluid in concentrated solar-power systems. Nitrates are strong oxidizing agents that would react with sodium, with the potential to generate large quantities of nitrogen and nitrogen oxides.

3.2 Heat-storage Options

There have been many previous studies and a recent assessment of sodium heat storage options [Niedermeier 2016] for concentrated solar power systems, but very limited studies for reactor systems [Forsberg 2018]. Much of the work has been for relatively small storage systems that may or may not be applicable to large systems where heat storage is measured in gigawatt hours.

3.2.1 Sodium tank storage

In a sodium intermediate loop, sodium can be used as the heat storage material with the same basic design of storage system used with commercial nitrate heat-storage systems in concentrated solar power systems. In this system, there is a hot and cold sodium storage tank (Figure 3-1). At times of low electricity demand, the reactor sends some hot sodium to the power cycle, and the remainder of the sodium goes to a hot-sodium storage tank. Cold sodium from the power cycle and from the cold sodium storage tank is sent back to the reactor that is operating at base-load. At times of high electricity demand, hot sodium from both the reactor and the hot sodium storage tank goes to the power cycle. Cold sodium from the power cycle goes to the reactor and the cold-sodium storage tank.

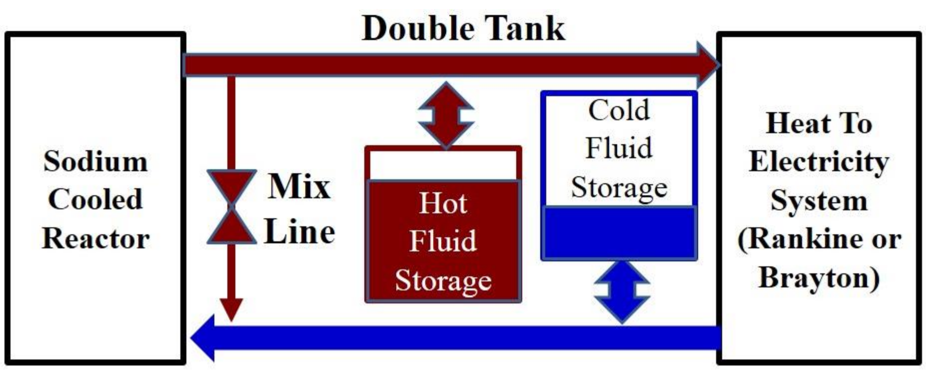

Figure 3-1. The two tank heat-storage option.

There is also the option of a single storage tank with hot sodium on top of cold sodium (Figure 3-2). Because of the high thermal conductivity of sodium, this may or may not be a practical option because of rapid heat conduction from the hot to the cold sodium. Two possible solutions would enable use of a single-tank option.

- *Hot/cold insulation layer*. An insulation layer could be placed between the hot and cold layers of sodium. That layer must move up and down as hot and cold sodium are moved in and out of the tank to maintain a position between the hot and cold sodium.
- *Series of tanks.* A series of tanks could act like a single tank, but with lower heat losses, as shown in Figure 3-3.

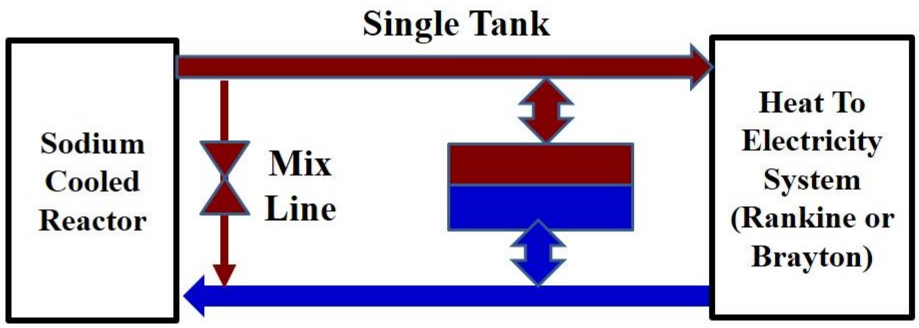

Figure 3-2. Singe tank heat-storage option.

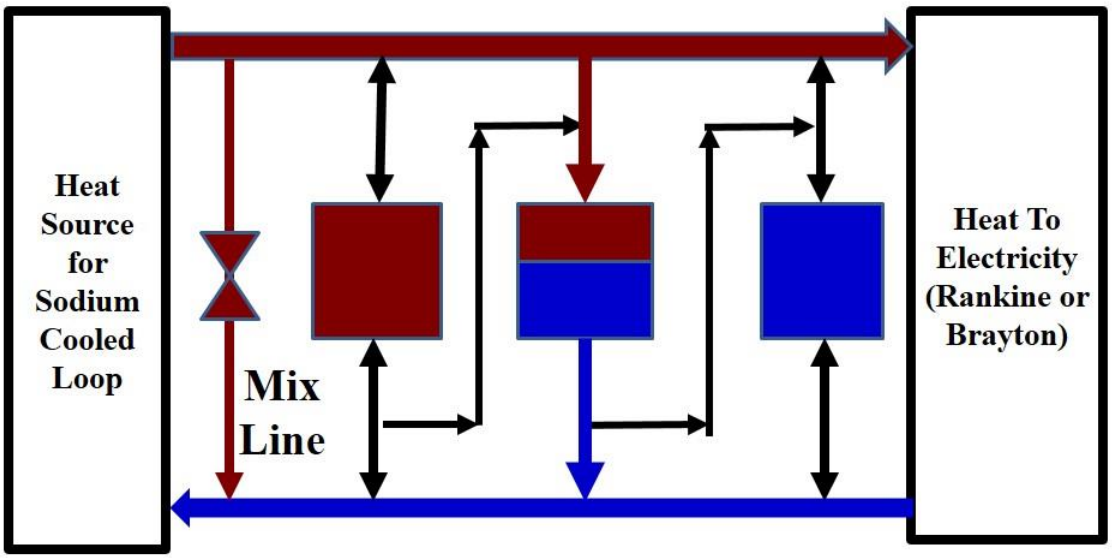

Figure 3-3. Single tank heat-storage option as multiple tanks in series.

Sodium is, volumetrically, the cheapest metal. It is produced in large volumes to make soaps and other products and shipped in tank-car quantities. The price of sodium is relatively low. The heat capacity of sodium is 28.2 J/(mol K) or 1.23 J/(g K). If one uses a gigawatt hour as a measure of heat storage and assumes a 100 K hot-to-cold temperature swing, one requires 30,000 metric tons of sodium per GWh or 30 kg/kWh. Sodium prices are typically near \$3000 per metric ton (\$3/kg) when ordered in ton quantities, implying sodium costs near \$100/kWh of heat storage. The storage volumes are relatively small. Metallic sodium has a density of 1 g/cm^3 or one metric ton per cubic meter. A GWh of heat storage is 30,000 m^3 of sodium, one large oil tank.

In a system with sensible heat storage, there is a large incentive to increase the temperature difference between hot and cold sodium in storage to reduce storage costs. In nuclear reactor applications, the temperature drop across the reactor core will be less than 100°C. There is the option of operating the sodium storage system over a much larger temperature range—in excess of 300°C. When producing peak electricity, hot sodium from storage would be sent to a power cycle that returns sodium back to storage at temperatures near 150°C. The heat-storage system requirement would partly determine power cycle design.

This would require that when the heat-storage system is being recharged, hot sodium will enter the system at 500 to 700°C while cold sodium exits storage at less than 150°C. This imposes the requirement to mix hot sodium from the reactor and cold sodium from storage to match sodium temperatures going back to the reactor. The storage system is to be “invisible” to the heat source. While there are inefficiencies in mixing hot and cold sodium for return to the reactor, the large hot-cold temperature range can reduce heat-storage costs by a factor of three or more.

3.2.2 Sodium-compatible sensible heat storage

The cost and safety of the storage system can be improved by adding a solid to the heat storage tanks to provide most of the heat storage capacity. Sodium becomes the heat-transfer fluid between the heat-storage media and the power cycle. While a massive amount of work has been performed on sensible heat-storage materials at lower temperatures, relatively little work has been done on sensible heat storage at higher temperatures. The goals are a lower-cost heat-storage material per unit of heat storage (kWh), a high heat capacity to minimize tank size, high thermal conductivity for efficient heat transfer, and compatibility with the sodium.

The simplest option is storing heat in iron or steel, materials with proven records of compatibility with sodium, but an option that has only recently been examined [Forsberg 2018]. One could fill a tank with square or hexagonal billets, 10 to 20 meters tall, with vertical grooves in the sides of each billet for sodium flow. This minimizes the sodium inventory in the heat-storage tanks to address potential safety concerns and reduce costs. Sodium is compatible with many iron and steel alloys. The geometric design of such a heat-storage system looks similar to the traditional geometric design of a sodium fast reactor with hexagonal fuel assemblies; thus, the thermal-mechanical design methodologies developed for fast-reactor core design in a highly simplified form are directly applicable to design of such a heat-storage system.

The heat capacity of iron is 25.1 J/(mol K) or 0.45 J/(g K). Most elements have similar heat capacities per mole. If one uses a gigawatt hour as a measure of storage and assumes a 100 K hot-to-cold temperature swing, one requires 80,000 metric tons of iron per GWh (80 kg/kWh). Steel prices are typically near $500 per metric ton when ordered in quantity or $0.50/kg implying iron costs near $40/kWh of heat storage. The storage volumes are relatively small. Iron has a density of about 7.8 gram/cm^3 or 7.8 metric tons per cubic meter. A GWh of heat storage requires a little over 10,000 m^{3}of steel. If the temperature difference between hot and cold is increased to 300°C, heat-storage costs are reduced by a factor of three. Tripling the hot-cold temperature range in storage cuts storage costs by a factor of three or more, with the potential to meet the DOE cost goal for heat storage of $15/kWh, excluding other system costs

There is a long list of lower-cost filler materials, such as quartzite (SiO_2) for sodium systems [Niedermeier 2016], but insufficient research is available to determine whether these options can meet the multiple requirements of a high-temperature heat-storage system. For many of these options, the heat-storage medium may need to be inside steel pipes or containers to minimize contamination of the coolant. In most of these systems, the sodium inventory in the heat storage tank or tanks will be considerably larger than with steel ingots with high density and good thermal conductivity that minimizes required sodium volumes.

3.2.3 Latent heat storage

There is the option of filling the heat storage tanks with a latent heat-storage material—a material that freezes at a specific temperature. These materials are packaged in steel or other containers, and heat is transferred from sodium to the latent heat-storage material. The big advantage for reactor applications is higher storage efficiency. The temperature drop for sodium across a reactor core is typically 50 to 100°C. It is highly desirable to store heat at high temperatures to maximize heat-to-electricity efficiency in the power cycle. A secondary advantage is that the heat storage per unit volume of these systems is an order or magnitude larger than with sensible heat-storage systems. For power plants with large sites, minimizing volume is usually not important—the goal is minimizing costs. However, minimizing heat-storage volume is important in other environments.

Many studies have identified candidate materials [Niedermeier 2016, Kenisarin 2010, Gil 2010, Medrano, 2010], but there have been limited assessments of the potential candidates if deployed at the gigawatt-hour storage scale. There are several major considerations:

- *Cost.* This is the first consideration. This includes both initial cost and long-term reliability. Can the system be cycled thousands of times without major maintenance?
- *Safety and reliability*. Latent heat storage implies that the heat-storage material goes through a freeze-thaw cycle thousands of times. In really large systems, it may not be credible to believe that package failures will not occur. The question is, then, what are the implications of the liquid latent heat material coming in contact with sodium? The issue is not just immediate chemical reactions between sodium and the storage material, but the effects of dissolution of the latent heat storage material in sodium in terms of corrosion resistance of the entire system and other effects. Does the latent heat-storage material need to be removed from the sodium and, if so, what technologies are available for sodium cleanup.

The leading candidate today for latent heat storage is probably aluminum [Fears 2018], but there are several other candidates. It has a freeze point of 661°C that matches what is required for an intermediate loop in a salt-cooled reactor. However, equally important is that there are a variety of eutectic alloys with much lower melting points. The very high thermal conductivity minimizes temperature losses in heat transfer. That is important because it enables latent heat-storage containers to be relatively large: both sodium and aluminum have high thermal conductivity. Large containers minimize total system costs. The mechanical design for any latent heat-storage system is a major challenge because of expansion and contraction in the freeze-thaw cycle.

3.2.4 Secondary heat storage (concrete, salt, other)

There are a large number of storage options if one is willing to use a heat exchanger with associated temperature drops and capital costs. We did not examine this large set of options.

3.3 Challenges and Observations

Several observations follow from our initial assessments:

- *Cooperation with concentrated solar power community*. Sodium is a leading candidate for next-generation solar-power towers that will have peak temperatures above 700°C. Both communities face the same challenge: developing an economic heat-storage system with the same basic constrains.
- *Heat storage in steel.* The leading candidate for near-term heat storage in a sodium system is steel. It is compatible with sodium, there is massive experience using steel in sodium piping systems, the cost is reasonably low, and a heat-storage system can be designed with a very low inventory of sodium—a major safety advantage. A near-term goal should be to develop such a design at the gigawatt-hour scale to provide a base-line cost estimate and a base-line to compare with any proposed alternative system. This provides a mechanism to evaluate alternative heat-storage systems and focus research on alternatives that can meet a certain set of minimum requirements.
- *Systematic evaluation of options*. We have not identified any systematic evaluation of heat storage options for sodium at the gigawatt-hour scale. This must start with a clear definition of the requirements and the basis for each requirement. This includes safety considerations that may not be a major challenge if storing a megawatt-hour, but may become a major challenge if storing gigawatt hours. Concentrated solar-power-tower heat storage will be at the gigawatt-hour scale while nuclear systems may have storage sizes that are an order of magnitude larger. As in certain chemical plants, safety can drive design as the scale increase.
- *Test facilities*. The history of sodium systems includes a very large number of failures due to thermal fatigue. Sodium is an extraordinary heat-transfer fluid because of its low viscosity and very high

thermal conductivity. The same properties have led to many cases of thermal-fatigue failure in piping, heat exchangers, and other components. A heat-storage system, by design, will go through thousands of temperature transients, many of these being relatively fast transients. This will likely impose the requirement to build a test facility with heat-input rates of megawatts to tens of megawatts with the full vertical dimensions of the heat-storage system to have high confidence in long-term system performance.

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4. HTGR HEAT STORAGE OPTIONS

4.1 HTGR Boundary Conditions

High-temperature gas-cooled reactors use graphite-matrix coated-particle fuel with high-pressure helium as the coolant. To minimize pumping power, there is a large temperature drop across the core. Typical HTGRs operate from 350 to 750°C. Advanced HTGRs may have exit temperatures near 900°C. Today, the Japanese operate the High-Temperature Test Reactor (HTTR), and the Chinese are starting up two commercial demonstration pebble-bed HTGRs.

4.2 HTGR Heat-storage Options

Five classes of heat-storage options are described. Only the first option is currently being developed. Three of the options store heat at reactor pressure. The other two options require heat exchangers to transfer heat from the helium system to a low-pressure system. In one case, it is to air and a hot-rock (or firebrick) storage system, and in the other case, it is to a liquid nitrate salt that is the heat storage media—essentially the same heat-storage system used in many concentrated solar-power systems today with gigawatt-hour storage capacity. The tradeoff is storing heat at reactor pressure versus using a heat exchanger to enable heat storage in a liquid or solid at low pressure, but with the higher losses associated with temperature drops across the heat exchangers.

Much work has been done on heat storage coupled to concentrated solar thermal systems [Pilkington Solar International GmbH 2000]. However, only a small fraction of this work is applicable to HTGRs because of the high temperatures. Existing concentrated solar power tower systems have peak temperatures near 500°C. This is changing. The research and development goals [Mehos 2017] for the next generation of solar-power towers are to have peak temperatures above 700°C. Because electricity price collapse occurs with large-scale deployment of solar (Chapter 2), all of these systems will include heat storage to enable electricity sales at times of higher prices. As a consequence, there is a growing overlap in heat-storage technologies for HTGRs and the next generation of higher-temperature solar-power towers.

4.2.1 Heat storage in the reactor core[b]

HTGR cores contain massive quantitate of graphite for neutron moderation and safety. Recent Japanese studies [Forsberg et al, 2017] propose to quickly vary power plant output by 20% relative to base load (Figure 4-1 and Figure 4-2) while the reactor fission-power output remains constant by allowing the reactor graphite fuel and moderator temperature to go up and down in temperature as a heat-storage medium. These studies are based on the proposed Gas Turbine High-Temperature Reactor (GTHTR300C). The rapid response is made possible by the direct-cycle gas turbine power-conversion system. In this particular reactor, the core of the 600 MWt HTGR has a thermal capacity of 373 MJ/K (373 MWs/K).

In the proposed system, the reactor core operates at base-load power at all times while producing variable electricity and variable hydrogen where (1) varying the reactor core temperature is used to provide rapid response to variable electricity demand and (2) varying hydrogen production is used to provide larger longer-term variation in the output of electricity to the grid. Hydrogen today is stored in underground caverns using the same technologies used for natural-gas production; thus, its rate of instantaneous production can be decoupled from demand.

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[b] This description with changes was extracted from reference [Forsberg 2017a]. The original description was written by X. Yan, a coauthor of that report.

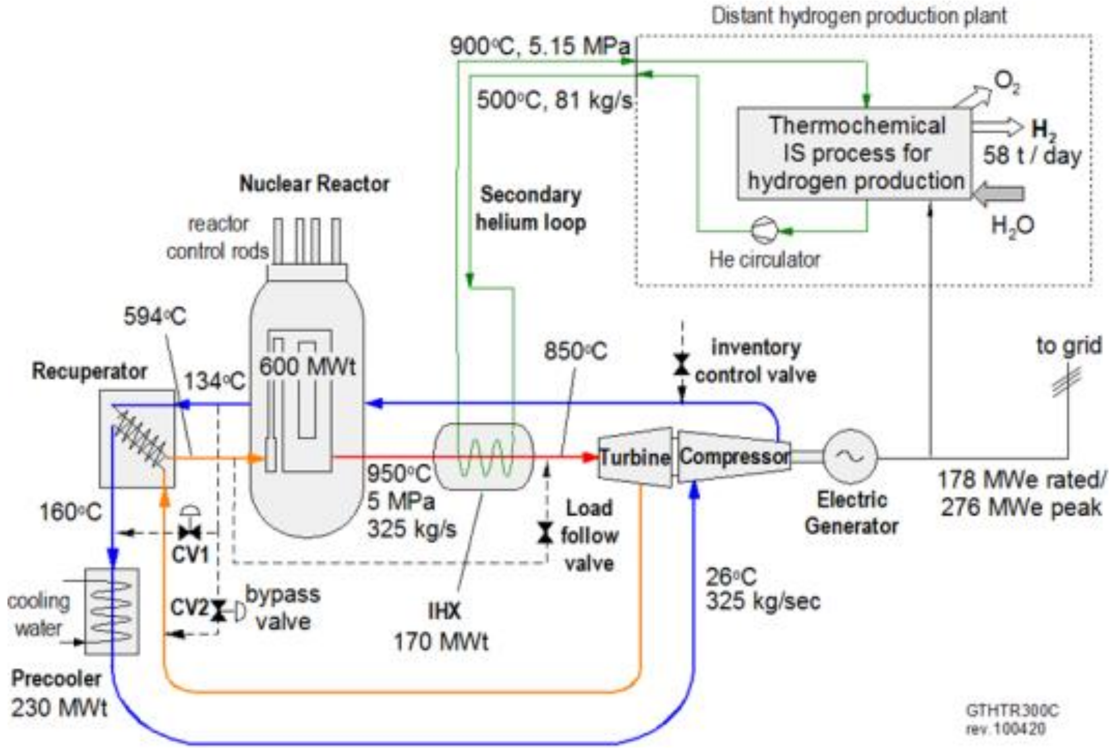

Figure 4-1. Schematic of GTHTR300C power system.

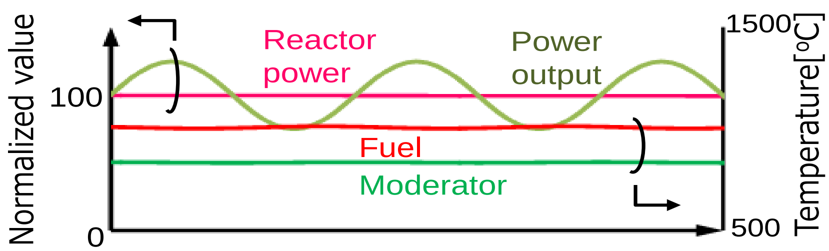

Figure 4-2. Reactor response to provide variable output on a minute scale.

The Japanese HTGR program has had long-term goals to develop a high-temperature reactor to provide high-temperature heat for industry, electricity production, and hydrogen production (Figure 4-3). The program built and operates the HTTR. The original goals did not include providing variable electricity to enable larger-scale integration of renewables into the electricity grid. Because of changing markets with the introduction of large-scale wind and solar, the Japanese have initiated studies in the last two years to examine this option.

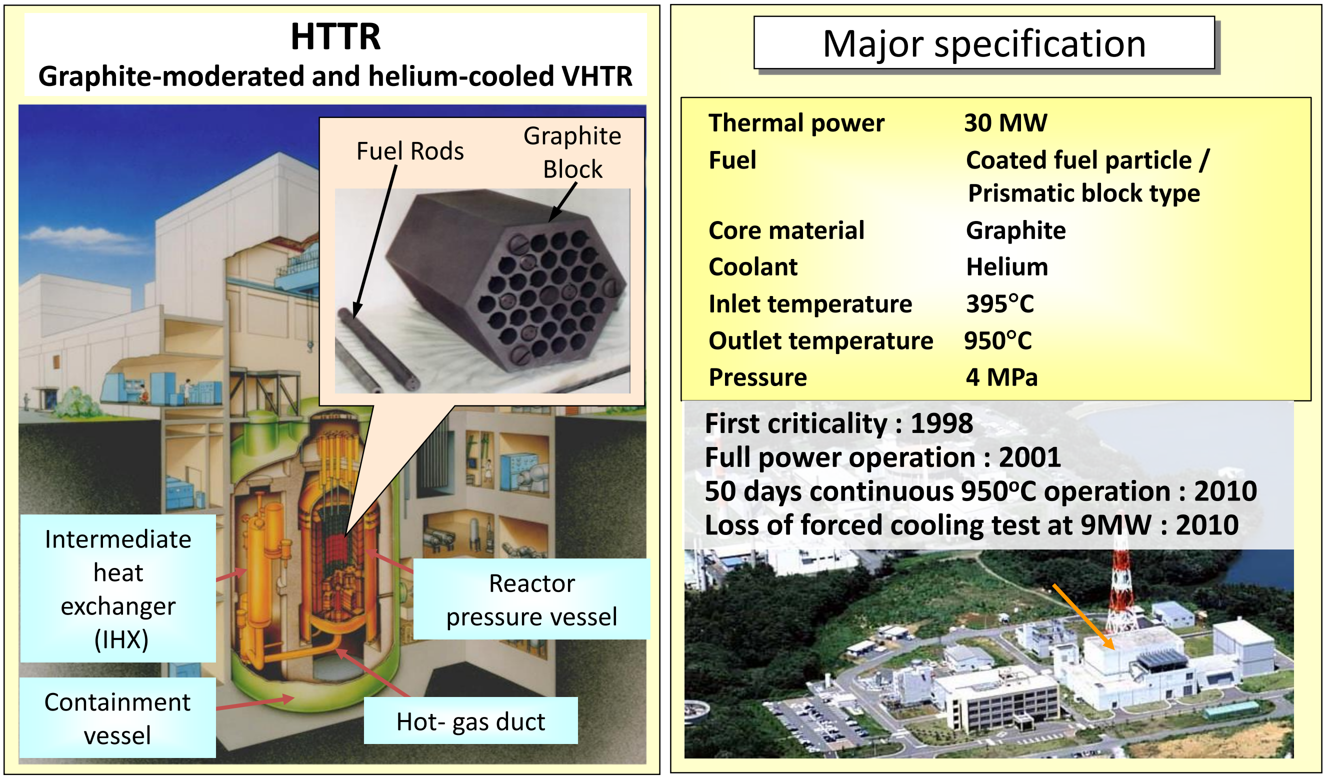

Figure 4-3. HTTR, a very-high-temperature test reactor constructed at JAEA Oarai R&D Center

Japan began development of an HTGR in 1970s [Saito 1994]. The development achieved its first milestone with completion of construction in 1998 of the 30 MWt HTTR [HTTR 2004]. Today the HTTR has achieved a series of successful runs (Figure 4-3, right) that have validated HTGR plant technologies, including fuel, structural graphite, metals, and operations and maintenance [HTTR 2004]. Performance features include high temperature (950°C) operation [Fujikawa 2004] and inherent safety for loss of forced coolant with reactor scram.

Based on the technologies developed as part of the HTTR and additional development for balance-of-plant technologies, the Japanese Atomic Energy Agency (JAEA) has proposed GTHTR300C, a Gen-IV very-high-temperature reactor (VHTR) design, as depicted in Figure 4-4 [Kunitomi 2007]. Along with power generation by direct cycle helium-gas turbine, the system has flexibility for a range of cogeneration applications, such as hydrogen production and desalination [Yan 2014]. Table 4-1 summarizes major technical parameters and production performance.

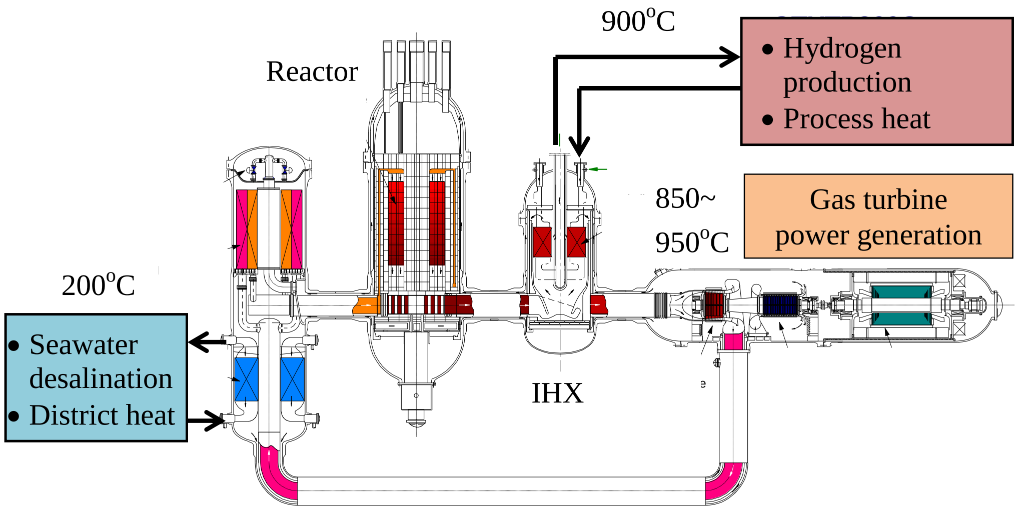

Figure 4-4. Japan`s VHTR system, GTHTR300C, with cogeneration options.

Table 4-1. Major technical parameters of the GTHTR300C.

Technology developer	JAEA with Mitsubishi Heavy Industries, Toshiba, Fuji Electric, Nuclear Fuel Industry, IHI, Kawasaki Heavy Industries, etc.	
Reactor type	Prismatic HTGR	
Reactor thermal power per unit (MWt)	600	
Reactor coolant temperature (°C):	950	Reactor coolant temperature (°C):
Electric power generation [Takei 2006, Sato 2014, Yan 2016]		
Net power generation (MWe)	302	274
Net generation efficiency (%)	50.4	45.6
Cost of electricity ($/MW)	2.87	3.20
Hydrogen cogeneration [Kasahara 2017]		
Power generation rate	204	
H_2 production rate [Nm^3/h]	31,863	
H_2 production efficiency (%)	50.2	
Desalination cogeneration		
Power generation (MWe)	302	274
Desalination (m^3/d)	49,46 0	54,550
Overall cogeneration efficiency (%)	87%	84%
Design capacity factor	>90%	
Design life (years)	40–60	
Coolant:/moderator	Helium/graphite	
Moderator	Graphite	

Primary circulation	forced circulation
System pressure	5–7 MPa
Reactivity control mechanism:	control rod
RPV height/diameter (m)	23/8
Integral design	No
Power conversion process	Direct Brayton cycle
Distinguishing features	Multiple cogeneration applications: electricity, hydrogen production, process heat supply, steelmaking, desalination, district heating.
High temperature process heat	Yes
Low temperature process heat	Yes
Design configured for process heat applications	Yes
Safety features	Inherent
Fuel type/assembly array	UO_2 TRISO ceramic coated particle
Fuel block length (m)	1
Number of fuel columns in core	90
Average fuel enrichment	14%
Average fuel burnup (GWd/ton)	120
Fuel Cycle (months)	36–48
Number of safety trains	2
Emergency safety systems	Inherent
Residual heat removal systems	Inherent
Refueling Outage (days)	30
Modules per plant	Up to 4 reactors
Estimated construction schedule (months)	24–36
Seismic design	>0.18 g automatic shutdown
Predicted core damage frequency	$<10^{-8}$/reactor year
Design Status	Basic design: HTTR and equipment validation

JAEA is developing the GTHTR300C based on the HTTR test reactor [Yan 2017]. The test plant of HTTR with gas turbine and hydrogen production aims to (1) demonstrate the capability of the GTHTR300C nuclear cogeneration commercial system described above for licensing, (2) confirm the operational control and safety of such a cogeneration system, and (3) improve accuracy of cost estimation for the cogeneration system. Construction and operation completion is scheduled for ~2030, and the test plant is expected to be the first of a kind HTGR-powered cogeneration plant operating on the two advanced energy conversion systems: a closed-cycle helium-gas turbine for power generation and a thermochemical iodine-sulfur water-splitting process for hydrogen production.

The ability of GTHTR300C to absorb unsteady power changes at various time scales in renewable energy for the purpose of grid stability was evaluated for the hybrid system, as shown in Figure 4.5.

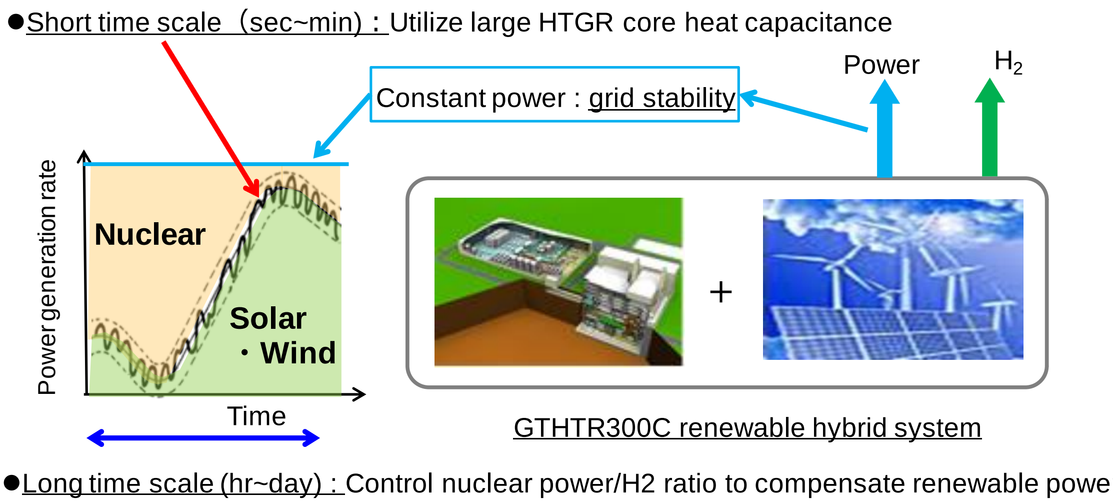

Figure 4-5. HTGR renewable energy hybrid system for grid stability.

4.2.1.1 Varying electricity output: hours to days

In response to variations in electricity demand over ranges between hours and days, the following strategies are employed for the control of nuclear plant. The goals are to maximize nuclear plant economics while minimizing undesired impact of frequent load-following on the nuclear reactor:

(a) Maintain constant reactor thermal power operation
(b) Minimize transient thermal stress in reactor internal components
(c) Minimize transient thermal stress in turbine blades
(d) Maintain the high thermal efficiency of power generation.

Four control methods are integrated in the design of an automated control system for the GTHTR300C:

(a) Reactor-coolant inventory control
(b) Turbine inlet-temperature control
(c) Heat exchanger heat-rate control
(d) Reactor outlet-temperature control.

In response to hourly/daily variations in electricity demand, the nuclear reactor's helium coolant is taken in or out of the primary circuit using coolant inventory-control system. Simultaneously, the heat exchanger heat rate for the hydrogen plant is adjusted by secondary helium flow rate. In addition, the load-follow control valve is adjusted to keep turbine inlet temperature unchanged. This sequence of controls was evaluated by RELAP5 simulation with the results in Figure 4-6. As seen, the reactor power and power-generation efficiency are kept constant at all time as intended.

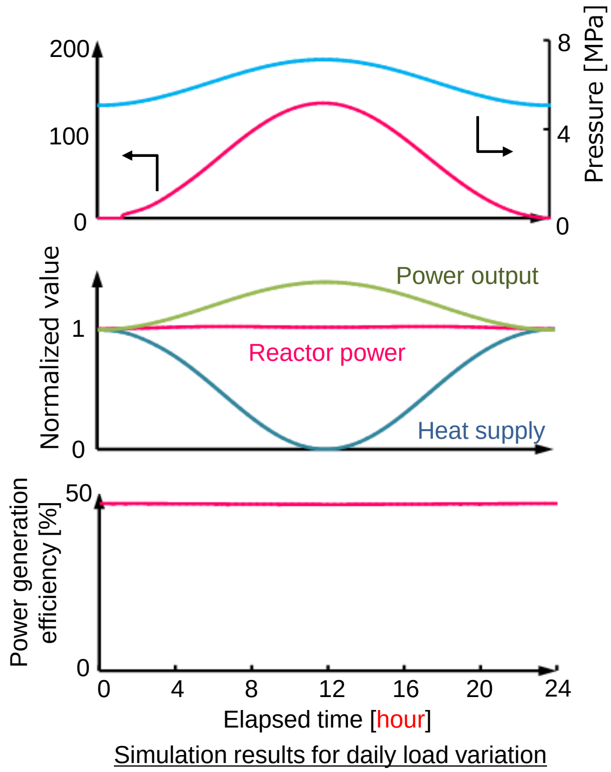

Figure 4-6. Reactor response to daily renewable-power-generation variation.

4.2.1.2 Varying electricity output: seconds to minutes

The operation strategy for rapid variation in electricity demand (seconds to minutes) takes advantage of an intrinsic design feature of the HTGR core: large thermal capacitance due to the massive amount of graphite used in the reactor core. For example, the core of the 600 MWt HTGR has a thermal capacity of 373 MJ/K.

The turbine speed is kept constant by coupling to the electricity grid. In case of absence of a large grid, turbine speed will be maintained by turbine flow bypass valve (CV1 in Figure 4-1). Furthermore, the power control rods are not moved in response to small changes of reactor outlet coolant temperature encountered, assuming that the power variation at short time scale is limited within ±20% of nuclear rated power.

Figure 4-7 shows a simulation of nuclear reactor operation to renewable power change at the minute scale, and Figure 4-8 simulates the same changes at the second scale. As can be seen, the reactor fission thermal power remains essentially constant at all times while the power generation of the reactor is varied by the extraction and storage of the heat in the reactor core to increase or decrease turbine power-generation output. Power generation efficiency is slightly changed because of the turbine bypass used to maintain turbine speed if the reactor is not connected to a large external grid.

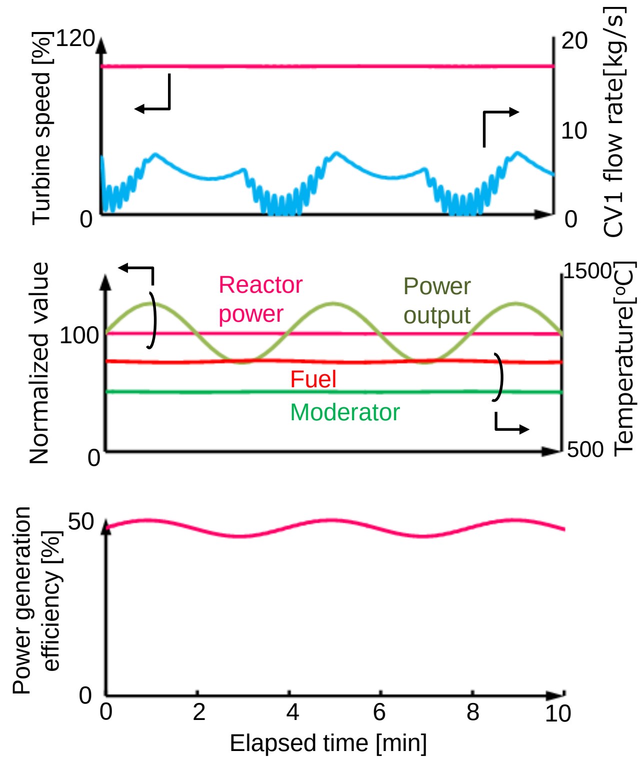

Figure 4-7. Reactor response to renewable power generation variation of minute scale.

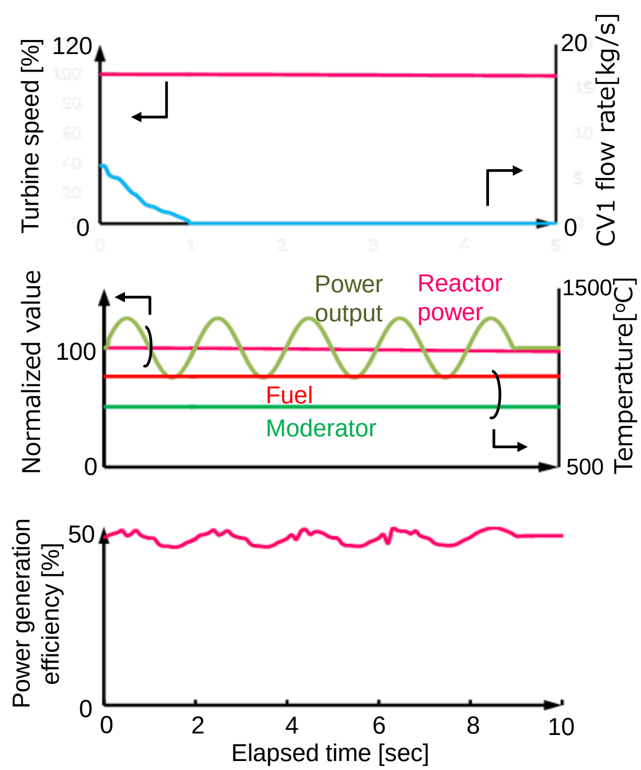

Figure 4-8. Reactor response to renewable power generation variation of second scale.

4.2.2 Secondary pressure vessel with solid sensible heat storage

In the industrial world, heat recuperators are used to store high-temperature heat. For example, recuperators are used in glass furnaces where natural gas is burnt to produce hot gases that heat the feed materials and convert those materials into a homogeneous molten-glass solution. The hot exhaust gases go through a firebrick recuperator where the gas is cooled before being sent to the stack. The recuperator is made of firebrick with gas-flow channels. As the hot gas flows through the recuperator, the firebrick is heated to a high temperature. When the recuperator is fully charged, air flow is reversed, and cold air is pumped through the recuperator. Natural gas is injected into the hot air as it leaves the recuperator to further raise its temperature before entering the furnace to melt glass. This saves energy. This technology has been used in various forms to store heat for centuries in the production of glass, steel, and other high-temperature materials.

The same technology can be applied to an HTGR for heat storage (Figure 4-9). The major difference is that the recuperator is inside a pressure vessel at reactor pressures. The reactor operates at base-load, constant power output. At times of low heat demand, some fraction of hot helium leaving the reactor core is diverted to a recuperator, goes through the recuperator, is cooled, and is sent back to the reactor core. The remainder of the hot helium goes to the power system or a heat exchanger to provide heat to industry. At times of high heat demand, hot helium from the reactor core and hot helium from the recuperator go to the power system or heat exchangers to provide heat to industry. The big advantage of this heat-storage system is that temperature losses are minimized in storing heat. The major disadvantage is that the entire heat-storage system is in an expensive pressure vessel.

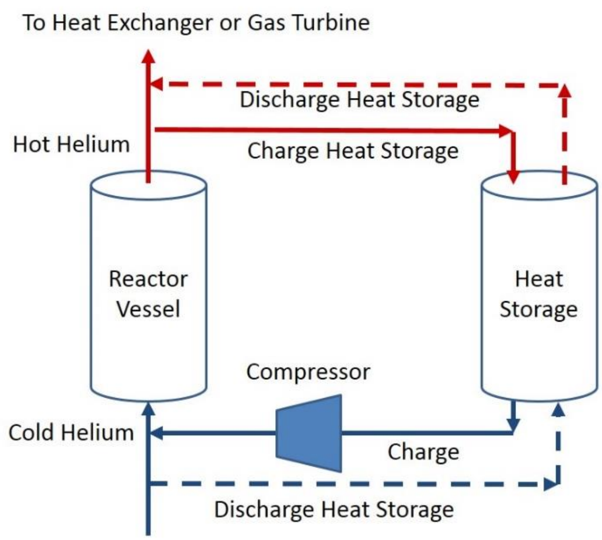

Figure 4-9. Simplified schematic of sensible heat storage coupled to HTGR.

Alternatively, a packed bed with different filler materials is considered. It would heated to store energy and cooled to release energy. There are many other geometric options for the recuperator. The filler materials considered were cast steel, gray cast iron, alumina (Al_2O_3), magnesia fire brick, silica fire brick, and carbon as graphite. Table 4.2 presents the properties and unit costs of these materials (Herrmann and Kearney (2002), Klein et. al. 2015, Valencia et. al. 2008, Auerkari 1996, Khare et. al. 2015, McEligot et. al. 2016, Focus Graphite 2015). The properties are averaged over the operating temperature range (450°C–750°C).

Table 4-2. Filler material properties.

Filler material	Specific heat (kJ/kg-K)	Density (kg/m³)	Thermal conductivity (W/m-K)	Volumetric Heat Capacity (kWh/m³)	Unit cost ($/kg)	Unit Cost ($/m³)
Cast steel	0.603	7600	27.4	3833	5	39616
Gray cast iron	0.66	6992	29	4615	1	9090
Alumina	1.207	3900	7.96	3544	1.3	5499
Magnesia fire brick	1.15	3000	5	3450	2	6000
Silica fire brick	1	1820	1.5	1820	1	1820
Carbon	0.94	2230	71.78	2096	1	2230

We assume a heat-storage system the same size as the reactor and a pebble bed heat-storage system. The General Atomics gas turbine modular helium reactor has a thermal power output of 600 MW_{th}. The vessel outer diameter is 8.2 m, the height is 31 m, and the wall thickness is 281 mm (Miza 2008). The volume of this vessel is calculated as,

$$V_{vessel} = \frac{\pi}{4}(OD - 2t)^2 H$$

where OD is the outside diameter, t is the wall thickness and H is the vessel height. The mass of filler material is dependent on the fraction of space in the vessel occupied by filler material. The void fraction is used in calculations to account for this. The void fraction is the ratio of volume in the bed not occupied by filler material to the total volume of the pressure vessel.

$$\epsilon = \frac{V_{void}}{V_{total}}$$

$$1 - \epsilon = \frac{V_{filler}}{V_{total}}$$

A typical void fraction for a packed bed of spherical particle is 0.363 (Torquato et al. 2000). The mass of the filler material is then,

$$M_{filler} = \rho_{filler} V_{vessel}(1 - \epsilon)$$

The thermal energy capacity of this pressure vessel using different filler materials is then calculated. The thermal storage capacity, TSC, of a system is,

$$TSC = M_{filler} C_p \Delta T$$

Where ΔT is the temperature difference between the fully charged and fully discharged state of the TES. The fully charged temperature was taken as 750°C, and the fully discharged temperature was taken as 450°C. The volumetric energy density of a packed-bed thermal energy storage (TES) is calculated using the given TSC and the total volume of the pressure vessel (the inner volume of the pressure vessel and the volume of the pressure vessel wall).

$$volumetric\ energy\ density = \frac{TSC}{\frac{\pi}{4}(OD)^2 H}$$

The height and diameter of the vessel are optimized to find the lowest cost for the pressure vessel (assumed to be made of 304 stainless steel), with the following constraints:

$$\frac{M_{filler}}{\rho_{filler}}(1-\epsilon) = \frac{\pi}{4}D^2H$$
$$Bi < 0.1$$

Where, ϵ is the void fraction for packed beds (assumed value of 0.36).

The specific energy-storage density is calculated using the mass of the filler material and the mass of the pressure vessel.

$$specific\ energy\ density = \frac{TSC}{\rho_{steel}\left(\frac{\pi}{4}(OD^2-(OD-2t)^2)H + t\frac{\pi}{4}OD^2t\right) + M_{filler}}$$
$$Specific\ energy\ density = \frac{TSC}{M_{total}}$$

M_{total} is the total mass,

$$M_{total} = M_{filler} + M_{vessel}$$

M_{vessel} is the mass of the pressure vessel and is dependent on the volume of steel in the vessel wall. The volume of steel is

$$V_{vesel\ wall} = \underbrace{\frac{\pi}{4}((D+2t)^2 - D^2)h}_{side\ walls} + 2 * \underbrace{\frac{\pi}{4}(D+t)^2 * t}_{top\ and\ bottom}$$

where D is the inner diameter of the vessel, t is the thickness of the vessel and h is the inner height of the vessel. The thickness is dependent on the vessel diameter and height. The mass of the vessel is

$$M_{vessel} = V_{vessel\ wall}\,\rho_{steel}$$

ρ_{steel} is the density of 304 steel taken as 7800 kg/m^3. The mass of the filler is found from the TSC,

$$M_{filler} = \frac{TSC}{C_p \Delta T}$$

ΔT is the temperature difference between high and low storage temperature and C_p is the filler material's specific heat capacity. Figure 4-10 shows the specific energy density per unit mass, and Figure 4-11, the volumetric energy storage density for MWh systems.

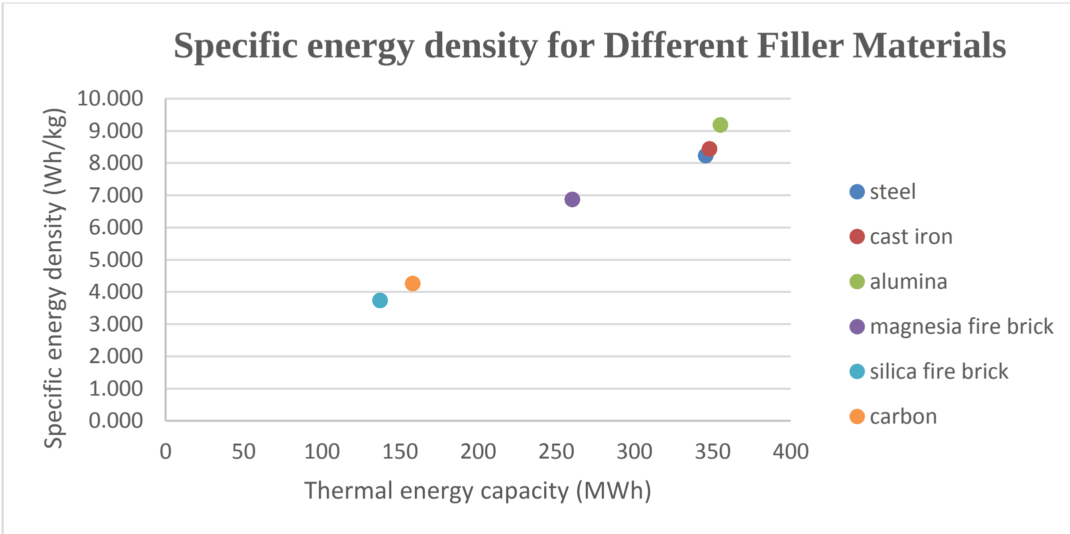

Figure 4-10. Specific energy density for megawatt-hour scale thermal energy storage system with filler materials.

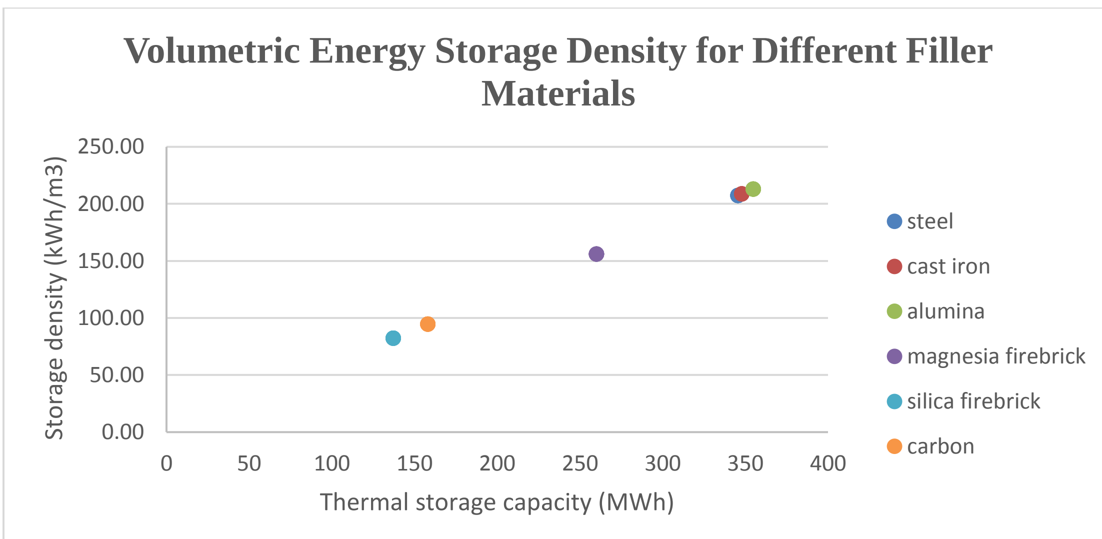

Figure 4-11. Energy storage density for megawatt-hour scale thermal energy storage system, assuming 300°C temperature difference and 64% of the vessel volume is the heat storage material.

As a point of comparison, the next-generation nuclear plant (NGNP) was being developed by the United States. This HTGR had a power output of 600 MWt. The pressure vessel volume was 1420 m^3 (Mizia 2008). If the heat storage vessel were the same size as the reactor vessel, with an allowable 300°C temperature swing, and the fill material were alumina with a fill fraction of 64%, the heat storage capacity would be 354 MWh.

Much larger pressure vessels for heat storage can be built using prestressed concrete reactor vessels. General Electric and RWE AG have been developing an adiabatic compressed-air storage system (ACAS) for electricity storage (Zunft 2014). In an ACAS system (Figure 4-12), at times of low electricity prices, air is adiabatically compressed to 70 bars and sent through a firebrick recuperator to lower the air temperature from 600°C to ~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 to recover heat from the recuperator and is sent to a turbine to produce electricity. The round-trip efficiency of electricity to stored energy (heat and compressed air) to electricity is about 70%. It is a thermal energy storage system equivalent to a battery or pumped hydroelectric facility.

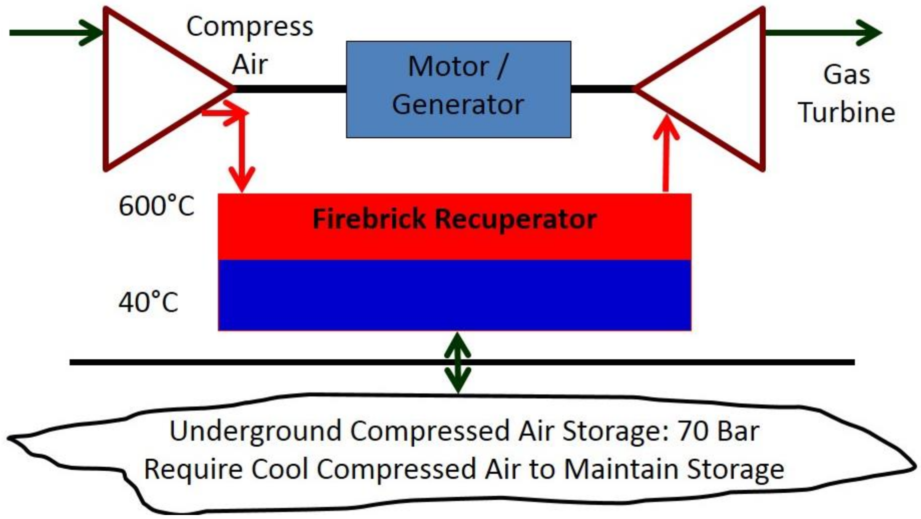

Figure 4-12. Adiabatic compressed-air storage system.

Figure 4-13 is a schematic of the ACAS firebrick heat-storage system, and the laboratory experiments for the design of a concrete pressure vessel for the firebrick. Significant experimental work has also been done on the recuperator that must operate at gas turbine pressures—similar to the pressures inside both an HTGR and the storage systems we are considering. This project has done much of the work that would be required to integrate large-scale heat storage into an HTGR at the multi-gigawatt hour scale.

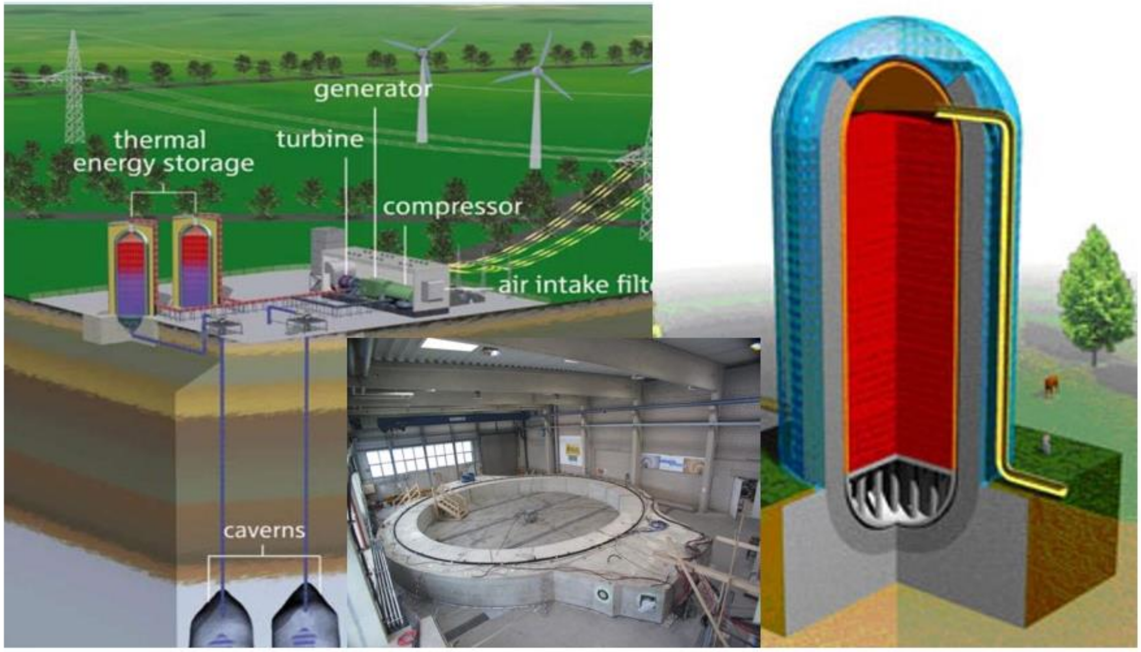

Figure 4-13. Project Adele system, laboratory section of prestress pressure vessel and schematic of the pressure vessel. Courtesy of General Electric, RWE AG, and Zublin.

With large-scale heat storage, there is the option of adding electric-resistance heaters to heat the storage media at times of low electricity prices in addition to heat input from the HTGR (Forsberg 2017c).

In a design, there are a series of cost and performance tradeoffs. Storage size that is partly dictated by market considerations may determine whether steel or prestressed concrete storage vessels should be used. If a steel vessel is used, the heat storage vessel can run hot or have internal insulation allowing use of lower-cost metals of vessel construction. A concrete vessel's insulation must be on the inside. Alumina has a high volumetric heat capacity, but low thermal conductivity that implies slower heat transfer. Metals have high thermal conductivities, but high densities, implying a very heavy vessel. There will be some radionuclide transfer from core to the heat-storage system; thus, the behavior of these radionuclides and long-term implications must be considered. Last, there are both good and bad impacts on possible accident scenarios. If system integrity is maintained and there is a loss of decay-heat removal systems, the heat-storage system could be a massive decay heat sink. If there is a pipe break, there will be an added inventory of helium in the blow down relative to a normal HTGR. An option to design the heat-storage system to minimize the high-pressure gas inventory would be possible.

4.2.3 Secondary pressure vessel with latent heat storage

There is the option to use latent heat-storage materials inside the heat-storage pressure vessel as discussed in the previous section (Figure 4-14). Heat is stored by melting a solid at a constant temperature. The incentive is that the heat storage per unit volume can be an order of magnitude greater than with sensible heat storage—drastically reducing the size of the pressure vessel per unit of heat stored. Latent heat storage is used in systems where there are incentives to minimize volumes. There are major challenges for such systems coupled to an HTGR.

- *Stacked latent-heat systems*. HTGRs have very large temperature differences from inlet to outlet. Efficient heat storage requires several latent heat materials at different melting points. For example, in an ideal three-component system, the melting points might be 450, 550, and 650°C to store heat over the total range of temperatures. Finding low-cost materials for such a range of temperatures will be challenging.

- *Thermal expansion*. Most materials experience thermal expansion in melting. For atmospheric-pressure latent-heat systems, the latent-heat material is often put into a sealed container with some gas space at the top of the container to provide expansion space. In an HTGR, large swings in temperature and pressure between refueling and operations must be addressed.

Whether low-cost materials for a practical system can be built is unclear. No studies have been found that have examined the options.

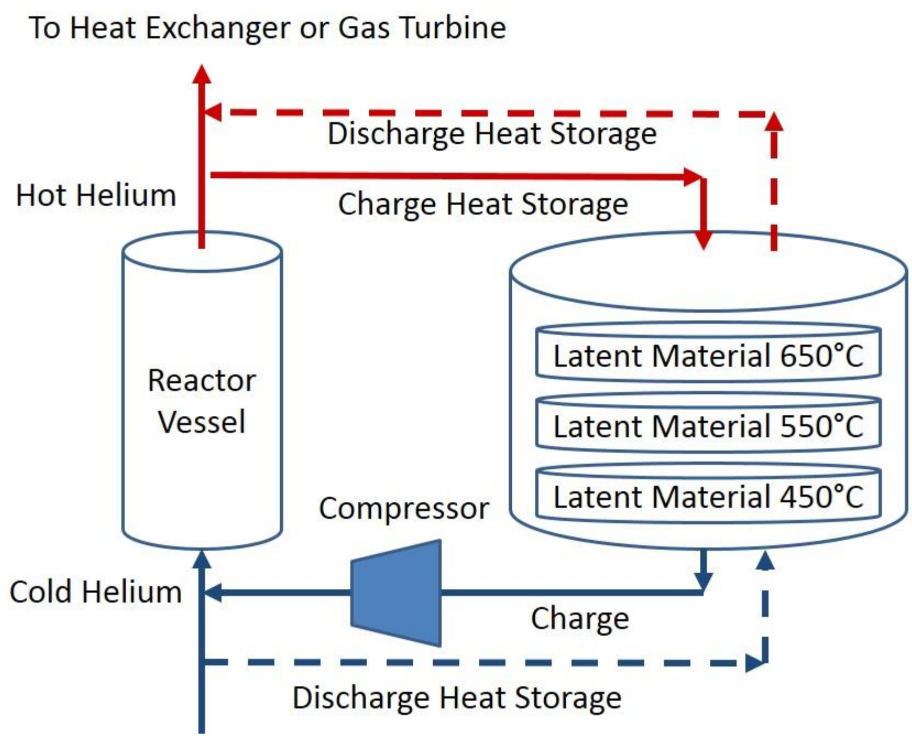

Figure 4-14. Stacked latent heat storage for pressure vessel.

4.2.4 Hot-rock heat storage

In a hot-rock energy storage system a volume of crushed rock with air ducts at the top and bottom is created (Figure 4-15). To charge the system, air is heated using a helium-to-air heat exchanger delivering heat from the reactor, then the hot air is circulated through the crushed rock, heating the rock. To discharge the system, the airflow is reversed, and cold air is circulated into the crushed rock at the bottom. The discharged hot air is sent to a boiler to produce steam that can be used to produce electricity or heat for industry. The cooler air from the boiler is returned to the hot-rock storage system to avoid sending warm air up the stack. Because the product of the hot-rock heat-storage system is hot air, if heat storage becomes depleted, there is the option to provide hot air to the steam generator by burning fuel to produce electricity. This provides assured generating capacity.

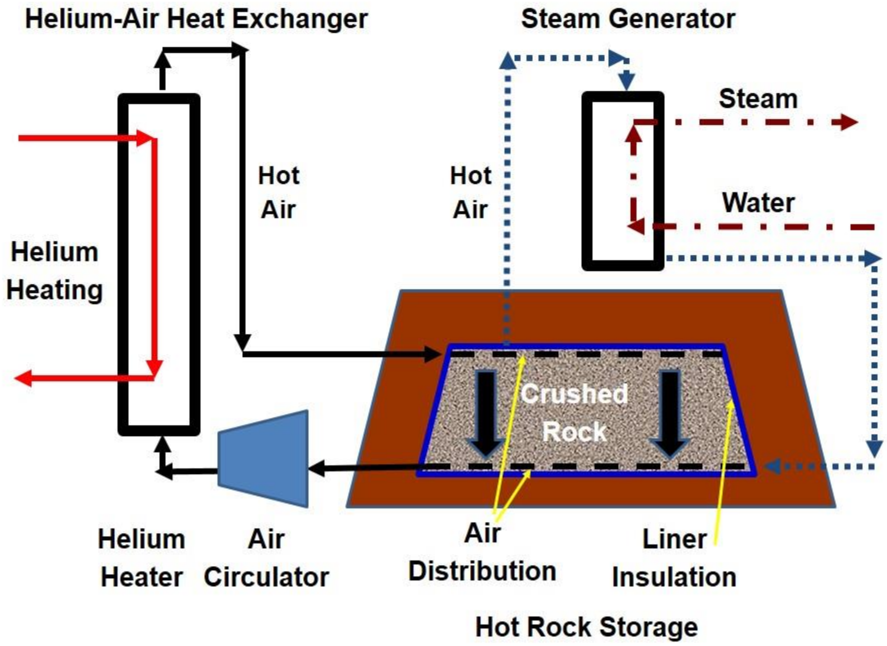

Figure 4-15. Hot-rock storage coupled to HTGR (solid lines and arrows indicate the charging mode.)

There are many variants of hot-rock storage, including using firebrick recuperators where the crushed rock is replaced by firebrick. The geometry is better controlled with lower-pressure drops across the heat storage media, but this entails higher costs. Hot-rock storage has the lowest incremental heat storage costs per kWh.

No work has been done on hot-rock storage coupled to an HTGR. There have been studies of hot-rock storage coupled to light water reactors [Forsberg 2017b, McLachlan 2018]. Several versions of this technology are under development for different purposes. Siemens [2017] in Germany is constructing a hot-rock heat-storage system where the air is to be heated by electric-resistance heaters using low-price electricity generated by wind before being blown through the crushed rock. For power production, cold air flows through the rock, is heated, and is fed to a steam boiler to produce steam for electricity production at times of high electricity prices. In effect, this is the same as the system envisioned for HTGRs, except the helium-to-air heat exchangers are replaced by electric resistance heaters. This is one variant of a family of concepts where the air is heated by various hot fluids (oil, salt, carbon dioxide, steam) from concentrated solar power systems or electricity. The hot air is then used to heat the rock, which serves as the storage media. A 100 kW test of the CellFlux concept [Steinmann 2014] (one variant) has been tested [Odenthal 2015]. There have also been tests to 800°C with another hot-rock variant with a variety of different rock types [Schroder 2018].

Red Leaf Resources [2018] is developing an oil-shale process where oil shale is crushed and placed in piles approximately 30 meters high. Hot gas is blown through the crushed hot rock to heat it up, decomposing the kerogen and releasing shale oil. It is a one-time process, but similar physics—heating crushed rock with hot gas at atmospheric pressure. Large-scale experiments are underway.

Hot-rock heat storage is also being experimentally investigated [Allen 2014, Koekemoer 2015, Barton 2013, Zanganeh 2012, Ha’nchen 2011, Jemmal 2016, Allen 2015, Laubscher 2017] for direct use with concentrated solar-power towers. In these applications, concentrated light would heat ceramic structures cooled by incoming air. The hot air would be sent directly to the hot-rock storage system. While the pumping power for air is higher than in solar-power towers with liquid coolants, air cooling with ceramic absorbers would avoid the normal temperature limits associated with the receivers. As with other systems, heat is recovered by blowing cold air through the hot rock to a steam boiler to produce electricity.

There are several observations from the various experimental programs. The capital costs of heat storage are very low. Many of the experimental challenges and inefficiencies become much smaller as the capacity increases such as heat losses. The system is well behaved with vertical gas flow with hot air in at the top and cold air out at the bottom. There has been significant work on horizontal gas flow options to avoid the need for the air inlet/outlet structure's supporting the full weight of rock, but major losses in efficiency are caused by stratification of hot air toward the top of a system with horizontal flow.

In the context of heat storage coupled to an HTGR, the major question is the cost of the helium to atmospheric-air heat exchanger, a gas-to-gas heat exchanger that will be large. The very low incremental cost of crushed rock may favor the use of this system where wind causes electricity price collapse because this tends to occur on a multi-day cycle that implies incentives for large storage.

4.2.5 Liquid-salt heat storage

Molten salts (mainly nitrate salts) have been used for thermal energy storage in concentrating solar power plants (CSPs) for decades and have proven to be an effective means of allowing CSPs to maximize electricity sales at times of high prices. Several salt storage concepts exist, but the most common concepts are two-tank direct and two-tank indirect thermal energy-storage systems. In a solar system, a two-tank direct system (Figure 4-16) functions by (1) pumping cold salt from the power cycle and/or out of a cold storage tank, (2) circulating the salt through a field of parabolic trough mirrors or to a solar-power tower where it is heated, and (3) sending the hot salt to a hot-salt storage tank and/or the power cycle. The larger systems store over a gigawatt-hour of heat.

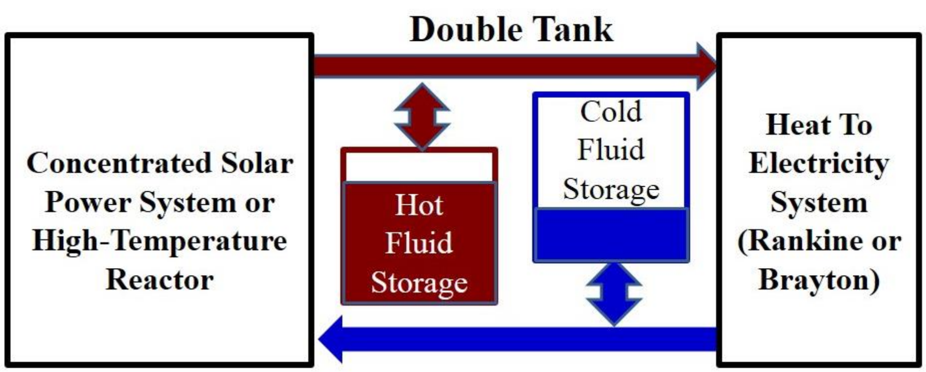

Figure 4-16. Two-tank heat-storage system.

The salts used in existing CSP applications are not stable at temperatures much above 600°C. The most common salt used in CSP plants is solar salt, a mixture of potassium nitrate and sodium nitrate (60% KNO_3 and 40% $NaNO_3$) which melts at 220°C and is unstable above 600°C (Kearney et. al. 2003). Solar salts can be used as a storage media for an HTGR, but they would not be able to store heat at the high outlet temperatures of the reactor (more than 750°C), and some of the improved thermal efficiency from higher outlet temperatures may be lost.

Molten salts used as reactor coolants are stable at temperatures above 750°C. One of the potential salts is FLiNaK, which has superior heat transfer properties compared to nitrate and chloride salts. FLiNaK is a mixture of 46.5% LiF, 11.5% NaF, and 42% KF; it has a melting point of 454°C and can operate above 750°C (Sohal et. al. 2013). However, it is relatively expensive. Another salt candidate is a mixture of 67% KCl and 33% $MgCl_2$ and has a melting point of 426°C; it is stable at temperatures above 750°C, although it has a higher vapor pressure then FLiNaK (Sohal et. al. 2013). The limitation on these salts is that freezing points are above the minimum helium temperatures in gas-cooled reactors. Table 4-3 presents the thermophysical properties of several of these molten salts.

Table 4-3. Storage temperatures and properties of the candidate salts averaged over their operating temperatures (Williams 2006, Sohal et al. 2013).

Salt	Melting temperature (°C)	Maximum temperature (°C)	Specific heat (kJ/kg-K)	Density (kg/m^3)	Cost ($/kg)	Cost ($/kWh)
Solar salt	220	600	1.50	1707	0.49	8
FLiNaK	454	>900	2.22	1872	11.3	97
KCl-$MgCl_2$	426	>900	1.15	1464	0.21	12

In the last several years, new chloride salts have been investigated that may prove superior for HTGR heat storage. These salts have lower costs and can go to much higher temperatures than nitrate salts. They are the leading candidates for the higher-temperature solar-power towers. In the U.S., the primary focus is on a sodium-potassium-magnesium chloride salt [Mehos 2017, Mohan 2018, Mohan et al 2018] for advanced high-temperature solar-power towers with operating temperatures above 700°C—significantly above the temperatures of solar power towers using nitrate salts. This salt has recently become the leading candidate for high-temperature solar-power tower systems for two reasons: (1) good physical properties, including melting point and (2) very low cost, enabling very-low-cost heat storage. There are significant uncertainties including controlling salt chemistry to minimize corrosion. The eutectic salt composition with a melting point of 383°C has a composition of 24.5 wt% NaCl, 20.5 wt% KCl and 55 wt% $MgCl_2$. If the temperature swing in storage is 200°C, the storage cost with this salt is estimated at $4.50/kWh, below that of nitrate salt storage or any other liquid heat-storage system that has been identified to date. The salt is highly hydroscopic, and water will react with the magnesium chloride. The melting point is near the inlet temperatures of current designs of HTGRs; thus, the use of such salts implies either higher inlet temperatures to the HTGR or some other change in the power system design.

A very-low-cost liquid for heat storage over the total temperature range of an HTGR would be ideal. No such liquids have been identified, but it may be that no systematic search for such liquids to match HTGR requirements has yet been made.

4.3 Observations and Conclusions

Heat storage in HTGRs is enabled by the large temperature rise across the reactor core that implies a large hot-to-cold temperature change in heat storage. If sensible heat storage is used, this implies a high volumetric heat capacity. The challenge is that HTGRs operate at high pressure, which places the storage media at high pressures or imposes a requirement for a large heat exchanger between the coolant and heat-storage system, with associated temperature losses.

Very little work has been done on heat storage coupled to HTGRs. No economic studies have evaluated and compared various heat-storage options coupled to HTGRs. The only detailed engineering studies on HTGR heat storage are those associated heat storage using the reactor cores that are underway in Japan.

The near-term heat-storage option is the use of low-pressure nitrate molten salts, a system used at the gigawatt-hour scale in some CSP systems. However, the peak temperatures are limited to slightly above 600°C. A better understanding of peak temperature limits for nitrate salts is needed for industrial systems—a need shared by other users of nitrate heat storage. The longer-term option is the use of chloride salts, but the challenge here is their higher melting points. No assessment of salts to match HTGR temperatures has come to light.

Storing heat at high pressures is potentially attractive for HTGRs, but that requires either steel or prestressed concrete vessels. The same technology is needed for ACAS [Siemens 2017] and for several advanced gas-turbine cycles [Forsberg 2017c, Forsberg 2018]. This creates significant incentives to develop this technology, recognizing that there are multiple potential customers. The challenge is development of a technology where the benefits may be very large, but the benefits are for several different customers who individually may not be able to justify such a development program.

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5. SALT SYSTEM HEAT STORAGE OPTIONS (LOW PRESSURE, SMALL DELTA T ACROSS CORE)

Salt reactor systems include (1) FHRs, with clean salt coolants and graphite-matrix coated-particle fuel, and (2) MSRs, with the fuel dissolved in the salt. Thermal neutron spectrum MSRs use fluoride salts with their low nuclear cross sections. Fast neutron spectrum MSRs may use fluoride or chloride salts.

5.1 Salt Boundary Conditions

The unique feature of salt-cooled reactors is the higher average delivered temperature to the power cycle or industry: ~650°C (inlet/outlet temperature: 600/700°) as shown in Table 5-1. This has major implications in terms of heat delivery to industry and electricity production, considering the system requirements for (1) heat storage, (2) assured peak electric-generating capacity and (3) ability to convert excess low-price electricity into high-temperature stored heat for later use. A recent report (Forsberg 2018b) reviewed heat storage technologies that couple to salt-cooled reactors and alternative power cycles. It provides additional information on salt-reactor storage options.

Table 5-1. Typical reactor coolant temperatures.

Coolant	Average Core Inlet Temperature (°C)	Average Core Exit Temperature (°C)	Average Temperature of Delivered Heat (°C)
Water	270	290	280
Sodium	450	550	500
Helium	350	750	550
Salt	600	700	650

Salt reactors can efficiently couple to Brayton power cycles with thermodynamic topping cycles. The incremental heat-to-electricity efficiency of the topping cycle may exceed 70%, substantially above a stand-alone natural-gas combined cycle plant. The heat input of the topping cycle can be burning a fuel (natural gas, biofuels, ultimately hydrogen) or very-high-temperature stored heat made from low-price electricity. That is, there is a potential electricity-to-heat-to-electricity storage option with the low cost of heat storage and efficiencies that are similar to electricity storage technologies such as pumped hydroelectric storage.

In a Brayton power cycle, air is compressed, heated, and sent through a turbine to produce electricity. With typical Brayton power cycles, the air temperature after compression is near 400°C. If nuclear heat is to be used, the temperature of the delivered heat must be considerably above this temperature, i.e., above the temperatures of LWRs. Salt-cooled reactors couple more efficiently to Brayton cycles than other reactors because that is what they were originally developed to do. The original molten salt reactor was developed as part of the U.S. Nuclear Aircraft Propulsion program in the 1950s. The goal was a jet-powered aircraft. The requirements of the jet engine (Brayton power cycle) defined the requirements for the reactor that led to development of salt-cooled reactors. What has changed are the advances in Brayton power cycles that make these power cycles practical for electricity production. For this class of reactors, heat storage in the Brayton power cycle may be as likely as heat storage in an intermediate heat-transfer loop.

Nuclear Brayton power cycles enable peak electricity production using auxiliary fuels (natural gas, biofuels, and ultimately, hydrogen or stored heat) with incremental heat-to-electricity efficiency that is greater than any other technology. That is, more electricity is produced with less auxiliary fuel. In each of these power cycles, with base-load operation, the power-cycle fluid (e.g., air or steam) is heated to near 700°C and sent to turbines to produce electricity. For peak electricity production, that fluid after nuclear heating is further heated by adding a combustible fuel or stored heat to raise the temperatures to between 1100 and 1500°C before being sent to a gas turbine. The combustible fuel is part of a thermodynamic topping cycle with auxiliary heat-to-electricity efficiency near 70%. There are multiple examples of these cycles:

- *Nuclear Air Brayton Combined Cycles.* These are variants of natural-gas combined cycles where the reactor operates at base load using nuclear heat delivered at temperatures up to 700°C to heat the compressed air before going into the power turbine. For peak power, the compressed air is further heated using combustible fuels to higher temperatures (1100 to 1500°C) for more efficient power generation. These are the only nuclear Brayton cycles that have been investigated in any detail.
- *Nuclear Steam-Injected Brayton Cycles*. In these power cycles, the salt reactor produces high-temperature steam that, during normal operations, is sent to a conventional steam cycle. For peak electricity production, some of that high-temperature steam is injected into an air Brayton power cycle after air compression. The auxiliary fuel then further heats the compressed air and steam to high temperatures (1100 to 1500°C) before being sent to the turbine. Conventional steam-injected Brayton power cycles are used today in some specialized applications for peak power production.

Thermodynamic topping cycles are not new. In the 1950s the Indian Point I pressurized water reactor in the United States was built with an oil-fired topping cycle. The reactor produced ~300°C steam that was sent to an oil-fired boiler to increase the steam temperature to about 550°C before being sent to the turbine. When built, this plant had the highest efficiency of converting incremental heat from oil into electricity. The cycles described above are similar, but for the fact that the peaking cycle is a gas turbine that allows peak temperatures to 1500°C, with much higher efficiencies—a modern version of the Indian Point I topping cycle using gas, rather than steam turbines.

There is also the option of converting excess electricity (wind and solar) into high-temperature stored heat [Forsberg 2018a] to partly substitute for the use of combustion fuels for peak electricity production. These power systems enable large peak to base load electricity output that can meet the capacity requirements for a low-carbon grid. Because gas turbines are cheap relative to the reactor, assured peak-generating capacity can be low-cost assured generating capacity.

Heat storage in the intermediate loop—the other heat storage location—is discussed below. For these reactors, the Brayton power cycles create another dimension of storage options that may strongly impact choices for heat storage in the intermediate loop. There have been no evaluations the implications of multiple storage options with heat stored both in the intermediate loop and in the power cycle.

5.2 Heat-storage Options

Salt reactors may have intermediate loops between the reactor and the power cycle or industrial heat market to (1) assure isolation of radioactivity, (2) transport heat to the industrial sector, and (3) provide heat storage. Two heat-storage fluids are described herein: nitrate salts and chloride salts.

5.2.1 Nitrate salt intermediate loops

Many large CSP towers use nitrate salt mixtures to (1) collect heat, (2) store heat on a gigawatt-hour scale, and (3) deliver variable heat to a steam cycle to produce electricity at times of higher prices to maximize revenue. Several existing solar power towers have more than a gigawatt-hour of heat storage in the form of hot nitrate salts. The same technology can be coupled to a salt reactor (See also nitrate heat storage option discussed in Chapter 4) . In addition, nitrate salts trap any tritium that diffuses through the heat exchangers from the reactor coolant. Tritium diffuses through heat exchangers in the hydrogen form. If it contacts nitrate salts that are highly oxidizing, the tritium is converted to water that does not diffuse through heat exchangers—it is trapped in the nitrate salt system. The tritiated water can be removed from the nitrate salt[c]. Because the nitrate salt can be used for heat storage and as a tritium trap, several salt-cooled reactor startup companies have proposed using nitrate salt intermediate loops.

The three major salts [Gil 2010] are solar salt (60 wt% $NaNO_3$- 40 wt% KNO_3), Hitec (40 wt% $NaNO_2$- 53 wt% KNO_3- 7 wt% $NaNO_3$) and HitecXL (48 wt% $Ca(NO)_2$- 45 wt% KNO_3-7 wt% $NaNO_3$). Solar salt is used in the Solar Two, Gemasolar, and Crescent Dunes solar power systems [Ushak 2015, Federsel 2015] as the heat-transfer fluid and storage media, with a temperature swing of 288 to 565°C. The peak salt temperature within some parts of the receiver are considerably higher, although the average salt exit temperature is 565°C. The nominal upper temperature limits for these salts is 600°C [Gil 2010, Kenisarin 2010, Medrano 2010] but this may be somewhat extendable with control of the atmosphere above the salt [Olivares 2012, Abengoa Solar, 2013].

Existing CSP systems with nitrate heat storage use two-tank systems that would be applicable to a nuclear reactor with salt storage. The reactor operates at base-load all the time. In a two tank system (Figure 3-1) at times of low demand, just enough hot salt is sent to the power system to operate it at minimum load to keep the turbine-generator online for fast return to full power. The remainder of the hot salt goes to the hot-salt storage tank. Cold salt from the power cycle and cold salt from the cold-salt storage tank goes back to the reactor. At times of high power demand, hot salt from the reactor and from the hot-salt storage tank goes to the power cycle. Part of the cold salt from the power cycle goes to the reactor, and part goes to the cold-salt storage tank.

There are several tradeoffs coupling salt-cooled reactors with nitrate systems.

- *Peak allowable nitrate salt temperature*. The peak allowable temperature is only slightly above 600°C, below the salt exit temperatures in many but not all salt-cooled reactors.
- *Minimum salt-cooled reactor coolant temperature*. The minimum reactor salt temperature is somewhere near 550°C. A large temperature change in the nitrate salt minimizes heat-storage costs. To minimize heat-storage costs, the nitrate salt can provide heat to the power cycle down to its minimum temperature—typically near 280°C. This minimizes the cost of heat storage. However, if this is done, the return nitrate salt temperature will be significantly below the freezing point of the reactor salt. Avoiding the freezing of the reactor secondary salt loop would require either a heat exchanger with a very large temperature drop across the heat exchanger (very small heat exchanger) or a mix of hot and cold nitrate salts to meet whatever temperature requirements are needed for the nitrate salt/reactor salt heat exchanger.

There are many design options of how to couple a salt-cooled reactor to nitrate intermediate loop, but no studies of these options was found.

5.2.2 Chloride-salt intermediate loops

A longer-term salt option for the secondary loop is the use of chloride salts. These salts have lower costs and can go to much higher temperatures than nitrate salts. The leading candidate for reactor systems in the U.S. is the same sodium-potassium-magnesium chloride salt that is the leading candidate [Mehos 2017, Mohan 2018, Mohan et al 2018] for advanced high-temperature solar power towers with operating temperatures above 700°C—significantly above the temperatures of solar-power towers using nitrate salts. That commonality exists because (1) most of the requirements for an intermediate-loop coolant for a salt-cooled reactor and for a coolant in a high-temperature solar-power tower are identical and (2) a much larger R&D effort is underway to develop this salt by the solar community than efforts in the nuclear community. Other candidate high-temperature salts include carbonate salts.

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[c] Nitrate salts are highly oxidizing; thus, oxygen enriched cover gases may be used to improve thermal stability. Tritiated water will tend to gather in the gas space. The quantities of tritiated water measured in grams are small; thus, small amounts of normal water may be added to the nitrate salt to sweep out tritiated water and minimize tritium inventories in tanks.

Chloride salt has become the leading candidate for high-temperature solar-power tower systems for two reasons: (1) good physical properties, including melting point, and (2) very low cost, enabling very-low-cost heat storage. The concentrated solar thermal power community has concluded that economic viability requires large-scale heat storage to avoid selling electricity at times of low prices; thus, minimizing heat-storage cost is an absolute requirement for concentrated solar power systems. There are significant uncertainties, including controlling salt chemistry to minimize corrosion. This includes using various additives to address corrosion concerns. The eutectic salt composition with a melting point of 383°C has a composition of 24.5 wt% NaCl, 20.5 wt% KCl and 55 wt% $MgCl_2$. If the temperature swing in storage is 200°C, the storage cost with this salt is estimated at $ 4.50/kWh, below that of nitrate salt storage or any other liquid heat-storage system that has been identified to date. The salt is highly hydroscopic because water will react with the magnesium chloride.

The salt could be stored using either a one- or two-tank salt heat-storage system. The two-tank system (Figure 3-2) would be similar to that described for nitrate salt systems and used today in concentrated solar-power systems. As with the nitrate system, there is a tradeoff between the reactor, power cycle, and storage system. The cost of the storage system is minimized by having a large temperature difference between the temperature of hot and cold salts. However, salt reactors typically have a small temperature drop across the reactor core. One option would be to operate the heat-storage system and the power cycle with large temperature changes and, at the same time, have a smaller temperature drop across the reactor core. This can be done with a bypass line that sends some hot salt from the reactor to the cold-salt return line to heat the cold salt to the desired inlet salt temperature for the reactor. The differences between chloride salts and nitrate salts is that the chloride salt (1) operates at higher temperatures (i.e., is more efficient), (2) has the potential for much lower costs, and (3) is not a commercial system. Significant R&D remains to be done on these systems.

There is an alternative system design: using a single salt storage tank. This has the potential to significantly lower capital costs, but uncertainties remain. In a single-tank system (Figure 3-3), hot salt flows to a heat-storage tank and the power cycle. At times of low demand, just enough hot salt is sent to the power system to operate it at minimum load to keep the turbine-generator on-line for fast return to full power. The remainder of the hot salt goes to the top of the salt-storage tank. Cold salt from the power cycle and cold salt from the storage tank goes back to the reactor. At times of high power demand, hot salt from both the reactor and storage goes to the power cycle. Part of the cold salt from the power cycle goes to the reactor, and part goes to the storage tank. There is one storage tank with hot lower-density salt on top of cold higher-density salt—stratified layers of hot and cold salt.

A large hot-to-cold temperature swing minimizes the cost of storage. However, liquid-cooled reactors typically have small temperature swings across the core. A large change in temperature in the storage system can be allowed, but this may require partly reheating the returning cold salt to the reactor by addition of some hot salt from the reactor through a mix line.

Single-tank hot and cold fluid storage is used in some large-scale air conditioning systems with cold and warm water storage; however, some heat is transferred from the hot salt to the cold salt. For high-temperature salt systems, conductive and radiative heat is transferred in the tank from the top to bottom and tends to even temperatures out over time. To minimize this heat loss, there is the option of a series of tanks that act like a single tank, but with lower heat losses, as shown in Figure 3-3. Another option is to include an insulated structure between the hot and cold fluids that rises and falls, as needed, to provide necessary insulation.

If the technology can be developed, this is a very-low-cost high-temperature heat-storage system that delivers high-temperature heat to the power cycle for peak power, with high heat-to-electricity efficiency. There are large economic incentives for the concentrated solar power community to solve the challenges to make these salts work for similar reasons.

5.2.3 Latent-heat storage

There is the option to use latent-heat storage materials where heat is stored by melting a solid at a constant temperature. The incentive is that heat storage per unit volume can be an order of magnitude or more greater than with sensible heat storage. The likely candidate for such a system is an aluminum alloy (Fears 2018). Aluminum has a melting point of 660°C with various eutectics at lower melting points.

Melting such materials produces thermal expansion; thus, the challenge is the design and the container material that separates salt from the heat-storage material. Aluminum does have the advantage of very good thermal conductivity. As with most other systems, there is the question of chemical compatibility if leaks develop in the heat-storage system.

5.3 Challenges and Observations

There is massive overlap between heat-storage technologies and power cycles for solar power towers and salt-cooled reactors. there are important differences. Nuclear reactors will be larger and thus will have economics of scale. Unlike solar, nuclear plants have no seasonal variation in power output; thus, nuclear systems will have higher capacity factors, and there will be more cycles of heat storage per year. If one doubles the number of times heat storage is used per year, the cost of storage per unit of electricity drops in half.

The other observation is that high-temperature heat can dramatically lower the cost of the heat-storage system and increase the heat-to-electricity conversion efficiency. This implies that there are potentially large economic advantages for salt-cooled reactors relative to other types of reactors in a world where dispatchable electricity from nuclear power stations is required.

5.4 References for Chapter 5

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6. CONCLUSIONS AND RECOMMENDATIONS

Historically, most electricity has been generated by burning fossil fuels. In an electrical grid where most electricity is generated by fossil fuels, the minimum electricity prices are set by the cost of fossil fuels. Nuclear reactors have high capital costs and low operating costs. They operate in a base-load mode. Fossil plants have low capital and high operating (fuel) costs; thus, they provide variable electricity that matches production with demand. The economics of each type of plant is determined by the ratio of operating-to-capital costs.

The electricity grid and electricity markets are changing because of (1) the large-scale addition of wind and solar and (2) the goal of a low-carbon electricity grid. Wind and solar are non-dispatchable and have low operating costs—below nuclear and other types of electricity-generating technologies. Their large-scale deployment results in wholesale electricity price collapse at times of high wind or solar output. The goal of a low-carbon grid requires a replacement for fossil fuels in the role of provider of assured dispatchable electricity. While there is a base-load electrical demand, there no longer is a base-load demand for electricity at a price of electricity set by fossil fuels—a price higher than the operating costs of a nuclear power plant. The new electricity market has times of zero or negative electricity prices and times of higher electricity prices.

These changes create economic incentives for nuclear reactors to operate at base load to minimize production costs while using heat storage to enable varying electricity production to maximize revenue while meeting variable energy needs. At times of low electricity prices, some heat is sent to the turbine to produce electricity at the minimum allowable output while the remaining heat is sent to storage. At times of high electricity prices, reactor heat and heat from storage are used to produce electricity at a rate greater than the base-load generating capacity of the nuclear reactor. If heat storage is depleted, a combustion furnace can provide incremental added heat to enable the power station to provide peak electricity. Most of the time, stored heat is used for peak power, so the combustion heater provides assured peak generating capacity, but is seldom used. The system can meet the requirements of a low-carbon world.

The economics are based on multiple factors: (1) heat storage is less expensive than electricity storage (e.g., batteries, pumped hydroelectric) and other options, (2) the cost of the nuclear power plant is in the nuclear reactor system, not the power cycle, and this creates large incentives for the reactor to operate at full capacity while making major changes to the power cycle by adding storage to enable variable electricity output to the grid, and (3) a low-cost combustion heater can provide assured generating capacity at lower costs than competing technologies, such as gas turbines, with little fuel consumption because peak electricity demand is primarily met with heat storage.

The combination of technologies potentially is the enabling technology for a replacement to fossil fuels in a low-carbon world and the enabling technology for larger-scale use of wind and solar by providing economic dispatchable electricity with power plants that can buy and sell electricity. The advanced reactor that best integrates heat storage and assured peak generating capacity will have significantly greater revenue than alternative reactor concepts and will thus have a large competitive advantage relative to other types of nuclear power systems.

This report is a first look at requirements for such systems and heat-storage options deployable at the gigawatt-watt hour scale with economics and safety as the primary selection criteria. The leading heat-storage candidate for sodium systems (low-pressure secondary system with small temperature drop across the reactor core) is steel in large tanks with sodium coolant in channels. For helium systems (high-pressure with large temperature drop across the core) the leading heat storage options are (1) varying the temperature of the reactor core, (2) steel or alumina firebrick in a secondary pressure vessel and (3) nitrate or hot-rock/firebrick at atmospheric pressure. For salt systems (low pressure, very high temperatures, small temperature drops across the reactor core), the leading heat-storage systems are secondary salts. In each case, options are identified and questions to be addressed are identified.