INL/EXT-19-54909
Revision 0

Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Workshop Proceedings: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

Charles Forsberg*, Piyush Sabharwall, and Hans D. Gougar

September 2019

*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

A collaboration between:

Massachusetts Institute of Technology

Idaho National Laboratory

Exelon

INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

Idaho National Laboratory

INL/EXT-19-54909
Revision 0

Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Workshop Proceedings: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

Charles Forsberg*, Piyush Sabharwall, and Hans D. Gougar

*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

September 2019

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

Electricity markets are changing because of (1) the addition of wind and solar that creates volatile electricity prices including times of zero-priced electricity and (2) the goal of a low-carbon world that requires replacing fossil fuels that provide (a) energy, (b) stored energy, and (c) dispatchable energy. Wind and solar provide energy but not the other two other energy functions that are provided fossil fuels. Nuclear energy with heat storage can provide all three functions and thus replace fossil fuels.

To address the challenges and opportunities for nuclear energy in this changing market the Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), and Exelon conducted a workshop on July 23-24, 2019 in Idaho Falls on Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems. The results from this workshop are described herein. The workshop included participation of the concentrated solar power (CSP) community because nuclear energy and CSP produce heat and thus face many of the same technological and institutional challenges. Some CSP plants today have several gigawatt-hours of heat storage to better match market needs.

The changing market requires a different nuclear plant design that incorporates heat storage. The base-load reactor sends variable heat to (1) the turbines to provide variable electricity to the grid and (2) storage. At times of high electricity prices, all the heat from the reactor and heat from storage is used to produce peak electricity output significantly greater than the base-load capacity of the reactor. At times of low or negative electricity prices, (1) minimum steam is sent to the turbine and (2) there is the option that electricity from the turbine operating at minimum output and electricity from the grid is converted into heat that is sent to storage. The nuclear plant has the capability to buy and sell electricity to increase revenue in these markets relative to a base-load nuclear power plant. Heat storage (salt, rock, concrete, etc.) is much less expensive than electricity storage (batteries, etc.) because of the low cost of the materials used in heat storage systems relative to materials used in electricity storage systems.

Generation IV reactors deliver heat at higher temperatures to the power cycles compared to water-cooled reactors. This lowers the cost of heat storage by two mechanisms. First, if the hot-to-cold temperature swing in a sensible heat storage system is doubled, the cost of heat storage is reduced by a factor of two assuming all other factors are equal. Second, the higher heat-to-electricity efficiency reduces the storage requirements per unit of electricity storage. This may become the primary economic incentive to develop Generation IV reactor technology.

Twelve heat storage technologies applicable at the gigawatt-hour storage scale were discussed that can be deployed between the reactor and the power cycle. Several of these technologies are deployed at CSP facilities. Nitrate salt heat storage is used at the gigawatt-hour scale in CSP systems and is proposed for salt and sodium-cooled nuclear plants.

Two storage technologies were examined that are incorporated into advanced Brayton power cycles. One proposes to use cold water to boost power when needed. The other uses a thermodynamic peaking cycle with incremental heat-to-electricity efficiencies of 70 to 75% when coupled to high-temperature reactors providing heat to the lower-temperature bottoming cycle. The heat for the topping cycle can be provided by natural gas, hydrogen, or stored heat produced by converting low-price electricity into high-temperature stored heat.

A nuclear plant capable of producing, selling and buying electricity is different than any existing plant. There are large incentives to demonstrate heat storage in existing light water reactors to improve light water reactor economics and address many of the operational, grid, and regulatory challenges that are common to all heat storage systems coupled to nuclear plants. There are large incentives for joint nuclear/CSP heat storage development and demonstration programs because the same technologies are being used.

CONTENTS

FIGURES

TABLES

ACRONYMS

CSP	concentrated solar power
DOE	U.S. Department of Energy
FHR	Fluoride-salt-cooled High-temperature Reactor
FIRE	Firebrick Resistance-Heated Energy Storage
HGTR	high-temperature gas-cooled reactor
HRSG	heat recovery steam generator
INL	Idaho National Laboratory
LFR	lead fast reactor
LWR	light water reactor
MCFR	molten chloride fast reactor
MIT	Massachusetts Institute of Technology
MSR	molten salt reactor
NACC	Nuclear Air-Brayton Combined Cycles
NRC	U.S. Nuclear Regulatory Commission
PCM	phase-change materials
PV	photovoltaic
PWR	pressurized water reactor
SFR	sodium fast reactor

Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

1. INTRODUCTION

Electricity markets are changing because of (1) the addition of wind and solar that creates volatile electricity prices including times of zero-priced electricity and (2) the goal of a low-carbon world that requires replacing fossil fuels that provide (a) energy, (b) stored energy, and (c) dispatchable energy. Wind and solar provide energy but not the other two other energy functions that are provided fossil fuels. Nuclear energy with heat storage can provide all three functions and thus replace fossil fuels in many of its roles.

To address the challenges and opportunities for nuclear energy in this changing market the Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), and Exelon conducted a workshop on July 23-24, 2019 in Idaho Falls on *Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors*: *Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems.* The results from this workshop are described herein. The workshop included the participation of the concentrated solar power (CSP) community because nuclear energy and CSP produce heat and thus face many of the same technological and institutional challenges. Some CSP plants today have several gigawatt-hours of heat storage to better match market needs.

Large-scale heat storage technologies are applicable to all heat generating technologies: fission nuclear reactors, CSP, geothermal, fusion (future), and fossil fuels. Some of the heat storage technologies are being developed for nuclear applications while others are being developed for CSP (Mehos 2017) and fossil applications. Heat storage has not yet been deployed at nuclear plants. Most new utility-scale CSP systems (Harvey 2017) include heat storage to avoid selling electricity at times of low prices and enable selling electricity at times of higher electricity prices. Currently, there are CSP systems with heat storage capacities at the multi-gigawatt-hour scale. Work is underway for coupling large-scale heat storage to fossil fuel plants to convert such plants into power stations for peak electricity production. If a station has three coal-fired units, two boilers could be shut down while operating the third unit that would produce heat for that unit and heat storage. At times of peak electricity demand, the fossil unit would produce electricity and the turbine-generator systems of the two other units would also produce peak electricity using heat from storage. It is a method to convert old base-load coal plants into plants with heat storage to produce peak electricity.

This proceeding first describes (Chapter 2) what has changed in terms of markets and the implications for the system design of a nuclear reactor incorporating heat storage. Chapter 3 discusses the integration of nuclear reactors with heat storage while Chapter 4 describes specific heat storage technologies at the gigawatt hour scale. Chapter 5 describes Brayton power cycles where heat storage is incorporated within the power cycle as part of a thermodynamic topping cycle. These two chapters include the technical summaries of storage technologies from this workshop (Forsberg, Gougar, and Sabharwall 2019) and the first workshop (Forsberg et al. 2017, Forsberg 2019) that focused on lower-temperature heat storage coupled to water-cooled reactors with saturated steam cycles. All higher-temperature GenIV reactors can incorporate lower-temperature heat storage technologies in their power cycles. The role of hydrogen, the other energy storage technology, is discussed in Section 6 with a summary of panel discussions in

Section 7. The four appendixes include the agenda, list of participants, the workshop viewgraph presentations, and the posters from the poster session.

There are large economic incentives to couple heat storage to higher-temperature GenIV reactors including sodium fast reactors (SFRs), lead fast reactors (LFRs), high-temperature gas-cooled reactors (HTGRs), Fluoride-salt-cooled High-temperature Reactors (FHRs), and molten salt reactors (MSRs). Heat storage costs are expected to be lower for these reactors than for light water reactors (LWRs). If using sensible heat storage, the greater the hot-to-cold temperature swing in storage, the less heat storage medium required per unit of heat storage. Doubling the temperature range of the sensible heat storage medium reduces storage costs in half. The second factor if store higher-temperature heat, the heat-to-electricity efficiency is higher that reduces the amount of heat that must be stored per unit of electricity.

2. MARKETS AND SYSTEM DESIGN

We describe herein the challenges and then the system design required for heat storage to meet those challenges. There are two challenges: (1) addition of wind and solar and (2) the goal of a low-carbon energy system. These two challenges are not necessarily connected. Wind and solar are not dispatchable; that is, they do not produce electricity at times of low wind and solar conditions. Their large-scale use today in the United States is primarily made possible by low-cost natural gas that provides dispatchable electricity when needed using gas turbines. A low-carbon energy system requires dispatchable sources of energy.

2.1 Markets: The Challenge

Wind and solar are non-dispatchable; that is, they produce electricity only when there is wind or solar input. Their large-scale use collapses wholesale electricity prices at times of high input and increases prices at times of low output. Figure 2.1 shows the impact of large-scale addition solar photovoltaic (PV) on the wholesale price of electricity between 2012 and 2017 in California on a spring day (Forsberg, 2019; Appendix C, Forsberg). In 2012, wholesale electricity prices were set by fossil fuels that set a minimum price for electricity. Fossil fuel plants shut down if the wholesale price of electricity went below the cost of fuel—the marginal cost of electricity. The marginal price of PV is near zero and there are subsidies for PV resulting in excess electricity production at certain times resulting in negative wholesale electricity prices. At times of low wind and solar output, wholesale prices went up. One requires electricity but the power plants that produce such electricity operate fewer hours per year and thus higher wholesale prices at times of low wind and solar output. Figure 2.2 shows the quantities of negative wholesale electricity prices in California by month. The combination of seasonal demand for electricity and wind/solar inputs results in large differences in wholesale electricity prices, including negative prices, by month.

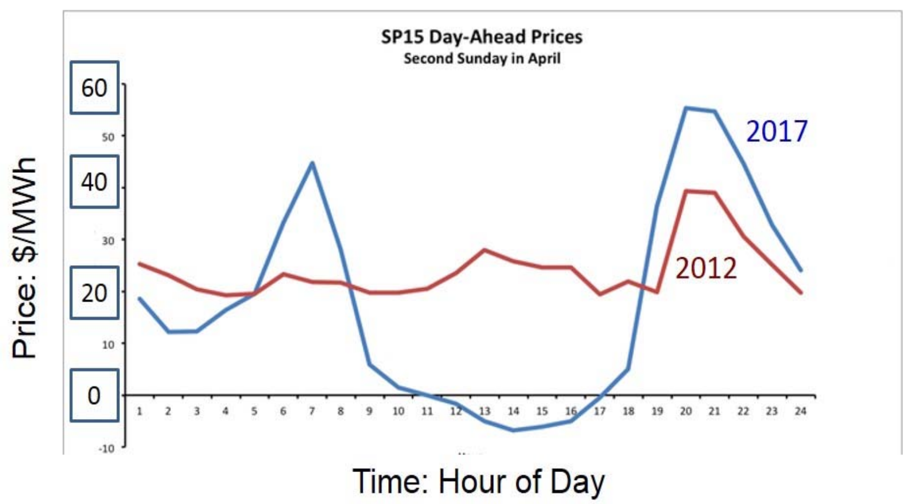


Figure 2.1. Impact of large-scale addition of solar for a spring day in California on wholesale electricity prices.

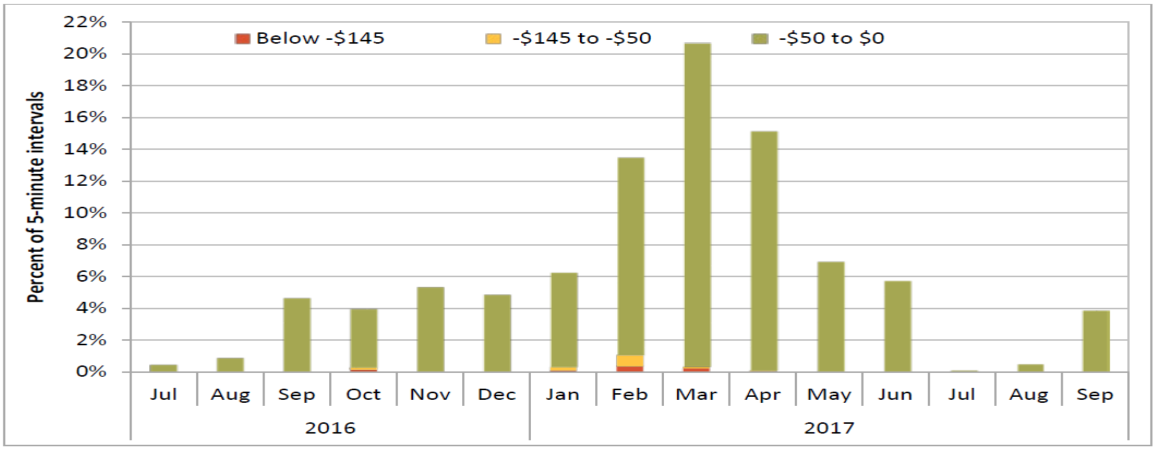


Figure 2.2. Percentage of the time with negative electricity prices by month in California.

Relatively small additions of wind and solar lower retail electricity prices; but, large scale additions of wind and solar have increased retail electricity prices Europe, California and other locations. One can't build wind and solar for negative prices; thus, subsidies are required to enable their large-scale use. The two sources of such subsidies are the taxpayers and ratepayers. Paying for the subsidies increases retail electricity prices. The limitations of non-dispatchable solar have resulted in no country in Europe producing more than 8% of its electricity from solar. California has somewhat better solar conditions and hydro (storage) that may allow larger-scale use of renewables. Wind and solar provide electricity (energy) but it is non-dispatchable. There are two requirements to use large quantities of lower cost wind and solar.

- *Low-cost energy storage*. Methods are needed to store low-cost energy (kWh) when available and provide it when needed.
- *Assured electricity generating capacity*. Storage by itself is insufficient. One must deliver electricity at the rate it is needed. A large coal pile provides a massive amount of stored energy, but one needs a power plant to convert that stored energy into electricity at the rate it is needed. Wind and solar are non-dispatchable and thus do not provide by themselves any assured electric generating capacity.

The goal of a low-carbon world requires providing energy to all electricity sectors. Figure 2.3 shows the energy flows in the United States from energy sources (natural gas, coal, nuclear, wind, solar, etc.) to energy users. Most energy is not used as electricity—it is used as heat. For example, the industrial sector demand for heat is about twice its use of electricity. Furthermore, the variation in demand with time is different than the electric sector. Most industrial facilities have a relatively constant demand for energy. In this context, there is an important distinction between heat and electricity. It takes several units of heat to produce one unit of electricity but one unit of electricity to make a unit of heat. Heat is less expensive than electricity. Nuclear reactors produce heat with three units of heat to produce one unit of electricity. As a consequence, the cost of heat from a nuclear reactor is low. Table 2.1 shows levelized costs of electricity and heat from different energy sources. Today natural gas is the low-cost heat source. Nuclear is competitive and for markets, such as industrial markets, produces heat at a nearly constant rate that matches demand. Decarbonization of the economy requires consideration of the entire energy sector—not just the electric sector. That implies massive production of heat where heat-generating technologies have a competitive advantage.

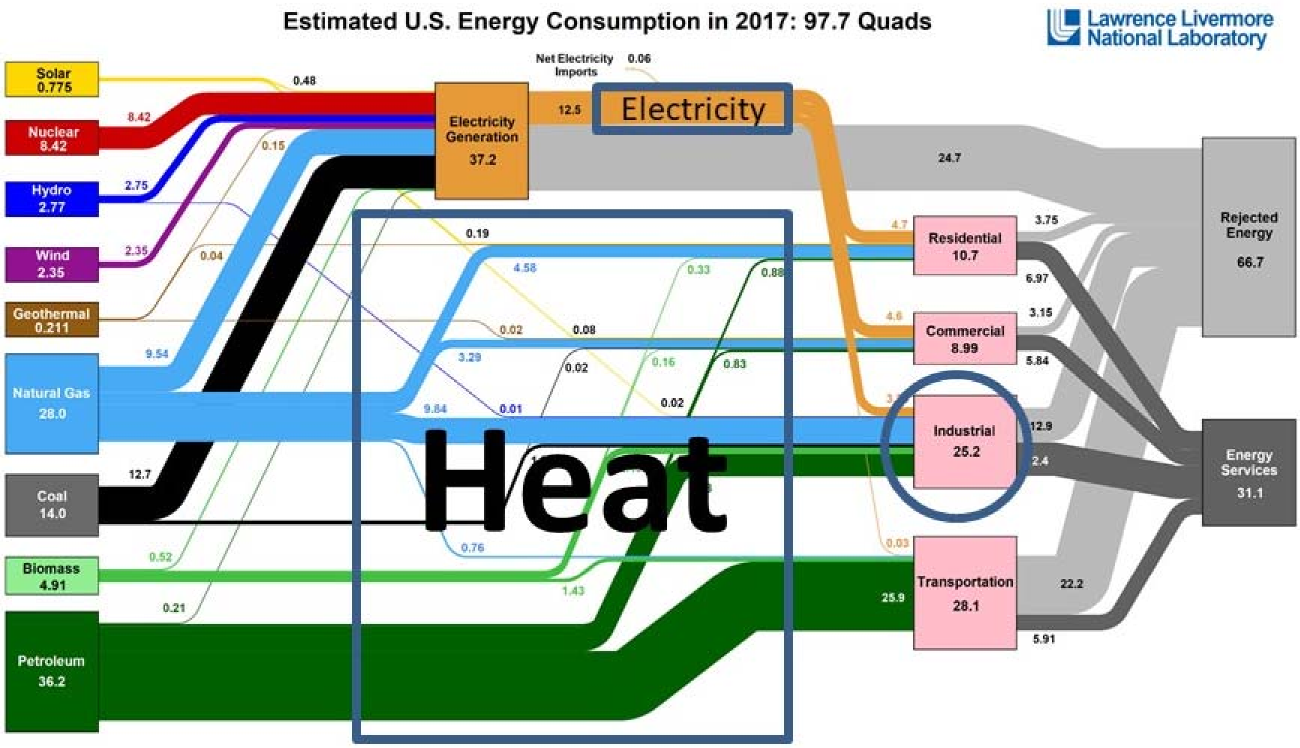


Figure 2.3. Energy flow diagram for the United States.

Table 2.1. Levelized cost of electricity and heat.

Technology	LCOE: $/MWh(e)	LCOH: $MWh(t)
Solar PV: Rooftop Home	187–319	187-319
Solar PV: Crystalline Utility	46–53	46-53
Solar PV: Thin Film Utility	43–48	43-48
Solar Thermal Tower with Storage	98–181	33-60
Wind	30–60	30-60
Natural Gas Peaking	156–210	20-40
NG Combined Cycle	42–78	20-40
Nuclear	112–183	37-61

Fossil fuels are a remarkable energy source that provides three services: an energy source, storable energy, and dispatchable energy (in the electric sector assured generating capacity). That combination enabled several billion people to obtain a middle-class standard of living and created a flat world of energy prices. The price of coal, oil or liquefied natural gas is about the same in New York harbor as Shanghai. The goal of any replacement system is to provide the same services at a reasonable price on a global scale everywhere. The above considerations define what is required—a system that (1) generates energy, (2) stores energy to match production with demand and (3) can provide assured electric generating capacity.

2.2 System Design

The fundamental division between energy sources is whether they produce heat or work (electricity). Wind and solar PV produce electricity that defines many of their characteristics. Nuclear energy produces heat that can be converted to electricity, directly used by industry or stored. Energy storage technologies are designed for either electricity (batteries, pumped hydro, capacitors, etc.) or heat (pressurized water, salt, concrete, oil, sand, etc.). This difference defines allowable system designs.

Figure 2.4 shows the system design (Forsberg 2019; Appendix C, Forsberg) for heat generating technologies with heat storage that applies to any heat generating technology (nuclear, CSP, geothermal, fossil fuels with carbon capture and sequestration, and fusion [future]) and low-carbon technologies that produce electricity. The red arrows are for energy flows of heat while the blue arrows are for energy flows of electricity. Unlike electricity storage technologies, heat storage, and heat to industry require co-located facilities.

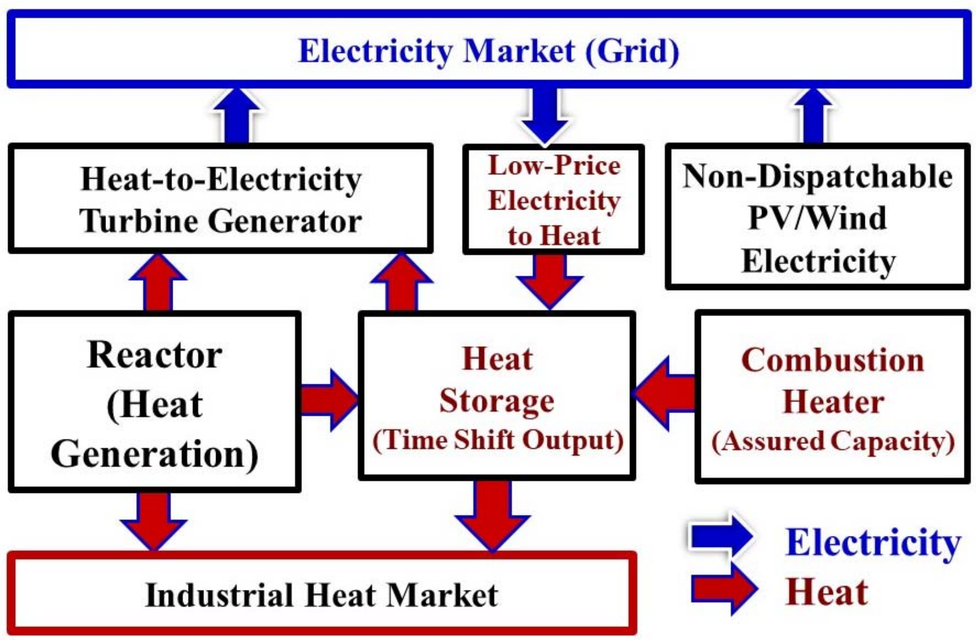


Figure 2.4. Integrated nuclear-renewable system with heat storage (Forsberg 2019).

The reactor can send heat in three directions depending upon demand: (1) the turbine generator to provide dispatchable electricity generation, (2) storage and (3) industry if operating as a co-generation nuclear plant. At times of low electricity prices, a minimum amount of steam goes to the power cycle to keep the turbine-generator on line and allow rapid return to full power. The rest of the heat goes to heat storage and industry. At times of high electricity prices, heat from the reactor and added heat from storage goes to the power cycle to generate peak electricity output—substantially greater than the base-load electricity generating capacity of the reactor. If electricity prices are low, electricity can be bought and converted into heat for heat storage using electric resistance heaters. To provide assured peak generating capacity if heat storage is depleted, a combustion furnace provides the heat equivalent that comes from storage to the power cycle for peak electricity production.

The Electric Power Research Institute (Appendix C, Sowder) current estimates are that heat storage is a factor of three to four less expensive today than lithium ion batteries per unit of stored electricity. The U.S. Department of Energy capital-cost goal for heat storage is $15/kWh(t) while the capital cost goal for electric battery storage is $150/kWh(e). The cost differences reflect the cost of raw materials for heat storage (pressurized water, salt, crushed rock, sand. concrete, oil, etc.) versus the cost of raw materials for electricity storage (lithium, cobalt, etc.). Stored energy must be converted back to electricity. For heat storage the capital cost of heat-to-electricity systems depends upon whether one has a stand-alone turbine-generator for peak power or at lower costs an incrementally larger turbine generator used for baseload and peak electricity. Technologies such as battery storage (Denholm et al., 2019) are only viable for short storage periods—typically four hours. The power conversion equipment with batteries doubles their costs. There are two fundamental differences between heat and electricity storage.

- *Assured generating capacity*. The cost of assured electricity generating capacity is much smaller for heat storage than electricity storage. The capital costs [Forsberg, March 2019; Forsberg, Brick and Haratyk, April 2018] for a boiler or furnace to backup heat storage if depleted are estimated at $100-300/kWe, less than the cost of a simple gas turbine ($500-600/kWe); the next cheapest alternative for assured generating capacity and the backup option if batteries or other electricity storage technology is used. The boiler or furnace can burn natural gas, biofuels or hydrogen. If one buys a heat storage system with the turbine-generator peaking capacity, only a heat source is needed for assured generating capacity because its peak generating system is already installed. If one buys an electricity storage system, the backup capacity is a gas turbine that includes a heat source, heat to electricity system, and the turbine-generator. Assured generating capacity is intrinsically more expensive with electricity storage systems.
- *Low incremental storage costs*. The incremental heat storage cost is low relative to batteries that have electricity storage and conversion to electricity built into the same package. Large-scale wind, large-scale solar and the weekday/weekend variations of electricity demand imply a future low-carbon electrical grid will have long times of excess low-price electricity. Electricity-to-heat storage provides a way to store very large quantities of energy at very low costs. Some of the heat storage materials (geothermal, crushed rock, sand, etc.) have incremental heat storage costs under a dollar per kWh(t).

A recent U.S. Department of Energy (DOE) report provided installed capital cost estimates for the competing electricity storage costs for different technologies in 2018 as shown in Table 2.2—excluding heat storage technologies. It is a snap shot in time of the competition. The costs are in $/kW(e)) (per unit of capacity) and $/kWh(e) (per unit of stored electricity) that depend upon the number of storage hours that are also shown. The competitive technologies are pumped hydro that depends upon finding a good site and compressed air energy storage that requires a salt dome or other very low-cost underground storage space. The battery technologies have limited lifetimes that is dependent upon the duty cycle.

Table 2.2. Summary of electricity storage cost (Mongird et al. 2019).

Technology	Total Project Cost ($/kW)	Total Project Cost ($/kWh)	Storage Time (Hours)
Sodium-Sulfur Battery	3626	907	4
Lithium-Ion Battery	1876	469	4
Lead Acid	2194	549	4
Sodium Metal Halide	3710	928	4
Zinc-Hybrid Cathode	2202	551	4
Redox Flow	3430	858	4
Pumped Storage Hydro	2638	165	16
Combustion Turbine	940	N/A	N/A

Compressed Air Energy Storage	1669	105	16
Flywheel	2880	11,520	0.25
Ultracapacitor	930	74,480	0.0125

3. INTEGRATING REACTORS AND STORAGE SYSTEMS

The choice of storage system depends upon the temperatures of delivered heat from the reactor to the heat storage system. Storage is applicable to large, small, and micro reactors. Table 3.1 shows nominal heat delivery temperatures for nuclear reactors and CSP systems with different coolants.

Table 3.1. Nominal inlet and outlet temperatures of nuclear and CSP coolants.

Power system	**Coolant**	**Nominal Inlet Temperature (°C)**	**Nominal Exit Temperature (°C)**
Nuclear	Water	270	290
Nuclear	Sodium	450	550
Nuclear	Helium	350	750
Nuclear	Salt	600	700
CSP	Nitrate	290	565
CSP	Chloride	500	725
CSP	Sodium	500	750
CSP	Sand	575	775

A wide variety of storage media are being investigated as shown in Table 3.2. The primary criteria for large-scale storage is low cost per unit of heat storage (kWh). Different materials have different allowable peak storage temperatures.

Table 3.2. Heat storage media and nominal allowable peak temperatures.

Storage Technology	Temp. Limit (°C)	Storage Technology	Temp. Limit (°C)
Nitrate Salt	<650	Hot Sand	>1000
Chloride Salt	<1000	Crushed Rock	800
Cast Iron	700/900	Geothermal	<300
Pressurized Water	<300	Liquid Air	<1600
Concrete	>600	Sodium	<700
Hot Oil	<400	Cold Water	~0
Graphite	>1500	Alumina	>1000

The only heat storage systems deployed today at the gigawatt-hour scale are nitrate molten salts in CSP systems. In solar power towers, molten nitrate salts are the heat transfer fluid. Hot nitrate salt from the power tower is sent to the power system and / or the hot nitrate storage tank (Figure 3.1). In the middle of the night when there is no solar input, all hot salt to the power cycle comes from the hot storage tank. Cold salt from the power cycle goes to the power tower if operating and the cold nitrate-salt storage tank. Typical cold salt temperatures are near 290°C to minimize the risk of freezing the salt. If the power cycle is not operating, cold salt from the cold storage tank can be supplied to the power tower. The operations of the power tower producing hot salt are separate from the power block. In a CSP system on a cloudy day the hot salt output from the power tower will go rapidly up and down when clouds block the sun. With heat storage the power block does not see these transients.

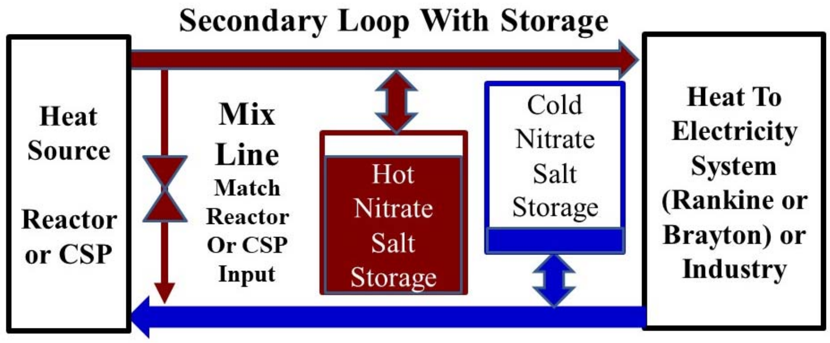


Figure 3.1. Nitrate heat storage system coupled to salt or sodium reactor or CSP system.

Nitrate salt intermediate loops are being proposed for SFRs by TerraPower, for FHRs with solid fuel and clean liquid salt coolant by Kairos Power and for several designs of MSRs with fuel dissolved in the salt. In salt-cooled reactors, the salt melting points are between 400 and 500°C. At the same time there are large incentives to maximize the temperature swing of the nitrate salt in storage to minimize heat storage costs. Doubling the hot-to-cold temperature swing of the nitrate salt doubles the amount of stored heat per ton of nitrate salt. There is the option of meeting both of these goals. In these nuclear systems, heat is transferred from the liquid reactor coolant to the nitrate salt intermediate loop where the hot nitrate salt can be sent directly to the power cycle or partly diverted to a hot nitrate storage tank at times of low power demand. The power cycle can be designed to lower the nitrate salt temperature to 290°C to minimize heat storage costs. If peak power is being produced, salt goes to the cold nitrate storage tank and the reactor. If the nitrate salt heading back to the reactor is too cold, it can be mixed with hot nitrate salt from the reactor to match the required inlet conditions for the reactor coolant-nitrate salt heat exchanger. HTGRs with large differences across the reactor core couple with salt storage systems.

There is also the single tank variant (Figure 3.2) for any liquid heat storage media with the hot liquid stored on top of the cold liquid. In a thermocline system, hot fluid is injected at the top of the tank, and cold fluid is injected at the bottom. Single-tank hot and cold fluid storage is used in some large-scale air conditioning systems with cold and warm water storage. For high-temperature salt systems, temperature gradients decrease with time because of heat conduction and radiative heat transfer from the top to bottom of the tank. There is the option to include an insulated structure between the hot and cold fluids that rises and falls, as needed, to provide necessary insulation. At high temperatures, the single-tank thermocline system has only been demonstrated at the 1 MWh(e) scale versus gigawatt-hour storage systems using the two-tank systems.

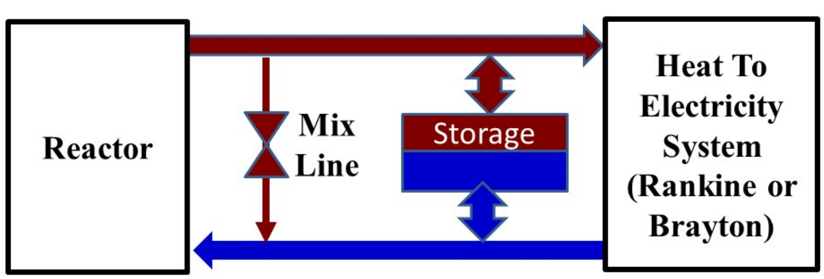


Figure 3.2. Single tank storage.

The single tank system allows the use of a separate solid storage medium in the tank and only use the fluid as a heat transfer agent from the reactor to storage to power cycle (water, salt, oil, sodium, etc.). Several advanced systems propose this system design. Westinghouse is developing a storage system where heat transfer oils move heat from pressurized water reactors (PWRs) or LFRs to storage where the solid storage media is concrete. Special concretes have much lower heat storage costs than heat transfer oils. In such a system, the oil is less than 5% of the storage tank volume. MIT is examining the use of cast iron with stainless steel cladding in SFRs, HTGRs, and salt reactors. The SFR would have the traditional sodium intermediate loop. The use of cast iron would minimize sodium in the secondary loop to reduce the risk of fire by reducing sodium used for storage and to reduce costs since cast iron costs less than sodium.

The single tank option reduces capital costs but there are heat losses from conduction of heat from the hot zone to the cold zone. These heat losses can be reduced by multiple tanks in series as shown in Figure 3.3 that limits heat conduction from the hot to cold zones to a single tank. Effectively one is creating a storage system with a large height to diameter ratio where the piping limits heat conduction from hot-to-cold to single tank and thus effectively limits the height of the hot-to-cold transition zone.

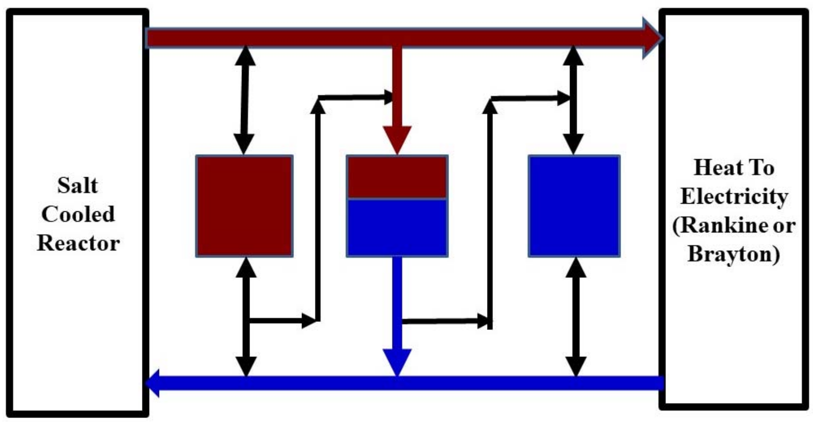


Figure 3.3. Series tank arrangement.

The heat storage system can be in the primary loop, secondary loop or the power cycle. Some storage systems can only be in one of these locations. Several heat storage technologies (steam accumulators, counter-current pebble bed, etc.) are designed for steam systems and are located between the steam generators in the reactor and the turbine system. Heat storage systems designed to be in the primary loop can have very high efficiencies because they avoid the temperature losses associated with heat exchangers; but this imposes other constraints including consideration of radioactive contamination of the storage system over time.

Heat storage may change reactor power-plant system design with the reactor facility inside the security zone and the storage and power blocks that convert heat to electricity outside the security zone. Figure 3.4 shows the plant layout for a CSP or nuclear plant where the salt tanks are used to allow independent operation of the heat generating technology (solar power tower or reactor) and the power block that converts heat to electricity. This is the arrangement used in CSP systems because heat storage dramatically simplifies operation. On partly cloudy days, the power output of a CSP system varies rapidly, depending whether the clouds are blocking the sun or not. With salt storage, the power block does not see such transients because hot salt is always available from the hot salt storage tank—greatly simplifying operations. Similarly, the power tower can operate independently of the power block by obtaining its cold salt from the cold salt storage tank.

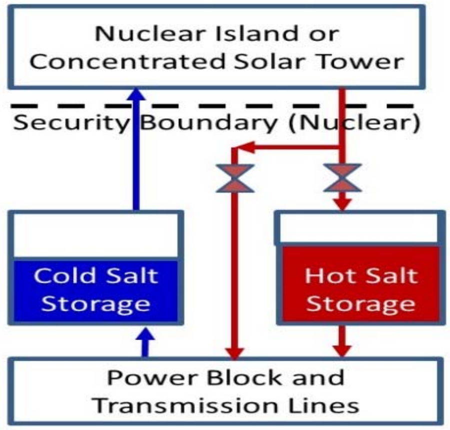


Figure 3.4. System design for CSP and nuclear with storage.

TerraPower (Appendix C, Walter) proposes the same design strategy for its SFR with a nitrate salt intermediate loop and its molten chloride fast reactor (MCFR) with a chloride salt intermediate loop. Current reactors put the power block (turbine generator) next to the reactor—a design that followed the design of earlier coal-fired power stations and that was developed before tight security requirements for nuclear power plants. The separation of the reactor and vital areas from the power block creates a clear division between areas with (1) requirements for nuclear security, maintenance, licensing, safety and construction versus (2) normal industrial requirements. This has the potential to reduce costs. Second, gigawatt-hour heat storage systems may become the largest set of structures on site. They will be in the protected area that has industrial safety and security requirements, but in some cases, may need to be some distance (100 meters) from reactor vital areas. Some heat storage systems (concrete heat storage) could be next to the reactor but other heat storage systems such as hot salt storage tanks may need to be some distance away because their failure would create a thermally hot area that could damage buildings and equipment next to such tanks. Last, storage isolates the reactor from the electricity grid and reduces transients from the grid-to-reactor and reactor-to-grid. The reactor becomes a heat generation system. Many of the regulatory and other constraints on rector operation that flow from tight coupling with the electricity grid disappear. Because the power block is decoupled from the reactor system, it can use totally automated systems designed to allow fast response depending upon grid requirements that can substantially increase revenue for auxiliary services. Recent work (Abel 2018) has examined the economic, licensing and safety implications for SFRs with nitrate salt storage systems.

4. STORAGE TECHNOLOGIES

Table 4.1 lists heat storage technologies being considered for nuclear and CSP applications based on their ability to store heat at the gigawatt-hour scale. For some options, there is the choice to obtain steam from the storage system that could be fed back to the main reactor turbine if that turbine was oversized. These options can also store heat for later use by industry. Some of these technologies have been deployed in solar thermal power systems (Kuravi 2013) while other technologies are primarily in the research stage. Most new utility-scale solar thermal power systems (Harvey 2017) include heat storage to avoid selling electricity at times of low prices. The storage times for different technologies vary from hours to seasons.

Table 4.1. Nominal heat storage option characteristics.

Sect	Storage Technology	Storage Time	Heat Input Method	Temperature Range (°C)	Round Trip Efficiency	Status of Technology
4.1	Steam Accumulator	Hours	Saturated Steam	250-300	High	Commercial (CSP)
4.2	Oil	Hours	Heat Exchanger	<400	Medium	Commercial (CSP)
4.3	Concrete	Hours to Days	Oil and Steam	400 600	Medium High	Laboratory Pilot Plant
4.5	Nitrate Salts	Hours to Days	Heat Exchanger	290-565	High	Commercial (CSP)
4.6	Chloride Salts	Hours to Days	Heat Exchanger	500-725	High	Laboratory
4.7	Sand	Hours to Weeks	Heat Exchanger	<1000	Medium to High	Pilot Plant
4.8	Crushed Rock	Hours to Weeks	Heat Exchanger	<800	Medium	Pilot Plant
4.9	Counter-Current Condensing Steam	Hours	Saturated Steam	250-300	Very High	Laboratory
4.10	Cast Iron	Hours to Days	Secondary Loop	100-700/900	High	Studies
4.11	Geothermal	Hours to Years	Heat Exchanger or Steam	<300	Low to Medium	Studies
4.12	Cold Water	Hours to Days	Heat Exchanger	0	High	Studies
4.13	Graphite	Hours	Primary Loop	<1400	High	Studies

One of the outcomes of the workshop is the observation that almost all of the heat storage technologies involve sensible heat storage. There are three major classes of heat storage technologies (Table 4.2): sensible, latent and chemical. Latent heat systems included in the above table involve the condensation of steam—the primary working fluid in most power cycles. There are several classes of thermochemical systems where heat is stored in chemical bonds. In hydride systems heat is used to decompose a hydride producing hydrogen. When the reaction is reversed the formation of the hydride releases heat. In carbonate systems the chemical reaction is conversion of a carbonate such as calcium carbonate into calcium oxide and carbon dioxide. Last, there are a set of chemical reactions that involve forming hydrates where steam is release when the hydrate is heated and heat is generated in the reverse direction. All of these systems are at an earlier stage of development.

Table 4.2. Characteristics of different heat storage systems (Liu 2018).

Characteristic	Sensible TES	Latent TES	Thermo-chemical Storage
Energy Density	Low (0.2 GJ/m^3)	Medium (0.3-0.5 GJ/m^3)	High (0.5-3 GJ/m^3)
Heat loss over time	Significant heat loss over time	Significant heat loss over time	Small heat loss or no heat loss over time
Temperature range	Charging step temperature	Charging step temperature	Ambient temperature, not temperature
Lifetime	Long	Limited	Depends on reactant degradation and side reactions
Transport	Small distance	Small distance	Unlimited theoretically
Advantages	Low cost and mature technology	Small volume and short distance transport possibility	High storage density, long distance transport possibility, low heat losses
Disadvantages	Significant heat loss over time; large volume needed	Small heat conductivity, materials corrosion, significant heat losses	Technically complex, high costs
Technical complexity	Simple	Medium	Complex

The sensible heat systems dominate for several reasons: weight or size is not a constraint for power plant applications, long lifetimes with 10,000 cycles are desired and low cost is the primary criteria. There is also a less apparent factor. In almost all of the sensible heat systems the peak power output (kW) and heat storage capacity (kWh) scale independently. The size of heat exchanger or turbine scale with the peak power output. The hours of storage depend upon the storage media. In contrast, in thermochemical systems the solids are immobile and thus heat is brought to the solid with heat transfer scaling with heat storage capacity. That is also true for most sensible heat storage systems (Fleischer 2015, Khare et al. 2012).

4.1 Steam Accumulators (<300°C: Saturated Steam Cycles)

A steam accumulator is a pressure vessel nearly full of water that is heated to its saturation temperature by steam injection (Figure 4.1). Heat is stored as high-temperature, high-pressure water. Liquid water has a high volumetric heat storage capacity of up to 1.2 kWh/m^3 (Medrano et al., 2010). When steam is needed, valves open and some of the water is flashed to steam and sent to a turbine (LaPotin 2016), producing electricity, while the remainder of the water decreases in temperature.

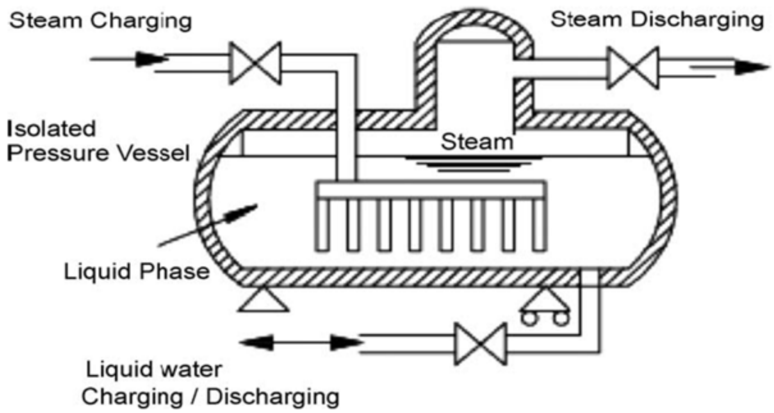


Figure 4.1. Steam accumulator schematic.

Steam accumulators have been used as pressure buffers in steam plants for over a century. The first large steam accumulator built in 1929 to produce peak electricity was the Charlottenburg Power Station built in Berlin with a peak electricity output of 50 MWe and a storage capacity of 67 MWh. The steam was provided by a coal-fired boiler and the accumulator had a separate turbine. This accumulator had 16 tanks each 4.3 meters in diameter and 20 meters high (Figure 4.2). There are multiple commercial suppliers of steam accumulators—but not at the size that would be associated with a nuclear reactor.

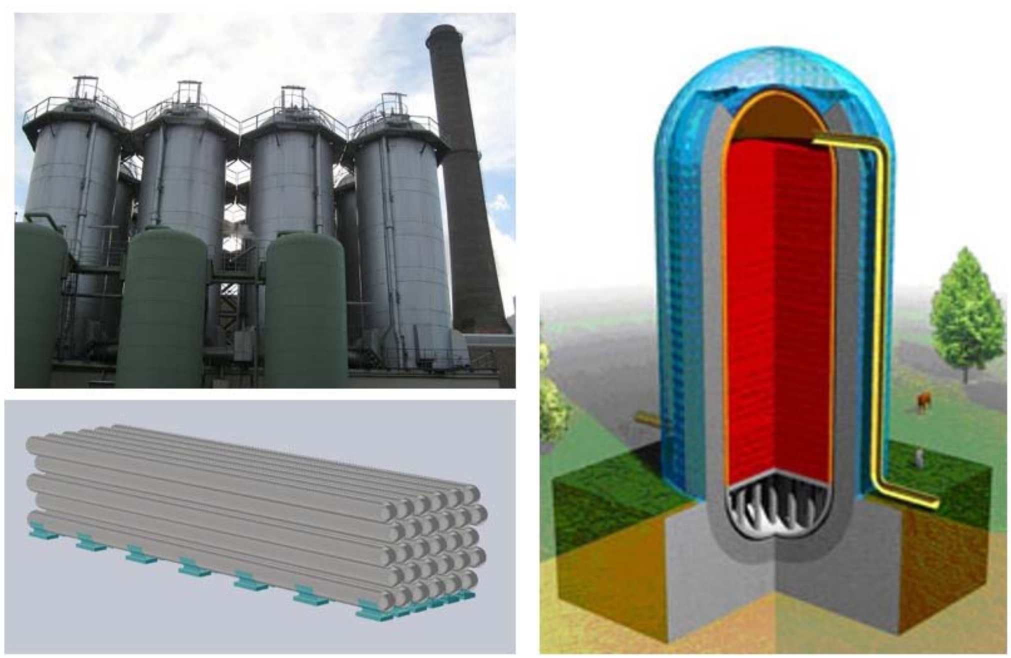


Figure 4.2. Alternative accumulator options: steel vessel charlottenburg power station accumulators built in Berlin in 1929 (upper left), proposed pipe rack accumulator (lower left) and prestress concrete vessel (right, proposed Adele prestress concrete vessel for adiabatic compressed air storage system (Zunft 2014). Schematic (right) courtesy of Zublin.

Steam accumulators have been installed in many concentrated solar power plants. The characteristics of some of these systems is shown in Table 5. Steam accumulators are well-suited for CSP designs where steam is generated in pipes located at the foci of parabolic or Fresnel reflectors (Steinmann 2006, Hirsch 2014). At the PS-10 and PS-20 plants near Seville, Spain, steam accumulators are coupled to the steam loops for heat storage, allowing them to produce electricity at times of high prices and low sunlight (Kuravi 2013). The operating temperatures and pressures of these solar power systems are close to those in LWRs.

Table 4.3. Solar power accumulators (Han, 2009; NREL, 2017).

Name	Location	Online	Type	Outlet (°C/MPa)	Power (MWe)	Energy Cap. (hours)
PS10	Sevilla, Spain	2007	CSP Tower	250/4.5	11	0.5
PS20	Sevilla, Spain	2009	CSP Tower	250/4.5	20	0.5
DAHAN	Beijing, China	2012	CSP Tower	400/4.5*	1	1
Khi Solar One	Upington, South Africa	2016	CSP Tower	530/4.5*	50	2
eLLO	Llo, France	2018	CSP Linear Fresnel	285/7.0	9	4

Most of the energy in a steam accumulator is stored as pressurized hot water because the energy storage density is higher. For a 100 MWh of electricity storage with steam delivered from 70 to 20 bars, one needs to store the equivalent of about 1,000 tons of steam (286°C, 70 bar) that would occupy 27,000 m^3. The same energy is stored in 7,900 m^3 of pressurized hot water or a reduction in storage volume by 3.4.

There are two classes of accumulators. The variable pressure (Ruths) accumulator is a single tank accumulator with sliding pressure during operation. It is the primary type of steam accumulator in current use. There is a more complex expansion accumulator that may be of interest for very large accumulators but is not generally used. The expansion accumulator involves two tanks: an accumulator tank that operates at constant pressure and an evaporator tank that delivers constant pressure steam. During discharge hot pressurized water is transferred from the accumulator tank to the expansion tank while cold water is added at the bottom of the accumulator tank to maintain a constant pressure with a thermocline separating the hot and cold water.

Steam accumulator performance can be improved by adding other heat storage materials to the system. Phase-change materials (PCM) such as sodium nitrate salts can be added within or around the stored water–vapor mixture to increase the total heat capacity of the system. During charging, heat is stored by melting the PCM (enthalpy of fusion), and it is released back into the water–vapor mixture during discharge, re-solidifying the PCM. Additional heat could be stored in sensible heat storage materials (e.g., high-temperature concrete) for preheating condensate water or for reheating or superheating steam from the accumulator. Reheating may be necessary in some designs to improve the steam quality that feeds into the turbine (Birnbaum et al. 2010). A demonstration project for these concepts was built at the Litoral de Almería coal-fired power plant in Spain (Laing 2011) to support steam accumulators for solar thermal power systems.

There have been limited studies of coupling steam accumulators to nuclear power plants for load following. Early studies (Gilli 1970, Gilli 1973) of such accumulators coupled to LWRs were done in the 1970s when the Arab oil embargo raised oil prices—the fuel used for peak power production. The

University of Texas has recently conducted a series of studies on the use of accumulators. This included steam accumulators (Lane 2016, Bisett 2017) that can provide heat to the feed-water heaters in the nuclear plant and boost the power output of the main nuclear steam turbine. Mann (2017) examined the economics in the context of the Texas electrical grid and under what conditions the economics were favorable.

The defining feature of a steam accumulator for nuclear applications is that the heat storage capacity requirement is significantly larger than for other applications. This will not change the technology for the power cycle but may change the technology used to store the hot pressurized water. Historically steel vessels have been used. For very large accumulators, there are two other options that may have lower costs per unit volume (Figure 7).

- *Steel pipe*. Recent studies have proposed kilometers of large steel pipe in racks inside an insulated building to avoid insulation of individual racks. Steel pipe used in pipelines is manufactured in very large quantities that will minimize manufacturing costs.
- *Prestressed concrete reactor vessel*. This would be a single large vessel. There has been recent work in Germany in development of such vessels as a component of an adiabatic compressed air storage system (Project Adele) at higher pressures and temperatures than in steam accumulators. The basis for that work is the lower projected costs for high volume storage at pressure. This work is directly applicable to steam accumulators.

4.2 Heat Storage in Hot Oil or Hot Oil and Secondary Storage Media

Hot heat-transfer oils are used in trough solar collectors operating below 400°C (Figure 4.3). In these systems concave mirrors focus light on a pipe with flowing oil. At night without sunlight the pipe temperature goes to ambient temperature. There is a massive piping network associated with these collectors; thus, large incentives for a low-pressure system. These constraints have resulted in the use of heat transfer oils that are liquids at low temperatures, have low vapor pressures and stable to ~400°C. Some oil-based solar collectors store energy as hot oil; however, most systems with storage transfer the heat to a secondary heat storage system because of the high cost of these oils.

Figure 4.3. Trough concentrated solar power systems with oil coolant (courtesy of National Renewable Energy Laboratory).

Two separate studies have examined coupling sensible heat storage to LWRs using these high temperature oils. The North Carolina State and Westinghouse designs enable peak power capabilities 20 to 25% higher than base-load power. Both studies concluded heat transfer oils are likely to be the preferred heat transfer fluid when coupling sensible heat storage to an LWR.

The North Caroline State University studies (Fitzhugh 2016, Edwards 2016, Frick 2017a, Frick 2017b) examined the use of oil heat transfer fluids for heat storage coupled to small modular pressurized water reactors for variable electricity production. The system can be scaled to any size. The analysis simulated reactor operations where the reactor operated at constant output with variable electricity to the grid and showed the viability of coupling a PWR to heat storage using these oils. Organic heat transfer fluids have been used in the chemical industry since the 1920s and since the 1980s in solar thermal power systems. In this case the chosen fluid is Therminol®-66 that has an operational range of -2.7 to 343.3°C, a boiling point of 358°C and a heat capacity of 1.039 kWh/(m^3-°C). The Nevada Solar One heat storage system uses Dowtherm A, a similar heat transfer fluid, for heat storage (Kuravi 2013). Westinghouse uses the heat transfer oils to transfer heat from the power cycle to storage and back—but the primary heat storage medium is concrete to minimize the use of expensive oil for the storage system (next section).

4.3 Concrete

Concrete can be used as a sensible heat storage media. Westinghouse (Appendix C, Stansbury) proposes using concrete up to 400°C as the heat storage media for stand-alone heat pump applications (electricity to heat to electricity), LWRs, and LFRs. For reactor applications this is a low-pressure system where heat-transfer oils move heat to and from the balance of plant. Bright Energy proposes to embed steam pipes in concrete with heat transferred to the storage system at temperatures up to 600°C. Both of these storage concepts use modified cements where there are no structural requirements except to be self-supporting. To avoid cracking and failure under thermal cycling, all of these cements have a low water content that can be obtained by appropriate formulation of the cement or using such processes as steam curing to remove excess water after the cement sets up. The development of cements for higher-temperature applications goes back many decades for specialized applications such as concrete in higher-temperature industrial environments, cementing of deep wells and cement waste forms for radioactive wastes.

Westinghouse (2016) has begun development of a sensible heat storage system (Figure 4.4) where a shipping container-sized storage module stores sufficient heat to generate approximately two MWh of electricity. The working fluid (depending upon reactor system) heats the low-pressure oil which then transfers its heat to a heat storage module. The heat storage tanks have vertically oriented concrete plates which serve as the primary heat storage media. Between these plates are formed passages through which oil may pass; depositing its heat energy. Concrete is used as the primary heat storage media rather than oil because concrete is much less expensive than oil and the concrete plates can be manufactured locally. The ability to design the flow passages in concrete reduces the oil volume and pressure losses when compared to a packed bed. Some investigated variants have a predicted oil volume comprising less than 5% of the volume of the storage tank. As the oil's flow direction is reversed during discharge, the assembly acts in a manner similar to a counter-flow heat exchanger, thus minimizing the round-trip (effective) approach temperature and maximizing efficiency. The discharged hot oil can be used to (1) heat CO_2 in a stand-alone pumped heat storage device, (2) manipulate balance of plant process flows in an integrated super-critical carbon-dioxide power cycle, (3) allow auxiliary heating of feed water, thus reducing extraction steam from the main turbine in a new-build LWR, or (4) tie to an auxiliary steam turbine. Figure 4.5 shows Westinghouse proof-of-principle testing.

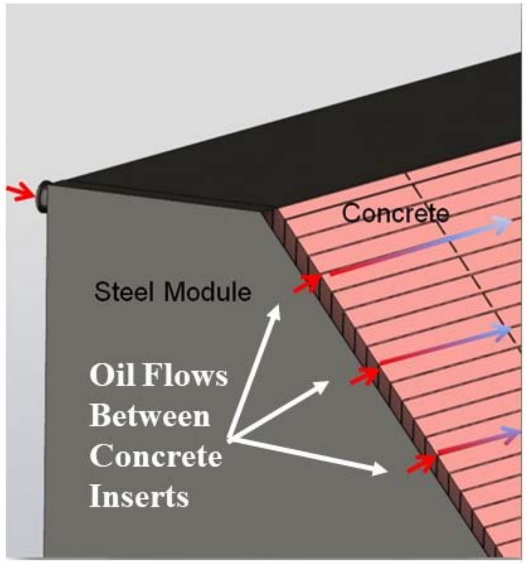


Figure 4.4. Westinghouse thermal heat storage module.

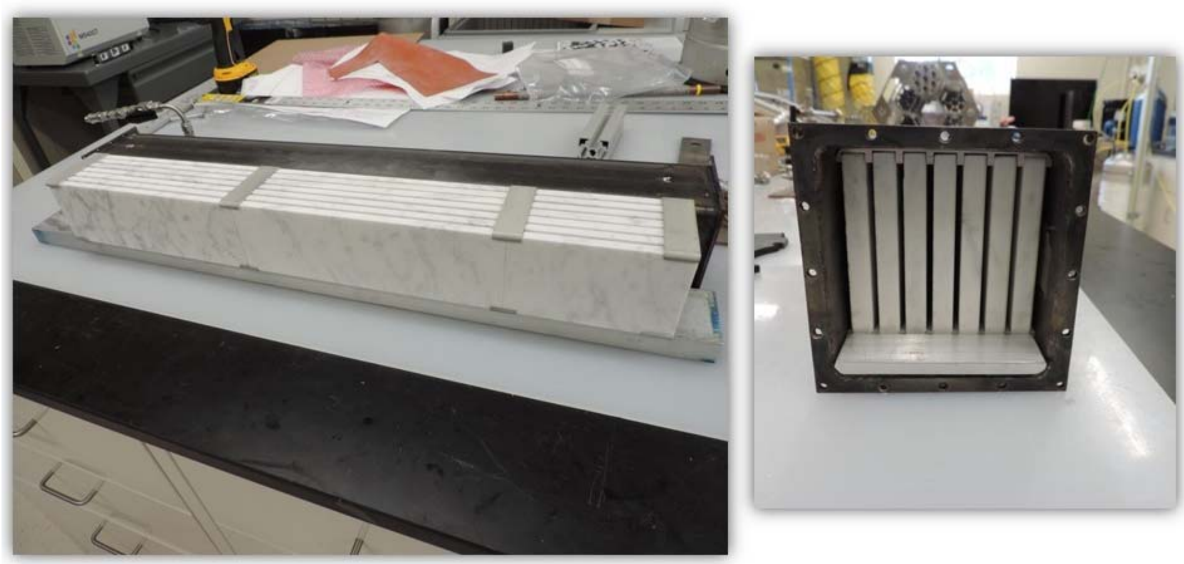


Figure 4.5. Westinghouse proof of principle testing.

Westinghouse envisions heat storage in excess of 500 MWh(e). The charge or discharge rate would be one forth the heat storage capacity; that is, if 500 MWh(e) of storage, the charge or discharge rate would be 125 MW(e). Modeling conducted on a theoretical new-build LWR plant with integrated storage, using the main turbine for all generation, showed that peak power output could be 20 to 25% greater than the base-load capacity. This arrangement minimizes capital costs and enables fast response. A schematic of the power cycle configured for heat input into the power cycle for peak electricity production is shown in Figure 4.6. At times of low electricity demand, high-pressure steam is used to heat oil that heats the concrete. During normal operation of an LWR, steam is extracted from the turbines to preheat feed water going to the steam generator. For peak electricity production the steam extraction from the high-pressure turbine is shut down, boosting the power output of the turbine. The replacement heat for the feed-water heaters at this time is provided by heat stored in the concrete. There would be a slight loss in base-load plant efficiency (~1%) during normal operation for this peaking capability because the turbine is oversized to enable peak power production that results in somewhat lower efficiency during base-load operation. Variants of this system are applicable to any nuclear plant with a steam cycle.

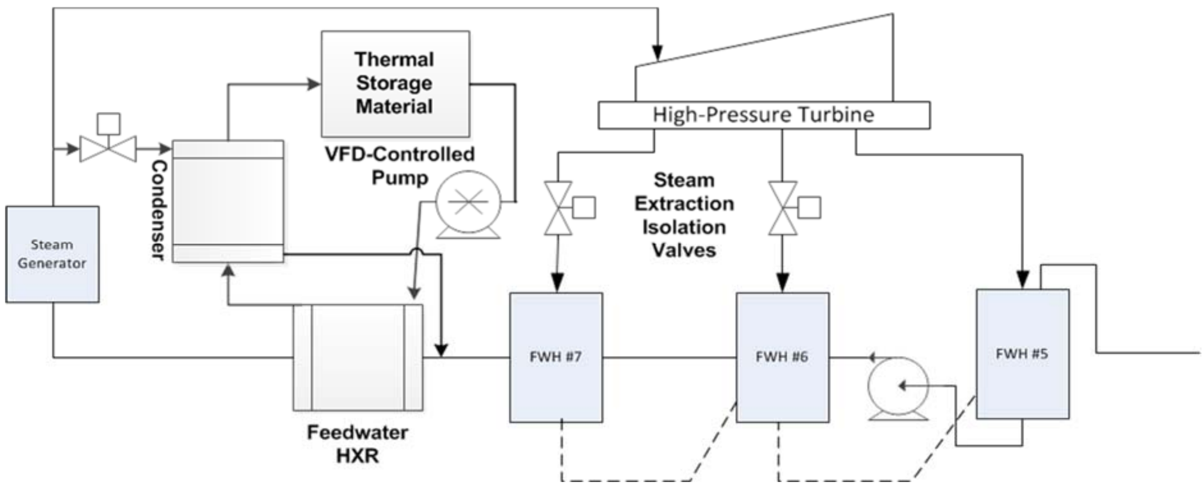


Figure 4.6. Configuration of the heat storage system within the power cycle.

Bright Energy (2019) (Appendix C, Pykkonen) is developing a heat storage system based on the high-temperature capabilities of special concretes up to 600°C. Spiral tubes with steam go through the concrete to heat up the concrete with liquid water exiting the pipes. To recover the heat, water goes in the reverse direction to produce high-temperature steam (Figure 4.7-9). For efficient recovery of heat, three modules are connected in series. Each module is 1 meter by 1 meter by 12.5 meters. The same system can be used to store heat from hot gases or other fluids.

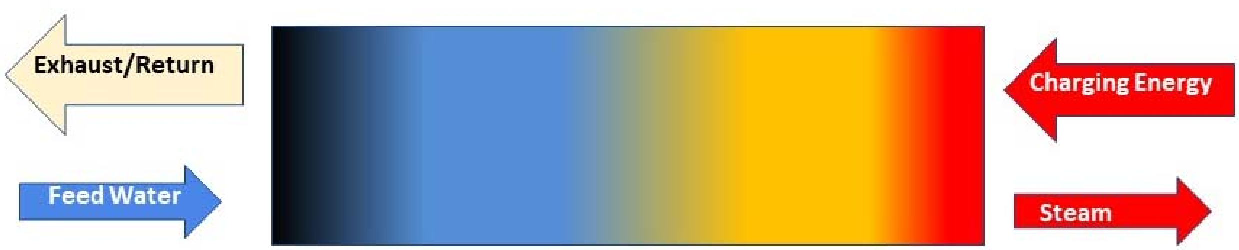


Figure 4.7. Counter-current heat flow in modular concrete modules.

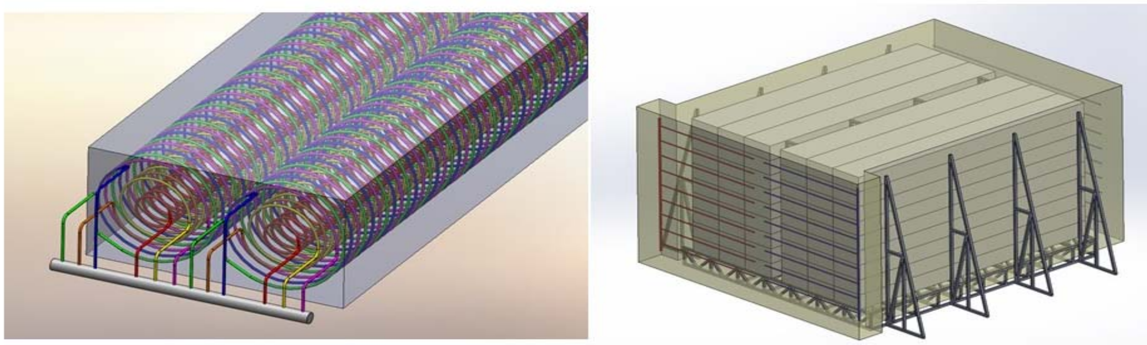


Figure 4.8. Modular concrete modules (1 m by 1 m) and Assembled Heat Storage Facility.

Figure 4.9. Thermal energy storage module details.

Bright Energy estimates the total project cost at \$278/kW(e) plus \$62/kWh(e). This assumes a separate steam peaking turbine cost of \$200/kW and a specific design with a 71% round trip efficiency; that is, if one kilowatt hour of electricity with the base-line system, one would deliver 0.71 kilowatt hours of peak electricity in a system with a steam inlet pressure of 62 bar, and a 20-bar discharge pressure. A 3 GWh system would have 75,000 tubes and be 100 meters by 30 meters by 50 meters.

A test of a 10 MWh(e) storage system is being planned by EPRI at the Gaston Steam Plant in Alabama to be commissioned in 2020. The near-term market is for fossil plants to convert them into plants designed for peak power production. For a three-unit coal plant, the boilers of two units would be shut down. The third boiler would provide steam to one turbine and to the storage system. For peak power, all three turbo-generators would be used—a potentially lower cost alternative to lithium ion batteries. Preliminary EPRI estimates are that the capital cost could be a third to a fourth of the capital cost of lithium ion batteries per unit of electricity storage. For a nuclear plant, a separate peaking turbine would be built for peak power (Figure 4.10).

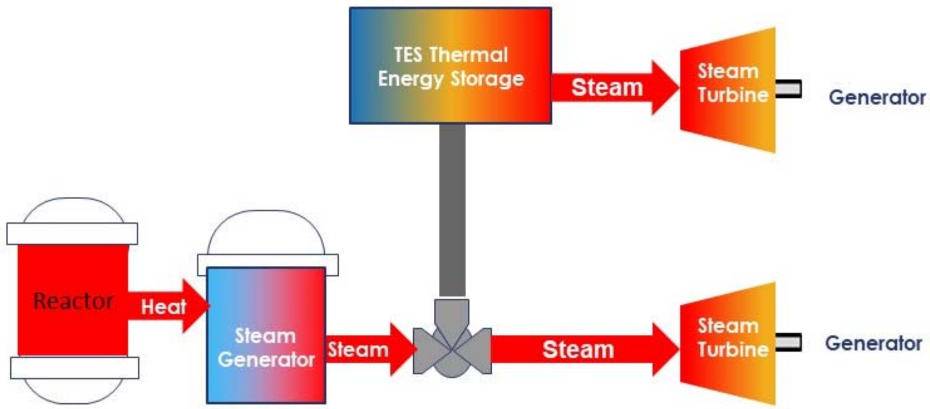


Figure 4.10. Heat storage system in discharge mode with separate steam peaking turbine.

Such a concrete system may also be used with a gas turbine where at times of low electricity demand some or all of the hot air from the turbine goes to a recuperator to reduce electricity output from the heat recovery steam generator. When the cooler air exits the recuperator, it is sent up the stack. At times of high demand hot air is sent to the heat recovery steam generator from (1) the turbine and (2) the recuperator by blowing cold air into the recuperator resulting in hot air exiting the recuperator. The same technology is applicable to Nuclear Air-Brayton Combined Cycles (NACC) as discussed in Section V.

4.4 Nitrate Salts

The only heat storage technology deployed today at the gigawatt-hour scale is nitrate salts in CSP systems (Appendix C, Kelly) such as at the SolarReserve (2019) Crescent Dunes project. Figure 4.11 shows the schematic of such a system. Sunlight is focused on the solar power tower where it heats nitrate salts with the hot nitrate salt flowing to the hot nitrate salt storage tank. Hot salt from that tank provides heat to the power cycle as needed and independent of the short-term output of the solar power tower. The cold salt from the power cycle flows to a cold salt storage tank and back to the solar power tower if the sun is shining.

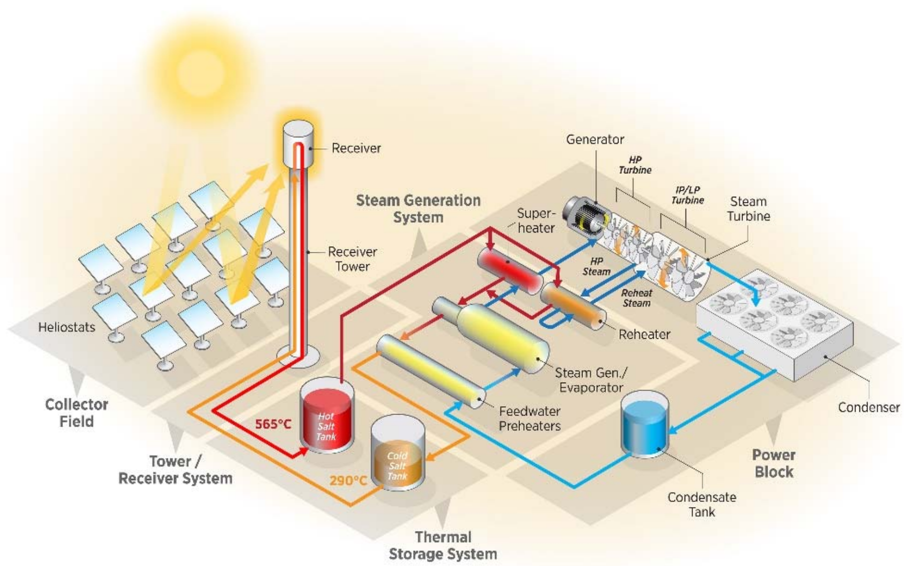


Figure 4.11. Nitrate salt concentrated solar power system (National Renewable Energy Laboratory).

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 the most common salt and 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, Medrano 2010) but this may be somewhat extendable with control of the atmosphere above the salt (Olivares 2012, Abengoa Solar 2013)—perhaps as high as 650°C. These salts are chemically stable in air and water with heat storage system capital costs in CSP systems near $20/kWh. The largest storage system sizes are measured in gigawatt-hours of capacity. Nitrate salts can be used to move heat to industrial customers.

There is now considerable experience with the nitrate salt storage systems with a significant learning curve. A large tank stores a gigawatt-hour of heat. The newest tanks are 12 meters high and 40 meters in diameter. The experience with pumps has been excellent. The total pump height is 15 to 16 meters with the pump section 12 m high. These pumps have the motor on top, pump shaft and pump at the bottom. This design avoids the need for seals in the hot salt. There have been reliability problems with valves that are in the salt resulting in the need for redundant valve systems. With the larger tanks there have been problems with foundations in the hot salt tanks caused by thermal expansion and contraction of the tanks. The weight of the salt results in a 5000-psi footing pressure. The more recent experience suggests that most of these difficulties have now been addressed.

Nitrate salt storage systems (Figure 4.12) are proposed for SFRs (TerraPower), FHRs (Kairos Power) with solid fuel and clean salt coolants, thermal-spectrum MSRs with fuel dissolved in the salt and fusion machines. In all of these reactor systems, the intermediate nitrate loop between the reactor and power block has multiple functions. In addition to providing heat storage, the low-pressure nitrate salt intermediate loop provides isolation of the reactor from the high-pressure steam in the power cycle. In SFRs, the nitrate intermediate loop avoids the risk of generating hydrogen from a sodium-steam interaction. For FHRs, MSRs, and fusion (Forsberg, Baglietto, Bucci, and Ballinge 2019) the salt serves two purposes: (1) heat storage and (2) tritium trapping. These reactor systems generate tritium in the coolant that may diffuse through heat exchangers. If tritium enters a nitrate salt, it is converted into steam that can be collected in the tank off-gas system. Hot nitrate storage acts as a backup tritium removal system.

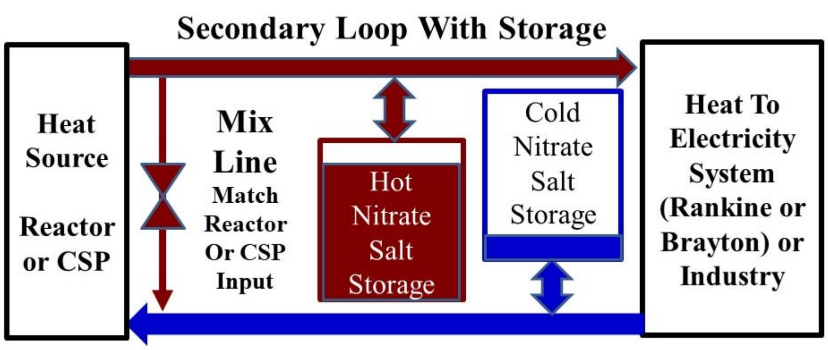


Figure 4.12. Nitrate heat storage system coupled to salt or sodium reactor or CSP system.

There are several other considerations in using nitrate salt storage systems with these reactor systems.

- Salt reactors: All of the salt reactors have coolants with melting points above 400°C. To minimize heat storage costs, one wants to maximize the hot-to-cold temperature swing in the nitrate salt system. If the nitrate cold salt is at 290°C, it will probably be mixed with hot salt for a higher minimum nitrate salt inlet temperature into the reactor salt / nitrate salt heat exchanger (Figure 4.12).

- HTGRs: The large hot to cold temperature swing of helium in a HTGR provides a reasonably good match with nitrate salts. Peak helium temperatures are typically about 750°C—above the maximum salt temperatures and thus caution is required (at temperatures >600°C) to avoid degrading the nitrate salt.

4.5 Chloride Salts

A leading longer-term salt heat-storage option for the secondary loop of higher temperature salt-cooled and helium-cooled nuclear reactors is a sodium potassium magnesium chloride salt being developed for CSP systems (Mehos 2017, Mohan 2018, Mohan et al. 2018, Appendix C, Turchi) with operating temperatures above 700°C—significantly above the temperatures of solar-power towers using nitrate salts and above the decomposition temperatures of nitrate salts. Other candidate high-temperature salts considered by the CSP program include zinc chloride blends and carbonate salts.

Magnesium chloride salt blends have 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, potentially enabling very-low-cost heat storage. The nominal salt composition is 40:40:20 mole percent $MgCl_2$:KCl:NaCl with a melting point near 400°C. The starting point for producing the salt is carnallite ($KMgCl_3$), a salt used in the production of magnesium metal and available at very low cost. Sodium chloride is added to the raw carnallite which increases the heat capacity and lowers the melting point. The magnesium industry uses a purified blend known as anhydrous carnallite (AC), which is also proposed as the feedstock for the thermal storage applications. The phase diagram for this salt system is shown in Figure 4.13. The yellow circle shows the target range of compositions. A single tight composition specification is not used because it would imply a more expensive salt.

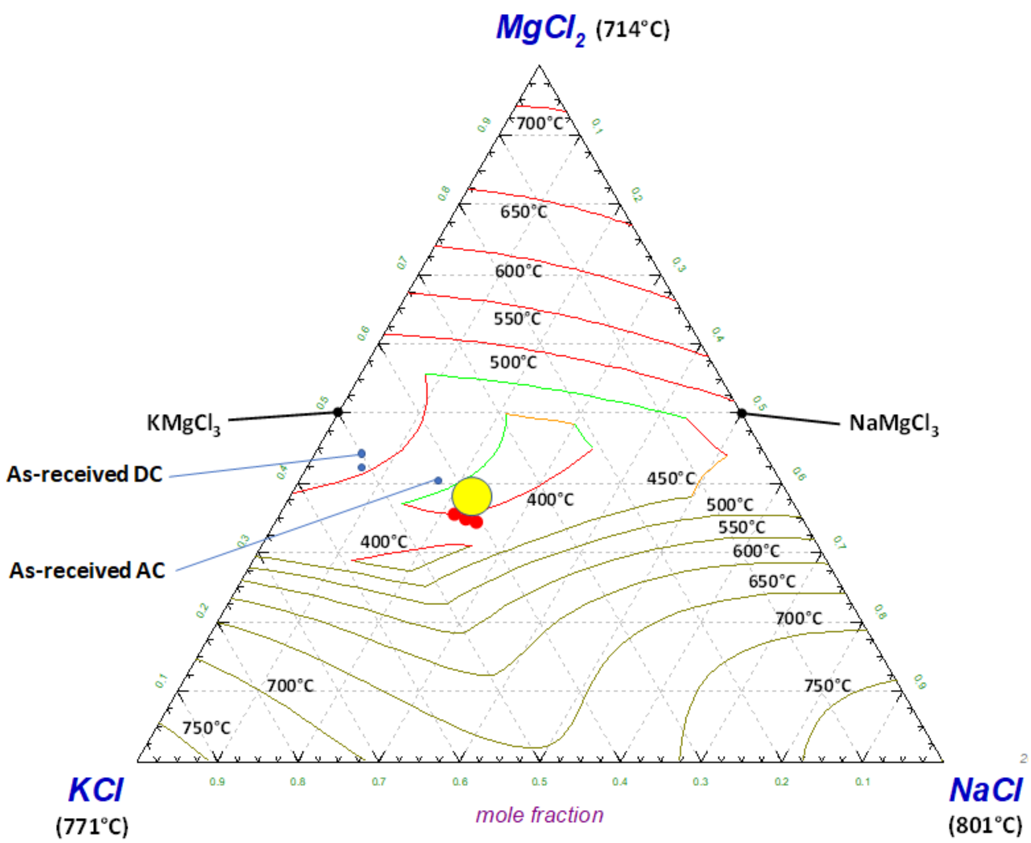


Figure 4.13. Phase diagram of chloride salt system (Mohan 2018).

The phase diagram of $MgCl_2$-KCl-NaCl is shown in Figure 4.13. 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.% $MgCl_2$. The salt is highly hydroscopic because water will react with the magnesium chloride. Current work is focused on developing a chemical redox control strategy using magnesium metal dissolved in the salt to control corrosion (Ding et al. 2018). Significant research and development remains to be done on these systems to confirm the effectiveness of the chemical control method under industrial conditions.

If the temperature differential in storage is 200°C, the storage cost for the salt itself is estimated at $ 5/kWh, below that of nitrate salt storage or any other liquid heat-storage system that has been identified to date—far below the TES system capital cost goal of $15/kWh. The cost of different heat-storage systems using different salts if built today is shown in Figure 4.14. Total costs for the higher-temperature chloride systems are dominated by the tank costs. This assumes using the same design strategy used for nitrate salt storage except higher quality steels that can operate at the higher temperatures with insulation on the outside of the steel tank. For these very high temperatures, this requires the use of very expensive alloys and thus high costs. Current work is on developing insulating ceramics on the inside of the tank to enable the use of cheap carbon steel tanks. In the magnesium industry, internally insulated tanks are used but at a much smaller size without the transients associated with a heat storage system. Work is underway to develop and demonstrate low-cost tank storage technologies.

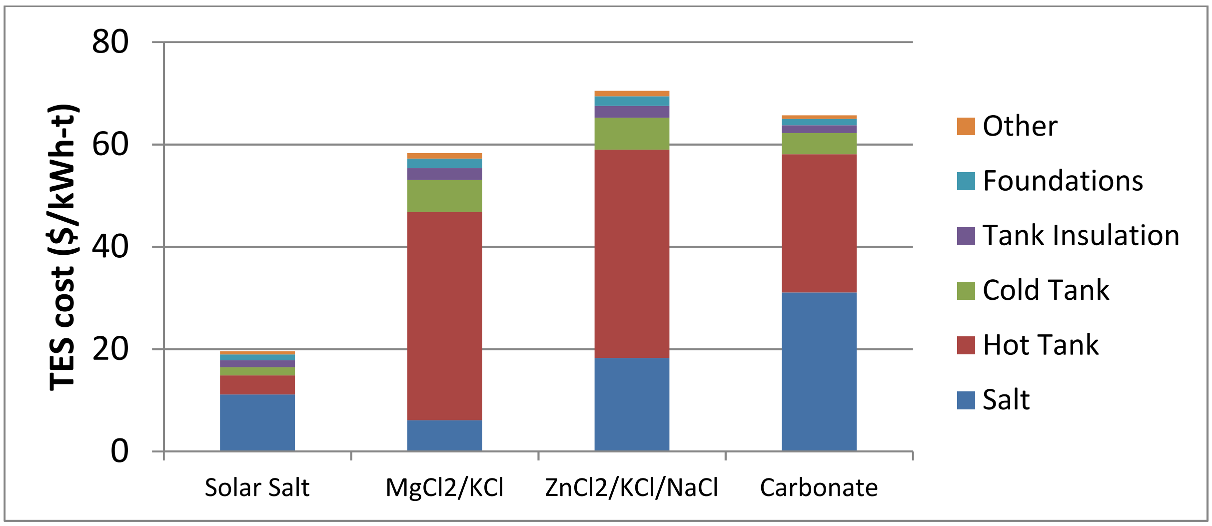


Figure 4.14. Costs of different salt thermal storage systems using traditional externally insulated salt tank designs (Mehos et al. 2017).

The salt could be stored using either a one- or two-tank salt heat-storage system. These >700°C salts are leveraging expertise from CSP industry use of nitrate salts at ~560°C, as well as prior research from the nuclear power sector. If the technology can be fully developed, this low-cost high-temperature heat-storage system can deliver high-temperature fluid to the power cycle for peak power, with high heat-to-electricity efficiency. There are large economic incentives for the CSP community to solve the challenges to make these salts work.

4.6 Hot Sand

One of the three pathways being pursued by the DOE CSP program is evaluating hot solid particles (“sand”) as the heat-transfer and storage media (Ho 2016, Ho 2017, Appendix C, Ho). Sand flows through the solar receiver at the top of a tower (Figure 4.15) where sunlight from hundreds or thousands of mirrors heats the sand. Peak temperatures can exceed 900°C. The hot sand flows to a storage tank so that it can be stored and used when needed. At times of high electricity demand, hot sand flows through a heat exchanger to produce steam or heat another working fluid that is sent to the power cycle. The “cold” sand is then returned to the top of the tower to be reheated. The use of sand in the solar receiver avoids the problems of burnout of receiver tubes and freezing of molten-salt—a major advantage in high-temperature systems.

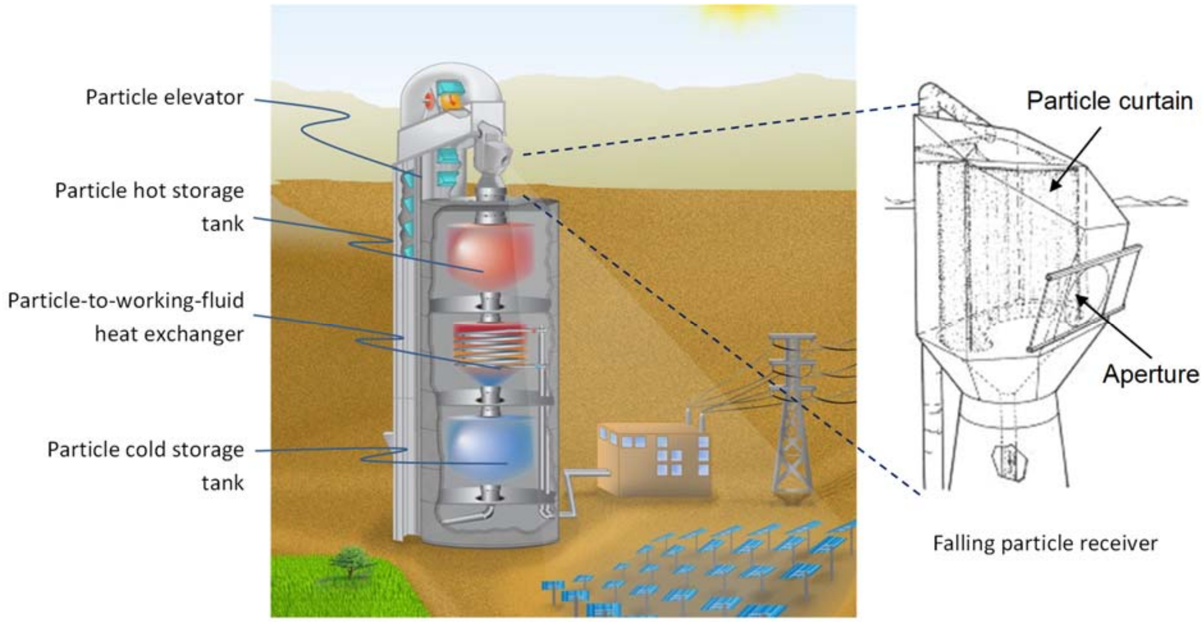


Figure 4.15. Particle bed solar towner.

Significant work is underway to develop this technology (Figure 4.16) including plans for a larger-scale pilot plant at Sandia National Laboratories. This includes experimental work and various assessments of the technology. Recent assessments have compared hot sand relative to other heat storage technologies (Table 4.3). One of the biggest challenges is the design of a flowing sand heat exchanger (Schwaiger 2015, Albrecht and Ho 2019)—sand has lower particle-side heat-transfer coefficients and can be abrasive. The Technical University of Vienna (Haider 2019) is starting a 280 kW fluidized bed sand heat exchanger that is part of a sand thermal energy storage system.

Figure 4.16. Sandia National Laboratory 1 MWt particle-receiver system.

Table 4.3. Comparison of different storage technologies (Ho 2016).

Technology	Levelized Cost ($/MWhe)	Round Trip Efficiency	Cycle Life	Toxicity / Environmental Impacts	Restrictions / Limitations
Solid Particles	10 – 13	>98% thermal storage ~40% thermal-to-electric	>10,000	N/A	Particle/fluid heat transfer can be challenging
Molten Nitrate Salts	11 – 17	>98% thermal storage ~40% thermal-to-electric	>10,000	Reactive with piping materials	< 600°C (decomposes above ~600°C)
Batteries	100 – 1,000	60 – 90%	1000 – 5000	Heavy metal environmental and health concerns	Very expensive for utility-scale storage
Pumped Hydro	150 – 220	65 – 80%	>10,000	Water evaporation/ consumption	Large amounts of water required
Compressed Air	120 – 210	40 – 70%	>10,000	Requires large underground caverns	Unique geography required
Flywheels	350 – 400	80 – 90%	>10,000	N/A	Only seconds to minutes of storage

The requirements for sand heat storage for nuclear heat storage applications are significantly less than for CSP where a black sand with the appropriate optical properties is desired to maximize absorption of sunlight. The biggest advantage of sand is the extremely low cost per unit of heat storage. Furthermore, hot sand is cheap to store—a firebrick-lined vault with outward-sloping walls enables low-cost storage. The incremental cost of added storage could be below a dollar per kWh. These characteristics may favor its use for multiday (wind price collapse) and weekday/weekend heat storage where there are incentives for gigawatt-days of heat storage. As a solid there are minimum safety hazards. The challenges are associated with development of the heat exchangers, which includes increasing particle-side heat transfer and reducing costs.

4.7 Atmospheric-Pressure Crushed-Rock Heat Storage

Hot rock storage is being developed for multiple purposes. The most advanced project is the Siemens Gamesa Renewable Energy electric thermal energy storage system (Siemens Gamesa Renewable Energy 2019, Proctor 2019). To charge the system at times of low electricity prices, air is heated with electric heaters and blown through the crushed rock, heating the rock to ~750°C. At times of high electricity prices, air is blown through the crushed rock to provide hot air to a steam boiler. The heat storage system is being designed as a retrofit to coal plants that are being shut down to convert them into large-scale storage systems to produce peak power. The 130 MWh pilot plant is shown in Figure 4.17. The pilot plant contains ~ 1,000 tonnes of volcanic rock as an energy storage medium. At commercial scale the system would store up to several gigawatt hours of heat. Such a system could directly couple to a helium or salt-cooled reactor.

Figure 4.17. Siemens Gamesa Renewable Energy Electric Thermal Energy Storage System Pilot Plant with 130 MWh of heat storage.

Hot rock heat storage systems have been examined for storing heat from nuclear reactors (Forsberg, Curtis, and Stack 2017) for multi-gigawatt hour heat storage. A volume of crushed rock with air ducts at the top and bottom is created (Figure 4.18). To charge the system, air is heated using a steam-to-air heat exchanger delivering heat from the reactor, then the air is circulated through the crushed rock heating the rock. To discharge the system, the airflow is reversed, and cold air is circulated through the crushed rock. The discharged hot air can be used to (1) produce steam for electricity or industry or (2) recuperated for collocated industrial furnaces to reduce natural gas consumption.

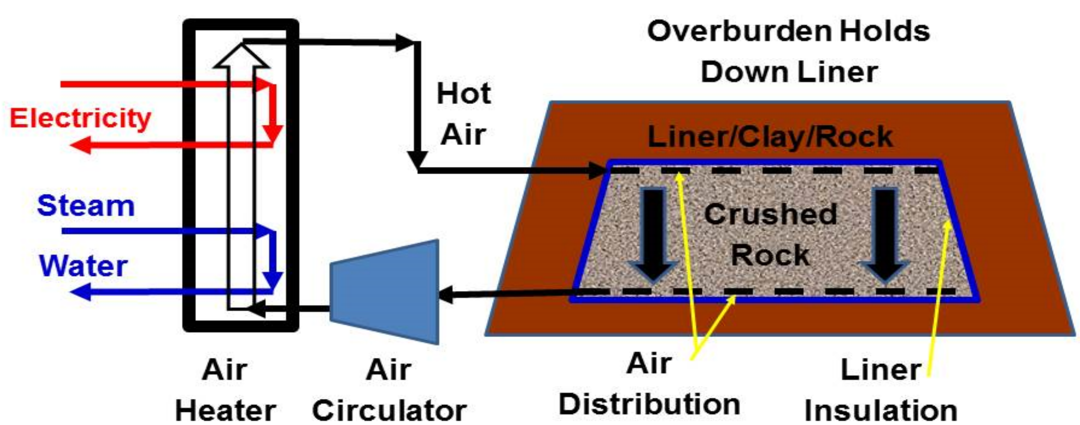


Figure 4.18. Hot rock storage with steam and electric input.

Heat storage systems are only charged at times of very low electricity prices. There is the option with this system to first heat the air with a steam-air heat exchanger and then further heat the air with electric resistance heating. LWR steam peak temperatures are near 300°C—well below the temperature limits of the crushed rock. Higher temperatures improve system efficiency and reduce costs. This can substantially boost rock temperatures and the efficiency of converting hot air back to electricity and reduce capital costs. Near atmospheric operating conditions increase safety and reduce storage costs.

A variant of large hot-rock systems is under development by the shale oil industry (Red Leaf Inc.) to produce oil. In that system the rock is crushed oil shale and heated hot gases are circulated through the rock to decompose solid kerogen into liquid and gaseous hydrocarbon fuels. For that system the rock pile will be about 30 meters high. Much of the technology required for hot rock heat storage is being developed by such projects.

There is an important feature of storage systems where the flowing fluid is non-conductive. The capital cost of electric heating systems is very low. At a power station the cost of bringing in electricity is low—the grid connections, switchgear and other systems already exist to enable export of electricity. The primary added capital cost is associated with the electric heaters and incrementally more of the heat storage media. In non-conductive media (air, hot rock, etc.) one can use uninsulated electric resistance heaters with 10kV across the heaters. The higher the voltage, the fewer the number of switches and other components to convert electricity into heat. In contrast, to date no one has developed an equivalently low-cost electric resistance heater when the fluid is conductive to electricity (nitrate or chloride salts). In those cases, resistance-heating system components must be electrically insulated.

4.8 Pressurized Counter-Current Condensing-Steam Solid Heat Storage

A packed-bed thermal energy storage system (Bindra 2013, Edwards 2016a, Edwards 2016b, Wilson 2019) consists of a pressure vessel filled with solid pebbles with a steam valve at the top and water outlet at the bottom. Heat is stored as sensible heat in the pebbles. At the end of a discharge cycle, the pebble bed is filled with cold water. To charge the system (Figure 4.19, left side), steam is injected at the top of the vessel as water is drained from the bottom of the vessel. The steam condenses as the cold pebbles are heated. Because of the extremely good heat transfer of condensing steam, the steam condensation occurs in a small band resulting in hot pebbles above the condensation zone and cold pebbles below the condensation zone. At the end of the charging cycle all pebbles are hot and are in a steam environment. Figure 24 (center) shows the charging cycle when coupled to a small pressurized reactor.

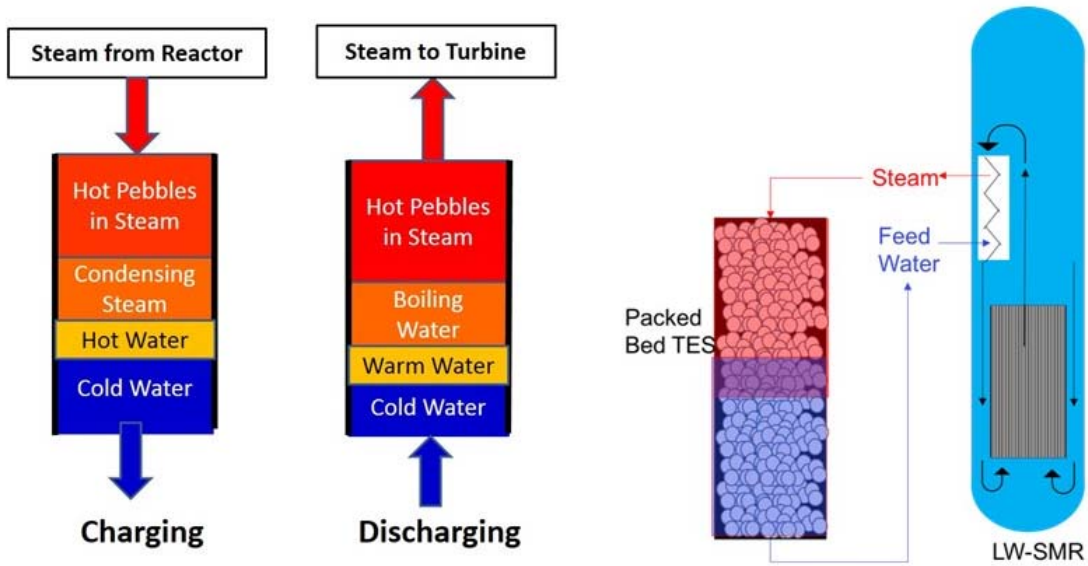


Figure 4.19. Operation of pressurized counter-current heat storage and coupling with small modular reactors.

During the discharge cycle, water is added at the bottom of the vessel. The hot water is converted into steam by the hot pebbles and sent to a turbine to produce electricity. Because boiling is highly efficient, heat transfer occurs in a small zone from bottom to top with the steam leaving the vessel as hot steam as it flows through the remainder of the hot packed bed.

In theory this should be the most efficient heat storage system in terms of round-trip efficiency. The heat storage system directly uses steam with no temperature losses in a heat exchanger in either direction—steam in and steam out. Packed beds are more thermodynamically efficient than other storage systems because they operate in a counter-current mode—the hottest steam sees the hottest pebbles. A sharp hot-to-cold front with small dimensions is only possible with a saturated-steam input where the very high heat transfer of condensation and boiling occurs over a very small zone in the bed. This is not true for superheated steam and other systems where the length of the heat transfer zone becomes excessively long relative to practical dimensions of real systems. There has been limited experimental work. Figure 4.20 shows some recent experiments with a packed column and the sharp line of condensation.

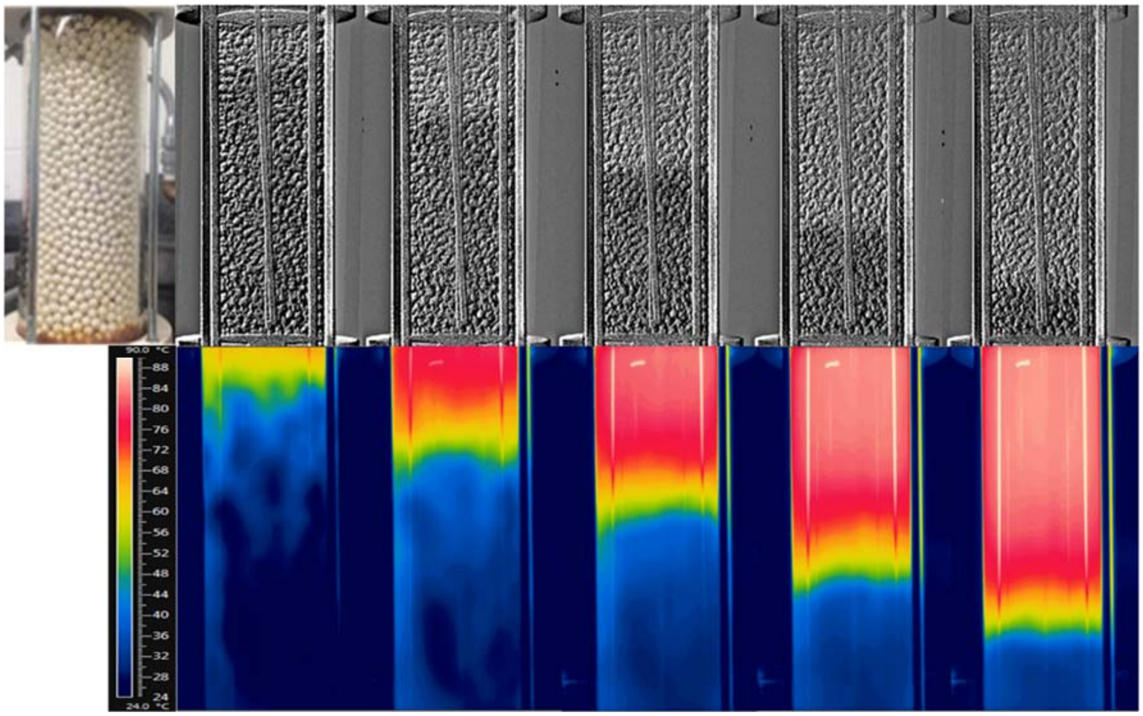


Figure 4.20. Atmospheric steam as heat transfer fluid and an alumina packed bed as storage media, x-ray and IR images every 10 seconds (Bindra et al. 2017).

The design options for packed-bed systems, including the range of suitable pebble materials and sizes, and the impacts of pebble choice on dynamic performance, are only partly explored. The storage economics is likely limited to hourly and daily cycles because of the cost of the pressure vessel. This storage technology is applicable to any reactor with a steam cycle at the point the steam cycle becomes saturated steam.

4.9 Cast Iron with Cladding

The cost and safety of the storage system can be improved in many cases by adding a low-cost solid to the heat storage tanks to provide most of the heat storage capacity. The simplest option [Appendix C, Forsberg] is storing heat in cast iron with a steel cladding with a composition chosen to be compatible with the coolant (Figure 4.21). The tank is filled with hexagonal billets, 10 to 20 meters tall, with spacing between billets for coolant flow and to provide space for thermal expansion. The cast iron occupies more than 95% of the volume to minimize cost and for coolants such as sodium to minimize safety hazards. The high density of iron translates into a high volumetric heat capacity relative to almost all other materials. Cast iron has a large temperature range relative to most other sensible heat storage materials. The cast iron has a cladding where the metal is chosen for corrosion resistance to primary or secondary reactor coolant (sodium, salt, lead or helium).

The allowable temperature ranges from 100 to between 700 and 900°C depending upon the iron composition. Cast iron undergoes a phase transition with a large change in volume that would likely cause major design challenges; thus, operating temperatures should be held below this transition temperature. That phase change for cast iron (iron with carbon) is at 727°C. With pure iron the phase change occurs at 917°C. The phase change temperature can also be altered by alloying the composition. The question is cost in going from the cheapest forms of iron to more expensive forms to for higher temperature capabilities.

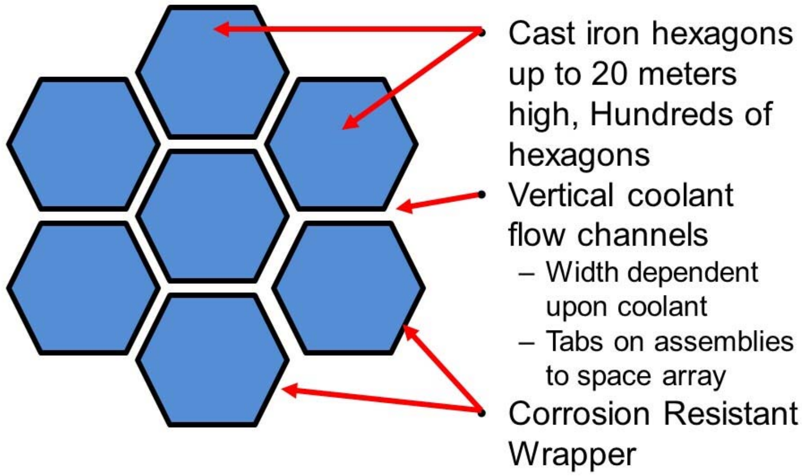


Figure 4.21. Hexagonal cast iron heat storage with corrosion-resistant wrapper.

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 DOE cost goal for heat storage of $15/kWh, excluding other system costs. Cast iron with cladding sets an upper cost of heat storage for any system because the choice of cladding makes cast iron compatible with any coolant. That has major implications for developers of storage systems. It provides a clear dividing line between potentially economically viable storage materials and those that are clearly non-economic.

There are multiple methods to bond the cladding material to the cast iron including (1) weld overlay, (2) co-extrusion, and (3) placing the iron hexagon in a container of the clad material, pulling a vacuum and heating to bond the clad to the iron. The characteristics of this option requires integrating into the design team the steel company to identify and implement the lowest cost manufacturing option—this is all about minimizing manufacturing costs.

For sodium-cooled reactors, heat storage would be placed in the intermediate sodium loop (Forsberg 2018, Forsberg and Sabharwall 2018). There has been previous work that examined many other options for CSP sodium systems (Niedermier et al. 2016). The use of metal ingots 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 is 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 cost of cast iron is less than half the cost of sodium. The system design would be similar to Figure 3.2 or 3.3 to enable a 300°C temperature drop across the heat storage media with a much smaller drop across the reactor.

4.10 Nuclear Geothermal Heat Storage

Geologic heat storage systems (Lee 2010, Lee 2011, Forsberg 2012, Forsberg 2013) combine the features of an enhanced geothermal energy facility with thermal energy storage. Thermal energy is stored

(Figure 4.22) underground by injecting hot water heated by the reactor from the surface into the rock reservoir; heat is primarily stored in the rock, and heat is recovered by water flowing through the rock back to the surface for electricity production in a conventional geothermal plant. Under certain circumstances, there may be the option to use carbon dioxide (Kulhanek 2012) as the heat transfer fluid. This is the only heat storage option that is a candidate for hourly through seasonal energy storage because of the extremely low cost of the storage media—hot rock. In most geologies, the peak temperature will likely be limited to ~300°C because of hot water/rock interactions that will plug water flow channels.

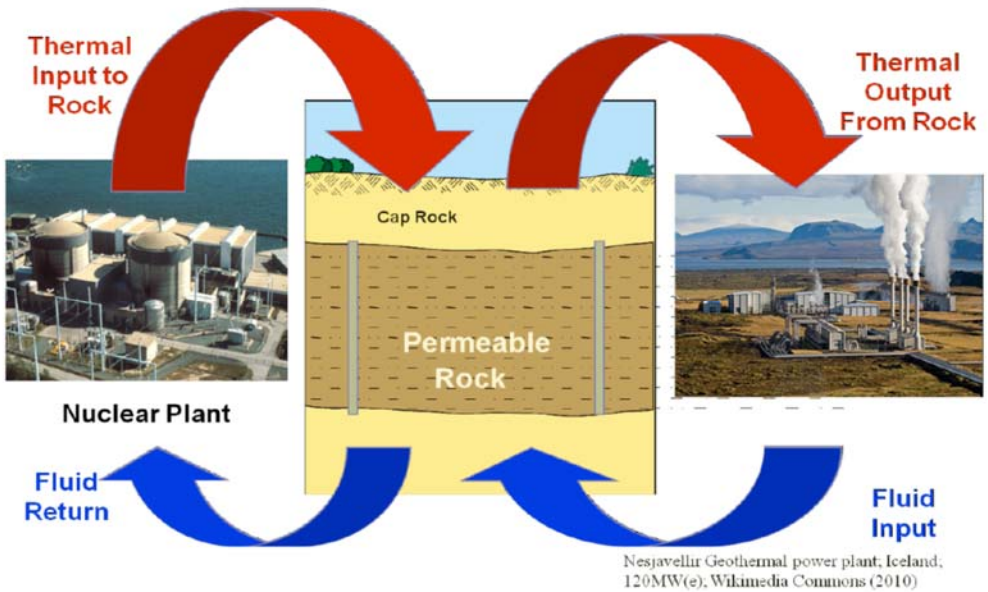


Figure 4.22. Nuclear geothermal heat storage.

It is not possible to insulate rock 500 to 1000 meters underground. There is always the slow loss of heat by conduction into surrounding rock. However, heat losses are proportional to the surface area of the storage zone while heat storage capacity is proportional to the volume. Heat losses vary by the square of the storage reservoir size while heat storage varies by the cube of the storage reservoir size; thus, heat losses decrease as the system size increases (Figure 4.23). The minimum heat storage is a tenth of a gigawatt year—30 to 40 GWd of heat if heat losses are to be limited to a few percent of the heat being stored. As a consequence, this system would be designed for hourly to at least weekly (weekday/weekend) storage. The minimum required scale matches nuclear plants or very large solar thermal systems.

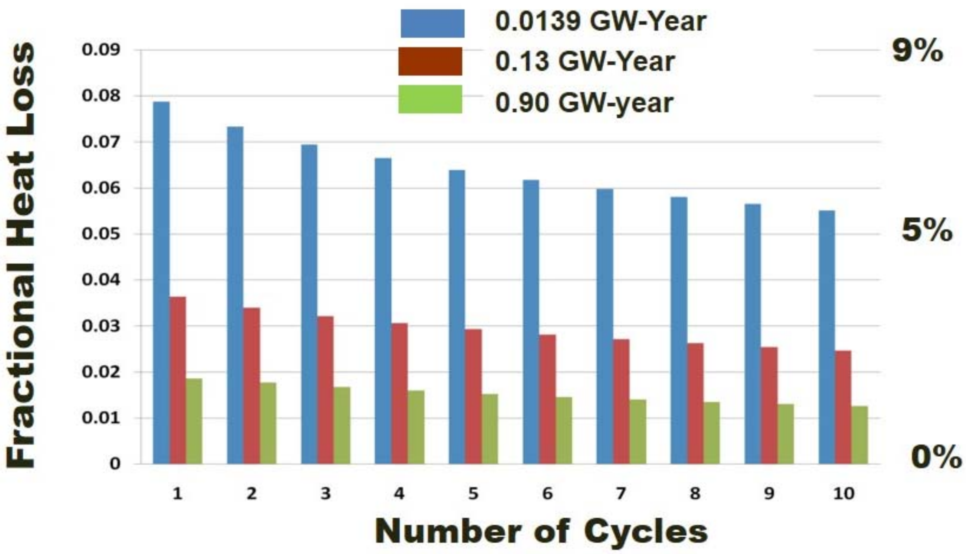


Figure 4.23. Fractional energy losses vs. cycle for three reservoir sizes.

Geothermal heat storage would couple to LWRs directly. For reactors with higher-temperature steam cycles, heat from those steam cycles could only be used after going through high-temperature turbines and reduction in temperature. As water temperatures increase in rock, different elements in the rock dissolve into the water or precipitate from the water. The practical implications are that LWRs are near the peak allowable temperatures for water-based geothermal systems—higher temperatures create conditions where rock dissolution and precipitation may block pores and channels required for efficient hot water flow through the rock.

Geothermal power plants have historically had relatively low efficiencies (Moon 2012). A nuclear geothermal power plant has two differences relative to traditional geothermal power plants that should improve efficiency and reduce costs. First, the power output will be hundreds of megawatts versus tens of megawatts with gains in efficiency associated with larger equipment and more optimized equipment. This includes three-stage and possible four-stage flash power plants that are more efficient than two-stage flash systems but require more equipment. Second, the reservoir will have much cleaner hot water than a typical geothermal power plant. In most geothermal plants the hot water or steam contains large quantities of carbon dioxide and other gases that lower steam cycle efficiency—including the need to remove large quantities of non-condensable gases from the condenser. In a nuclear geothermal system these gases and other impurities are “washed out” of the rock in the first few cycles of operation because the same rock is used again and again.

Heat can be added in three ways. The first option is to pump cold water from the underground geology, send it through a heat exchanger, and then inject it into the hot storage zone. The second option is to send steam to a jet pump to heat the water, boost the pressure and replace the conventional pumps. This option eliminates the temperature drops and costs associated with the heat exchanger resulting in higher round-trip efficiencies. It avoids the issues associated with fouling the heat exchanger with geothermal water. This would provide a low-cost method to send large quantities of heat into the storage reservoir. However, it comes with the added cost of needing large quantities of clean makeup water for the reactor steam generator. The third option is to pump the groundwater through an electric heater that dumps heat into the water at times of low electricity prices. Nuclear geothermal heat storage is dependent upon appropriate geology. Unlike other storage systems, it can’t be built at all locations.

4.10.1 Earth Battery

Recent work on advanced underground energy storage systems (Buscheck 2014, 2015, 2016, 2017) have combined underground heat storage, compressed gas storage (CO_2, N_2, or air), and potentially carbon dioxide sequestration (Figure 4.24). These are enabled by advances in the ability to characterize underground rock formations and advanced drilling techniques developed for oil and gas recovery using fracking. Controlling hydrostatic pressures can create high pressure "walls" to minimize the migration of hot water and compressed gas from the system. This enables storing compressed gases—a second form of geological energy storage. This implies that the energy input at times of low electricity prices may be heat from reactors to create hot-water storage volume (and to heat rock) and electricity from the grid to create a compressed gas storage volume. The compressed gas can be used directly as an energy storage system or to pressurize the system so that there is no need to pump hot water for heat recovery when the geothermal plant is operating. The waste heat of gas compression can also be stored together with heat diverted from the LWR. In principal, this approach could take all the diverted thermal energy and remaining generated electricity from an LWR nuclear power plant during periods of over-generation.

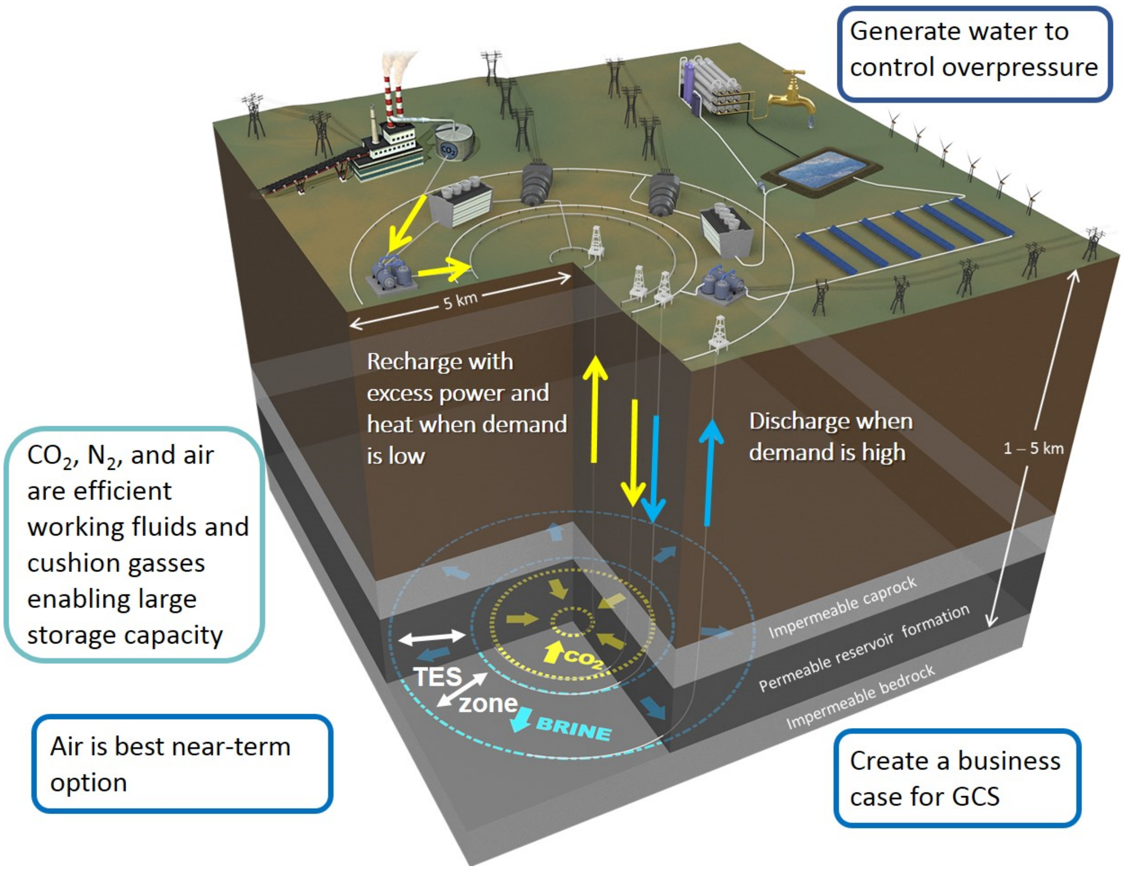


Figure 4.24. An earth battery system with CO_2 is shown.

4.10.2 Unique Characteristics

The unique feature of nuclear geothermal energy storage is the ability to enable seasonal and multiyear energy storage—and with that capability assured generating capacity. The incremental cost of added heat storage capacity in many geologies is near zero. The primary cost of seasonal or multiyear storage is the cost of the heat. This characteristic creates the option of a strategic heat storage reserve—similar to strategic oil and natural gas storage reserves to guard against disruptions in fossil-fuel supply. In a low-carbon world those disruptions could be of biofuels (weather), hydrogen if imported, unexpected weather events such as multiyear droughts that limit hydroelectric output and major weather events such as large hurricanes or typhoons that result in large scale damage to wind production capacity. This also implies that such a storage system could obtain capacity payments because of the assured ability to generate electricity on demand. It is the only storage system that has equivalent assured capacity to a nuclear reactor or fossil fuel plant.

4.11 Cold Water

The limits of power cycle efficiency are controlled by peak temperatures and heat rejection temperatures. If heat rejection temperatures can be reduced, power cycle efficiency can be increased. The French Alternative Energies and Atomic Energy Commission (CEA) for SFRs is developing a Brayton power cycle (Figure 4.25) (Mauger et al. 2019, Bertrand et al. 2016, INPI 2018, Appendix C, Mauger) that uses stored cold water (0.5°C) to improve plant efficiency. The specific application is to enable the power plant to rapidly vary its power levels by 7% by varying water temperatures to the coolers before the compressors to provide frequency control for the grid for a period of 15 minutes. For this application, a swimming pool of cold water is required.

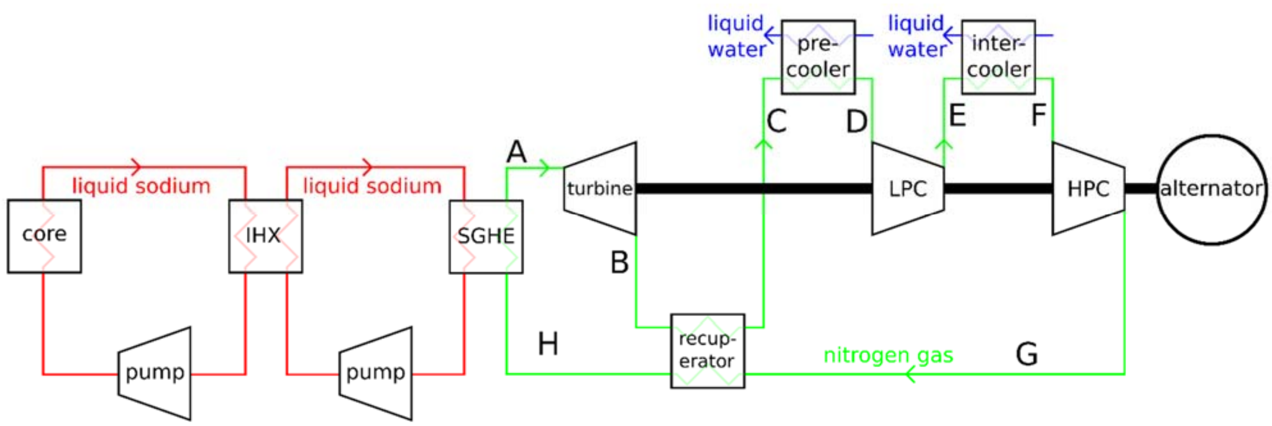


Figure 4.25. Brayton Power Cycle coupled to sodium fast reactor.

The cold water is produced by a refrigeration system (Figure 4.26) at times of low electricity demand or using waste heat from the Brayton cycle to run an absorption chiller. There has been massive research, development and deployment of cold-water storage systems for air conditioning. This includes everything from tanks to ponds with covers for insulation to storing water in underground reservoirs and in certain geologies. As a consequence, there is the potential to extend the time for peak power production to many hours for such Brayton power cycles.

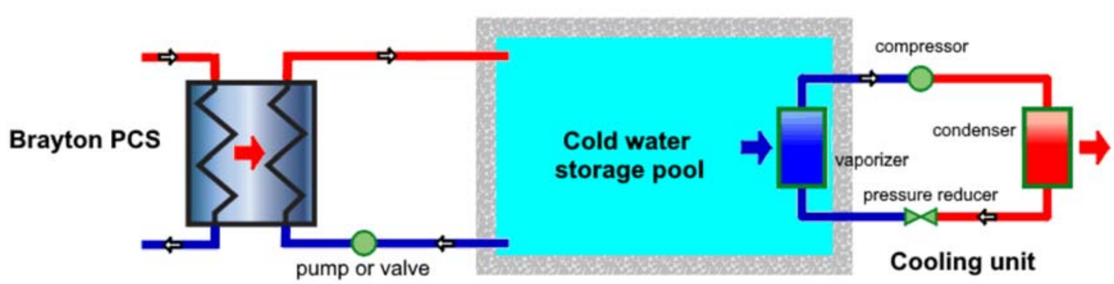


Figure 4.26. Brayton Power Cycle coupled to cold water storage pool.

4.12 Graphite

HTGR cores contain massive quantitate of graphite for neutron moderation and safety. Recent Japanese studies (Forsberg et al. 2017, Yan and Sato 2018) propose to vary power plant output by 20% relative to base load (Figure 4.27 and Figure 4.28) 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). Unlike other heat storage systems, this system allows very rapid changes in power output 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 always operates at base-load power 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.

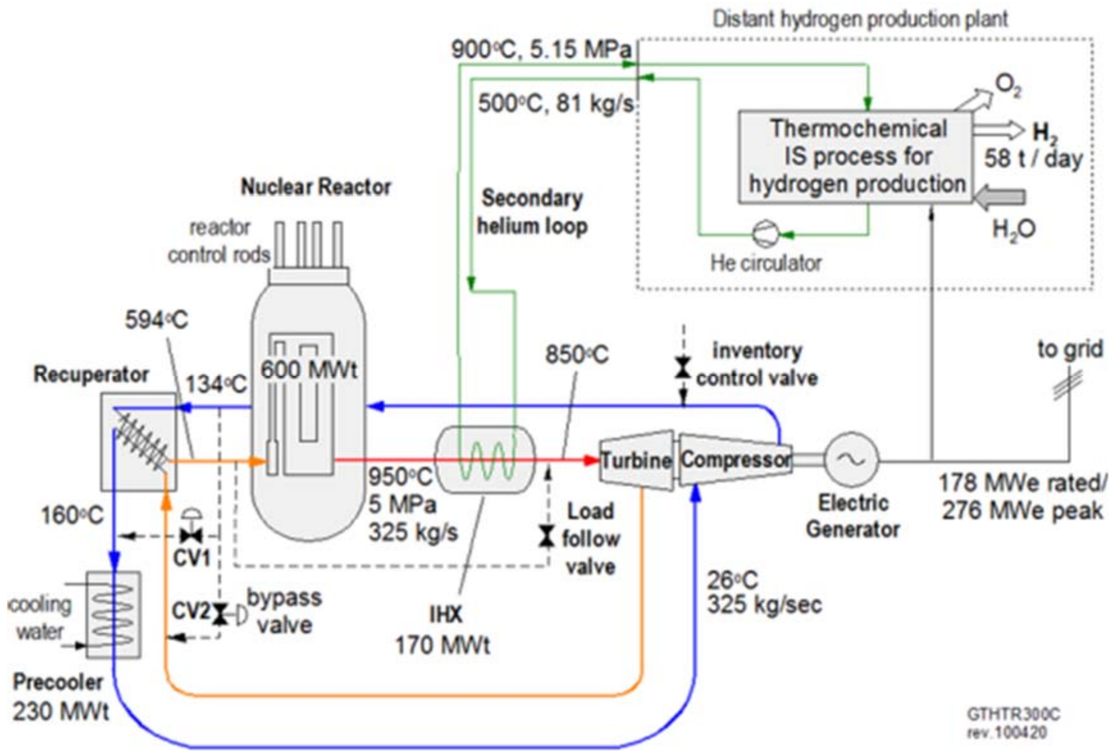


Figure 4.27. Schematic of GTHTR300C power system.

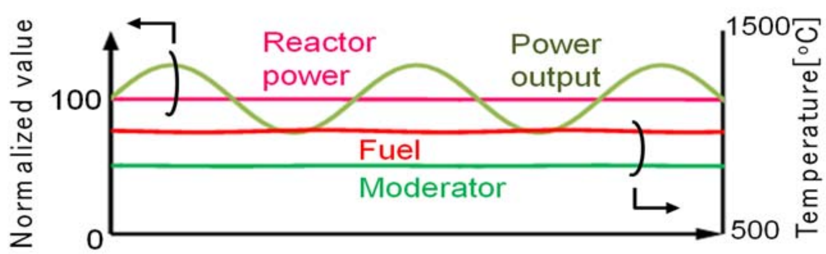


Figure 4.28. Reactor response to provide variable output on a minute scale.

Based on the Japanese work, a new design of Modular High-Temperature Gas-cooled Reactor with enhanced heat storage capabilities has been proposed (Forsberg 2019) with a long-lived reactor core that uses HTGR fuel within its existing operating limits. An HTGR with an output of 200 MWt is emplaced in a reactor vessel designed for a 600 MWt reactor—effectively tripling the heat capacity of the reactor core per unit output. A larger pressure vessel is purchased to enable in-core heat storage with the capacity to rapidly vary electricity output to the grid to boost revenue while the core power remains constant. The larger heat capacity of the core per unit output simplifies safety and other systems that reduce costs elsewhere in the plant.

5. POWER CYCLES WITH HEAT STORAGE AND THERMODYNAMIC TOPPING CYCLES

In most power cycles, heat storage replaces or supplements heat provided by the nuclear reactor. There is a class of power cycles where the heat is provided at higher temperatures. These power cycles have unique capabilities in terms of peak-to-base-load output and efficiency. Two such systems are described herein. In both cases one is designing a power cycle that includes storage rather than adding storage to an existing power cycle.

5.1 Nuclear-Air Brayton Power Cycles with Thermodynamic Topping Cycles

Nuclear air-Brayton power cycles can be designed to operate in two modes: (1) baseload and (2) a peak power mode, where (a) the output is much larger than the base-load output and (b) the incremental heat-to-electricity efficiency in converting the fuel that provides the added peak power is much higher than the base-load efficiency. All heat for base-load operations is from the nuclear reactor. The added heat for peaking power could be from burning natural gas, oil, biofuels, or hydrogen. Alternatively, the added heat could be stored heat. Such systems can incorporate heat storage in multiple configurations. Such options did not exist 20 years ago because the gas turbine technology was not good enough. A practical system required the development of efficient turbines. We describe (1) the first such complete design based on the technology of the GE 7FB combined cycle gas turbine coupled to a FHR delivering heat to the power cycle between 600 and 700°C and (2) recent design studies that examined the broad set of options for different reactors operating at different temperatures.

5.1.1 Nuclear Air-Brayton Combined Cycle (NACC) with Storage Options

Figure 5.1 shows a NACC and alternative storage options based on the GE 7FB gas turbine with heat delivered to the gas turbine by a liquid salt over the temperature range of 600 to 700°C (Andreades et al. 2014, Forsberg and Peterson 2016, Andreades et al. 2016, Forsberg and Peterson 2017). The black lines show air flow for base-load electricity production. During base-load operation, (1) outside air is compressed [A], (2) heat is added to the compressed air from the reactor through Heat Exchanger 1 [B], (3) hot compressed air goes through Turbine 1 [C] to produce electricity, (4) air is reheated in Heat Exchanger 2 [D] and sent through Turbine 2 [E] to produce added electricity, (5) the warm low-pressure air exiting the second turbine goes through a heat recovery steam generator (HRSG) [F] to generate steam [G] that is used to produce added electricity or sent to industry and (6) air exits up the stack [H]. The base-load heat-to-electricity efficiency is 42%.

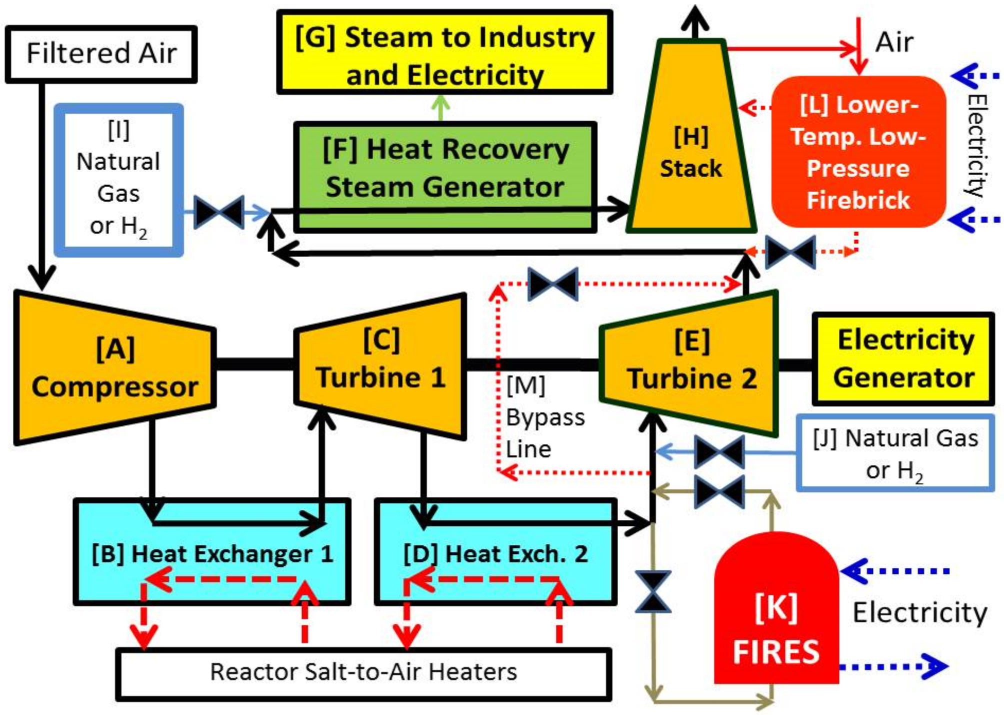


Figure 5.1. NACC with two heat storage systems and use of auxiliary fuels (natural gas, hydrogen, other).

Modern utility gas turbine compressors raise the gas inlet temperature to between 350 and 450°C. This requires that the nuclear heat input be in the temperature range of 550 to 700°C. Salt-cooled reactors (FHR, MSR, fusion) couple efficiently to NACC because salt-cooled reactors were originally developed to couple to Brayton power cycles. The original development of the MSR was for the Aircraft Nuclear Propulsion Program to develop a jet aircraft of unlimited range—the reactor was designed to match the requirements of a Brayton power cycle. High-temperature lead-cooled reactors and modified HTGRs can be coupled to NACC.

The NACC base-load temperature is determined by the materials of construction of the reactor-coolant gas-turbine heat exchangers that with typical materials is near 700°C. While these are high temperatures for heat exchangers (B and D), they are low temperatures for gas turbines, where there are industrial gas turbines with peak inlet turbine temperatures over 1400°C. Higher temperatures are possible because gas turbine blades can be cooled from the inside and ceramic coatings placed on the outside to insulate the turbine blade from the high combustion temperatures. Consequently, with a NACC there is the option of adding heat after the nuclear heating in Heat Exchanger 2 [D] to further raise compressed gas temperatures before entering Turbine 2 [E]—a thermodynamic topping cycle. The added high-temperature heat can be provided by natural gas, hydrogen, another combustible fuel [J] or stored heat [K]. Auxiliary heating the compressed air after nuclear heating to 1065°C results in an incremental added heat-to-electricity efficiency of 66.4%; that is, 66.4% of the energy from combustion of the fuel is converted to electricity. For comparison, the same GE 7FB combined cycle plant running on natural gas has a rated efficiency of 56.9%. The total efficiency (peak electricity out / (nuclear heat + peaking fuel)) is about the same as a conventional combined cycle plant. It just that the heat has been added in two steps—reactor heat and peaking heat. An overview of this cycle is shown in Figure 5.2.

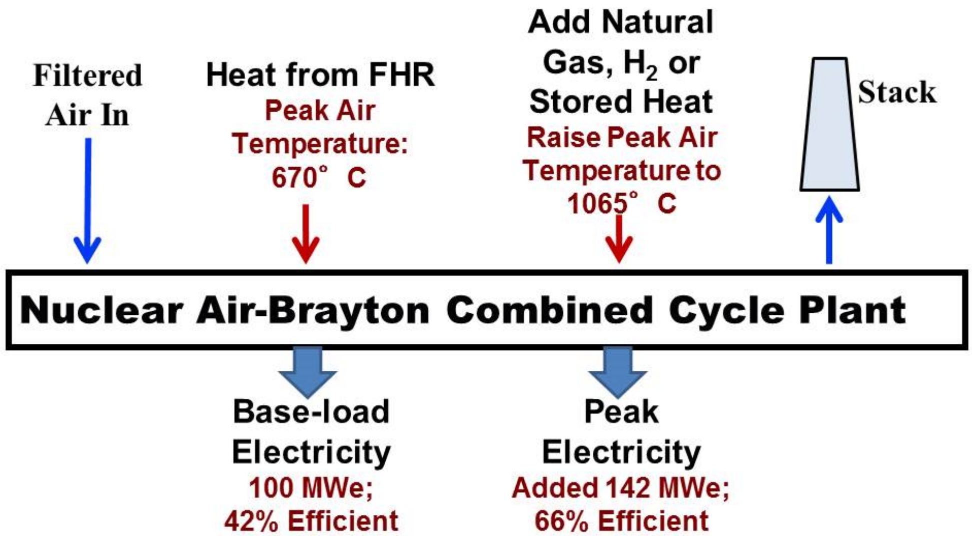


Figure 5.2. Nuclear air-Brayton combined cycle.

This design was optimized for base-load electricity. If optimized for peak power efficiency (radiant heat boiler section in HRSG [F], higher temperature gas turbine blades, etc.), the incremental heat-to-peak electricity efficiency would approach ~70%. The thermodynamic characteristic of a high-temperature topping cycle is the very high incremental efficiency in converting heat into electricity. The economics are based on using a low-cost fuel (uranium) to provide heat at lower temperatures (~700°C) for base-load electricity production and a more expensive fuel (natural gas, stored heat, hydrogen, etc.) to provide added heat to the power cycle at higher temperatures and efficiencies for added peak electricity output.

In a low-carbon grid there will be times when electricity prices are low or negative if subsidized. Firebrick Resistance-Heated Energy Storage (FIRES [K], red silo) is a new technology that is under development [Forsberg et al, June 2017, Stack 2019] to use this low-price electricity to replace natural gas in NACC and other applications. Electricity is bought when the electricity price is less than the price of natural gas and is used to resistance-heat firebrick up to temperatures that can approach 1800°C. When peak electricity is needed from NACC, the compressed air after nuclear heating in Heat Exchanger 2 [D] is sent through the firebrick [K] to be heated to higher temperatures and then to Turbine 2 [E]. Exit temperatures from FIRES [K] are controlled by either (1) cooler compressed air or steam from the HRSG to lower temperatures or (2) natural gas [J] (which self-ignites) to increase temperatures. In a low-carbon world, hydrogen or biofuels may replace natural gas. FIRES is the only technology that can store high-temperature heat for the peaking cycle because heat is directly transferred from high-temperature firebrick to compressed air that avoids the temperature limits of the heat exchanger.

In the operation of NACC with FIRES [K] providing the heat source for peak electricity production, (1) the reactor would operate at baseload, (2) electricity would be bought when prices are low and stored as high-temperature heat using FIRES—including the electricity generated by base-load reactor operations, and (3) the reactor and FIRES high-temperature heat would produce peak electricity at times of high prices. The system enables base-load reactor operation with variable electricity to the grid and increasing revenue relative to a base-load reactor.

Heat storage can be added between Turbine 2 [E] and the HRSG [F] in the form of a firebrick, crushed rock or other type of recuperator [L]. If electricity prices are low or heat (steam) demand is low, the hot air exhaust from Turbine 2 [E] is partly or fully diverted from the HRSG [F] into an atmospheric pressure recuperator [L] where it heats firebrick, concrete or crushed rock and then is exhausted to the stack [H]. At times of high electricity or heat demand, fans send cold air through the recuperator [L] that is heated to provide added hot air for the HRSG. There are several modes of operation.

- *Recycle Air*. If natural gas [I] is not being used as an auxiliary fuel for the HRSG [F] that requires oxygen and heat is to be recovered from the recuperator [L], there is the option to use warm stack gas rather than colder external air to transfer heat from recuperator [L] to HRSG [F] to improve efficiency.
- *Bypass Turbine 2[E]*. If the electricity demand is very low, there is the option of taking hot air exiting the salt-to-air Heat Exchanger 2 [D] and bypassing the second turbine [E] with that warmer air sent through a throttling valve directly to the recuperator [L] (dotted red line). This air will be at a higher temperature (670°C) than air exiting Turbine 2 [E].
- *Resistance Heating*. If electricity prices are low or negative, there is the option to include electric resistance heaters to heat the recuperator [L] for later use to produce steam in the HRSG.

The recuperator [L] operates at low pressure and relatively low temperatures enabling a low-cost heat storage system coupled to the HRSG [F]. This includes a lower-temperature FIRES system or options such as hot-rock storage. With large-scale deployment of wind or solar, there will be excess energy on weekends when the demand for electricity decreases with weekend price collapse. Very low-cost atmospheric pressure recuperator heat storage allows heat from the reactor and low-price electricity to be converted into heat on the weekends for production of added power during the five weekdays. However, the lower-temperature recuperator will have a lower heat-to-electricity efficiency than FIRES because lower-temperature heat is being delivered to the HRSG. Any single system may have one or more of these storage options.

5.1.2 Optimized Brayton Power Cycles with Thermodynamic Topping Cycles

More recent studies (Zohuri and McDaniel 2018; Zohuri and McDaniel 2019; Zohuri, McDaniel, and DeOliveria 2015; Appendix C, Zohuri] have done parametric studies of alternative power cycle designs using current turbine technology; that is, designing an optimum system without the constraints of an existing turbine system (GE 7FB turbine). Their optimized NACC design is shown in Figure 5.3 for sodium and salt cooled reactors. Such cycles could also be coupled to HTGRs.

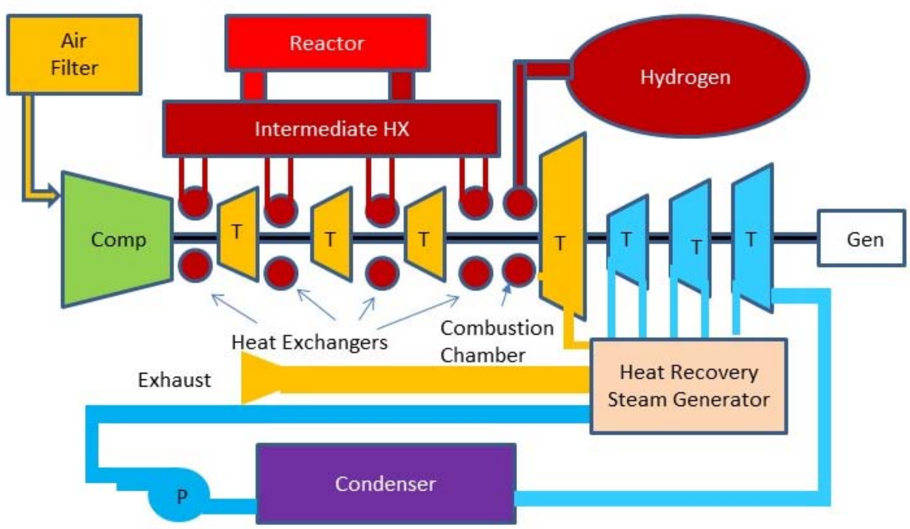


Figure 5.3. Nuclear Air-Brayton Combined Cycle with three Brayton turbines, three steam turbines and peak power using hydrogen.

The performance for sodium and salt reactors with different inlet temperatures is shown in Table 5.1. In each case there is the option of adding hydrogen to boost the temperature going into the third turbine after nuclear reheat for peak electricity production. The results would be similar if the auxiliary fuel was natural gas, biofuel or FIRES. There are several features of these thermodynamic topping cycles.

- *Efficiency.* The efficiency in converting added hydrogen to electricity is between 71 and 75%--far above the efficiency of conventional combined cycle gas turbines. Two alternative peak turbine temperatures are shown for each reactor type. One is for a gas turbine with uncooled blades and the second is for a gas turbine with internally cooled blades—what is used in high-efficiency GTCCs. The overall efficiency defined as total electricity divided total heat input (nuclear plus peaking fuel) is about 60% when using the higher-temperature internally cooled blades, about the same as a conventional natural-gas fired combined cycle plant. Uranium fission is providing the low-temperature heat to about 700°C while the auxiliary fuel provides the heat to go to higher temperatures.
- *Peak Power Production*. In these designs the peaking cycle boosts the power. In the first case with an SFR, for every megawatt of base-load power, adding hydrogen boosts the Brayton cycle power to 1.464 megawatts (46% increase in output) and the total plant output to 2.522 megawatts (152% increase in output). In the second SFR power cycle design with a higher peak turbine inlet temperature, for every megawatt at base load, 5.744 megawatts are generated when the plant is operating in peak mode—an increase in the power level of 474%. This is an extraordinary capability for providing added assured generating capacity.
- *Implications of higher temperature reactors*. Salt-cooled reactors with higher temperatures allow for higher base-load electricity efficiency and higher incremental heat-to-electricity efficiency but somewhat lower peak-to-baseload power output. Separately these systems are more efficient in coupling to industrial heat loads.
- *Implications of lower-temperature heat storage*. As discussed earlier, there is the option to include a recuperator for heat storage between the gas turbine and the HRSG. For the baseline SFR, about 18% of the power is from the steam cycle. Because this recuperator operates at relatively low temperatures, it can be built of firebrick, concrete, or crushed rock as discussed earlier. This can reduce electricity production at times of low electricity prices with higher production of electricity at times of peak electricity prices.

Table 5.1. Performance of different NACC cycles with thermodynamic topping cycles.

Turbine 1&2 Exit Temp	Turbine 3 Nominal Exit Temp	Turbine 3 Boosted Inlet Temp	Base Efficiency	Fraction Base from Steam	Hydrogen Burn Efficiency	Combined Efficiency	Brayton Gain	Overall Gain
Sodium Near-Term System (Nominal Inlet Temperature 773 K (500°C))								
680.5 K	640.5 K	1100 K	32.8%	18%	71.1%	48.4%	1.464	2.522
680.5 K	640.5 K	1700 K	32.8%	18%	74.2%	60.4%	2.347	5.744
Molten Salt Advanced System (Nominal Inlet Temperature 973 K [700°C])								
792.5 K	722.5 K	1100 K	45.5%	24%	74.5%	51.1%	1.168	1.403
792.5 K	722.5 K	1700 K	45.5%	24%	75.0%	61.6%	1.834	3.070

There is a second class of gas turbines that use air recuperators and avoid the need to use water. This involves the use of air-to-air heat exchangers with no Rankine bottoming cycle. Such systems have been used naval applications and in some specialized gas turbines such as in military tanks. However, these systems have not been used in large utility-scale gas turbines. Figure 5.4 shows a schematic of one such a system while Table 5.2 shows the performance parameters for one set of designs. In these power cycles, the medium-temperature air leaving the last turbine on the right is used to preheat the compressed air going into the first turbine on the left—there is no steam bottoming steam cycle. Heat is rejected from this power cycle as warm air and thus no need for cooling towers.

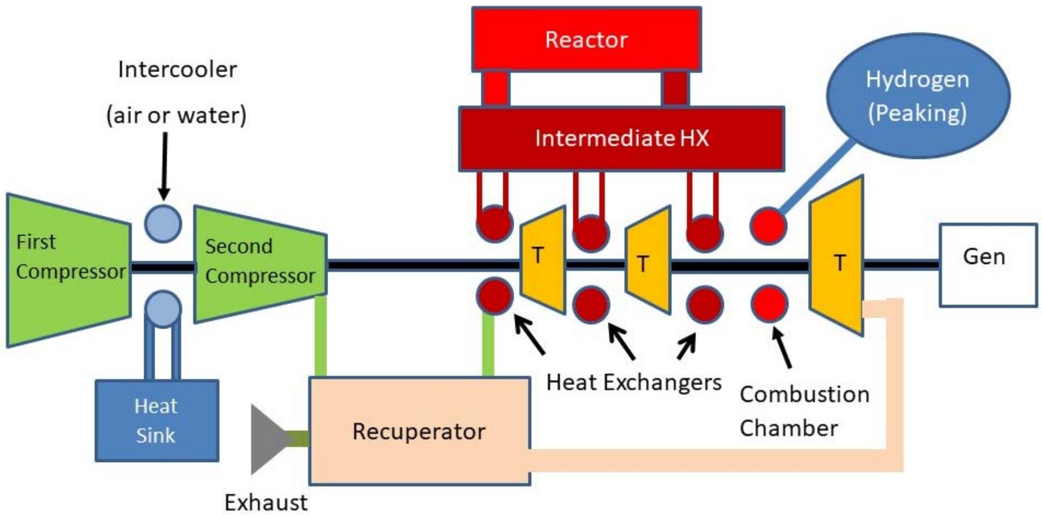


Figure 5.4. Nuclear Air-Brayton Recuperated Cycle with three Brayton turbines, a recuperator, and peak power with hydrogen.

These systems, as shown in Table 5.2, have some unusual features and complex design tradeoffs (Zohuri and McDaniel 2019) between base-load efficiency, peak-to-base power output, and incremental heat-to-electricity efficiency. The incremental heat (hydrogen) to electricity efficiency in peak power production can be above 80% in some of these systems but if operating at peak power mode, the amount of heat from the reactor to the power cycle must be reduced. The far right column indicates the heat input required from the reactor when operating in peak electricity production mode compared to base-load. What is happening is that in peak power mode burning of the hydrogen raises turbine inlet temperature of the last turbine (far right) that in turn raises the exit temperature of the last turbine. The temperature of the air going into the air recuperator goes up and the compressed air inlet temperature to the first turbine from reheat goes up that reduces needed heat input from the reactor. The reactor power to the system is less than 30% when the system operates at base-load mode. There is the option to either reduce reactor power or divert this heat to a second peaking electricity production system. The peak power output is 39 to 45% greater than the base-load electricity production and most of the heat output from the reactor is now available for some other power system. In these recuperated systems, a greater peak-to-base power ratio can be achieved but it lowers the base-load reactor efficiency. Also shown are the effects of adding intercoolers between the front-end air compressors that reduce the energy input of air compression. This boosts efficiency but adds complexity and cost to the power cycle that has limited their use for utility applications.

Table 5.2. Performance of different NARC cycles with thermodynamic topping cycles.

Turbine 1&2 Exit Temp.	Turbine 3 Nominal Exit Temp.	Turbine 3 Augmented Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Fractional Reactor Power
Sodium Near-Term System (Normal Inlet Temperature 783 K)							
765.5 K	655.5 K	958.7 K	40.9%	78.8%	47.3%	1.390	0.220
Sodium Near-term System (Normal Inlet Temperature 783 K, Intercooled)							
748.0 K	618.0 K	1011.6 K	43.7%	83.4%	51.1 %	1.447	0.285
Molten Salt Advanced System (Normal Inlet Temperature 973K)							
922.5 K	762.5 K	1204.2 K	48.5%	81.1%	54.8%	1.409	0.203
Molten Salt Advanced System (Normal Inlet Temperature 973K, Intercooled)							
902.5 K	722.5 K	1268.7 K	51.5%	84.7%	58.4%	1.448	0.276

Like the previous NACC design based on the GE 7FB, heat storage can be incorporated into these systems in various locations. It is to be emphasized that until about 15 years ago, the gas turbines were not good enough to enable such power cycles. The capabilities of these cycles will improve with time with advancing gas turbine technology. Until 5 years ago, there was no economic incentive to consider such cycles. The economic incentive came with (1) the large-scale addition of wind and solar that created very volatile energy prices including times of very low prices and (2) the goal of a low-carbon electricity grid and the need for dispatchable electricity from non-fossil sources. There remains much added work before the full set of design options are well understood. Today the primary engineering challenge is not the gas turbine. It's designing efficient reactor coolant to air heat exchangers for these systems.

5.1.3 System Implications of Thermodynamic Topping Cycles

Thermodynamic topping cycles are not new. In the 1920s, General Electric developed a mercury topping cycle and a steam bottoming cycle for coal-fired power plants. In the 1970s, the Indian Point Nuclear Power Plant produced saturated steam that then was heated to higher temperatures with an oil-fired super-heater. At that time, it was the most efficient oil-to-electricity plant ever built. What has changed is the development of efficient air-Brayton gas turbine with external combustion where high-temperature heat does not need to be transferred through metal heat exchangers and their associated material temperature limits. This bypasses the materials limit found in closed power cycles using steam, carbon dioxide and other working fluids. This allows much higher incremental heat-to-electricity efficiencies.

Economic assessments (Forsberg and Peterson 2016) of the NACC cycle based on the GE 7FB gas turbine with heat delivered to the power cycle between 600 and 700°C indicate that NACC using natural gas will have 50% more revenue in states such as Texas and California than a base-load nuclear plant after paying for the natural gas. The FHR with NACC converts natural gas to electricity with an efficiency of 66.4% versus an efficiency of ~60% for a stand-alone natural gas combined cycle plant and ~40% for a stand-alone natural gas turbine. That implies the first "natural gas" plant that is dispatched is the salt reactor NACC, then the stand-alone natural gas combined cycle plants followed by the simple natural-gas turbines. As long salt reactors with NACC do not dominate the market, peak electricity prices will be controlled most of the time by stand-alone less-efficient natural gas plants that set higher electricity prices because of their lower efficiencies in converting natural gas into electricity. The higher efficiency in peak power mode of NACC (more electricity for less natural gas) provides added revenue in a competitive electricity market. The major gas turbine manufacturing companies have longer term goals to increase combined cycle plant efficiencies to 65%. The same turbine technologies that will enable this increased efficiency will boost NACC turbine for auxiliary fuel-to-electricity efficiency above 70%. The system performance improves as the gas turbine technology improves.

In a very low-carbon world with strict limits on fossil fuel usage or high carbon taxes, the very high incremental heat-to-electricity efficiency has major implications in the total electricity system. The FIRES round trip electricity-to-heat-to-electricity efficiency can be above 70% because the efficiency of converting electricity to heat is near 100% and the heat-to-electricity efficiency is above 70%. The round-trip efficiency is near that of pumped hydro facilities without the siting constraints of hydro and close to that of battery systems. The incremental capital cost for gas turbine peaking capacity is far below that of batteries with a very low-cost to convert low-price electricity to heat. The technology will continue to improve with gas turbine technology. This could become the primary method to provide dispatchable electricity to the grid—enabled by advances in gas turbines.

5.1.3.1 Cryogenic Liquid Air Storage

A cryogenic air energy storage system (Chen 2007, Li 2014, Ding 2016, Highview 2019) stores energy by liquefying air. At times of low electricity demand, air is liquefied. At times of high electricity demand, the liquid air is compressed, vaporized and sent to a turbine to produce peak electricity. The source of heat to vaporize the air can be any ambient source of heat. A commercial demonstration plant (5 MW/15MWh) started operation in April 2018 in the United Kingdom.

This system can be coupled to a nuclear power plant to boost the round-trip storage efficiency (Figure 5.5). A less tightly coupled cryogenic system would use electric motors to drive the chilling process; the option exists to more tightly integrate the chilling process with the nuclear plant and provide steam for steam turbines in the air liquefaction plan. This is a common chemical industry practice because of the lower cost of steam turbines compared to large motors. During the liquefaction process, the compression heat can be stored for reuse in the power recovery (discharge) process; whereas waste cold during the discharge process can be stored for later use in the liquefaction process to reduce power consumption. The liquefied air can be stored in facilities similar to those used to store liquefied natural gas. The energy storage capacity of the liquid air reservoir and round-trip efficiency can be enhanced through the integration of a sensible/latent heat and cold storage system.

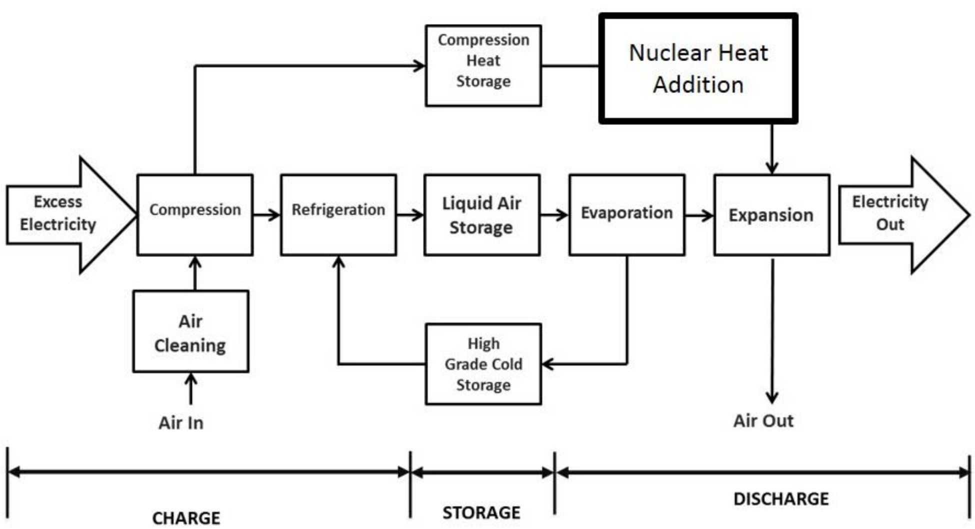


Figure 5.5. A schematic diagram of the cryogenic energy storage technology (Ding 2016).

To produce electricity, the liquid air is compressed to high pressures, converted to a high-pressure gas using ambient heat and available waste heat including that from the nuclear power plant tertiary side (warm cooling water), further heated in a heat exchanger using steam from the nuclear power plant secondary side and sent through a gas turbine before being exhausted to the atmosphere. This potentially provides a low-cost peak power cycle. During this power recovery process, cold energy can be recovered through heat exchange for use in the liquefaction process as mentioned above.

If only warm cooling water from the nuclear plant or other low-temperature heat source is used, the estimated round-trip efficiency of a stand-alone system is about 60% (Ding 2016). With an integrated cryogenic-nuclear power plant system using a light water reactor (steam to heat compressed air) the round-trip efficiency can be between 70 and 75% (Ding et al. 2013, Li 2014) with a peak power up to 2.7 times the base-load power plant capacity. The reason for the high efficiency and power output is that the LWR steam is adding heat to boost the efficiency of a liquid-air cycle and is a thermodynamic topping cycle. Normally one does not consider LWR steam to be high-temperature heat but in a power cycle where the bottom temperature is the temperature of liquid air (-194°C, 79°K), 270°C steam is hot. Higher round-trip efficiencies are possible with higher temperature reactors. This storage technology is applicable to any reactor type. What changes is the entry temperature of the air into the gas turbine—a simple change because modern gas turbines operate at temperatures far above any reactor coolant temperature. The round-trip efficiency goes up with the temperature.

6. HYDROGEN

The workshop addressed the question of the roles of hydrogen in the electricity grid relative to heat storage. Hydrogen can impact the grid in three ways.

- *Electricity demand*. There is a massive industrial demand for hydrogen. If made from electricity it can become a large-scale user of electricity including the option of consuming electricity at times of low electricity demand.
- *Electricity production*. Hydrogen can be made, stored and used to produce peak electricity at times of high prices.
- *Heat storage*. Thermochemical heat storage systems are being developed that use hydrogen to store heat. These can be coupled to nuclear reactors like any other heat storage technology.

The United States consumes 10 million tons of hydrogen per year for fertilizer production, oil refining and production of various chemicals. In a low-carbon world hydrogen will likely replace coal as a chemical reduction agent to produce iron and other metals from their ores. Hydrogen may be used directly as a fuel for vehicles or in the production of biofuels. One can almost double the yield of high-quality fuel per ton of biomass with hydrogen addition. Last, it may be used for heating and peak electricity production including in NACC systems. However, hydrogen is a higher-cost source of heat. It takes several units of heat to produce one unit of electricity for electrolytic production of hydrogen; thus, the cost of heat to industry would be half to a third from a nuclear reactor than heat from combustion of hydrogen. One could have a future where 10 to 20% of all primary energy is used for hydrogen production. Unlike electricity, hydrogen has been stored at low-cost for decades in underground geologies, like natural gas. This enables hydrogen to be stored on an hourly to seasonal basis.

6.1 Using Hydrogen Production to Consume Low-Price Electricity

Today almost all hydrogen in the United States is made from steam methane reforming of natural gas. Hydrogen can be made by room temperature electrolysis and high temperature electrolysis that requires steam and electricity that can be provided by a nuclear plant. High-temperature electrolysis is more efficient. There are large incentives for centralized hydrogen production because of the economics of scale associated with hydrogen handling, including compressors, pipelines and storage. However, the capital costs of hydrogen production (Figure 6.1) are much higher than for heat storage. Economics requires that a hydrogen production plant operate many more hours per year. Recent studies (Boardman 2019; Appendix C, Westover and Boardman] for coupling hydrogen production to existing LWRs are beginning to provide a strategy for nuclear hydrogen production when coupled to the electricity grid.

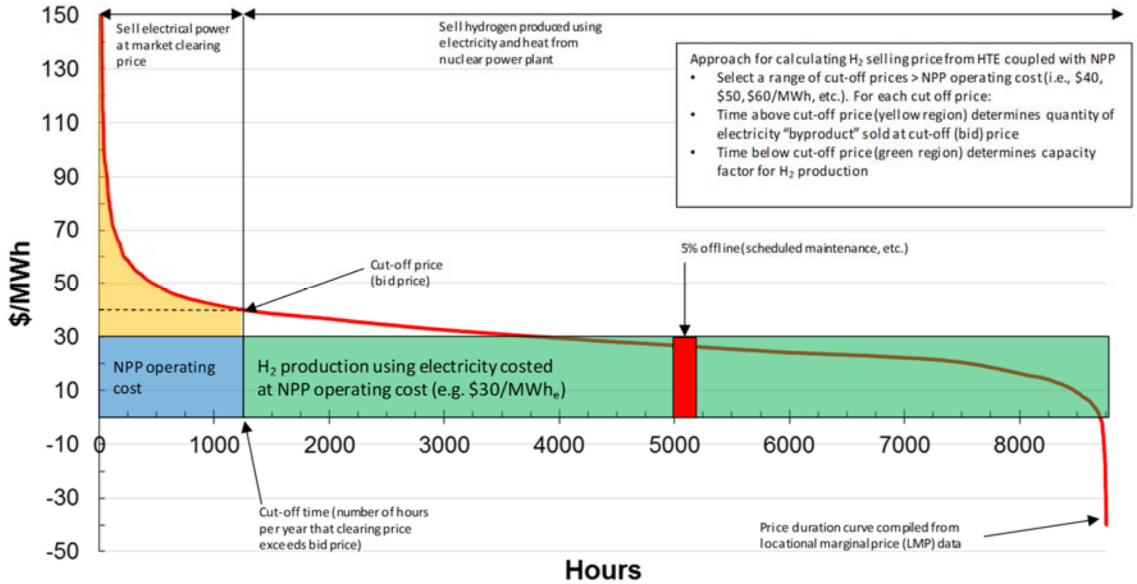


Figure 6.1. LWR operation for electricity and high-temperature hydrogen electrolysis.

The figure shows the price of electricity over a year. The hydrogen plant operates at times of lower electricity prices—in this case over 7,000 hours per year. The number of hours the nuclear plant produces hydrogen versus electricity depends upon the price curves for hydrogen and electricity. The nuclear plant is operating almost like a natural gas peaking turbine today in terms of sending electricity to the grid only when prices are high. This operating strategy would apply to any reactor.

6.2 Electricity from Hydrogen Production with Brayton Cycles Coupled to Heat Storage

Hydrogen can be used to produce peak electricity using (1) conventional gas turbines with almost no changes in the gas turbines, (2) nuclear-air Brayton combined cycles (Chapter 5) that may include various internal heat storage systems or (3) power systems that couple high-temperature reactors to nitrate-salt heat storage systems. The last set of options have been studied by Abel (2018) using SFRs bout would be applicable to any higher-temperature GenIV reactor. These systems could be extended for an integrated system with hydrogen production as shown in Figure 6.2. The central components are the hot and cold nitrate storage tanks with different system components.

- *Nitrate heat storage tanks*. The same nitrate heat storage system is used as in CSP systems. Heat input is from reactors and gas turbines. Heat output is to steam plants, high-temperature electrolysis and other industrial heat loads. Other heat storage options can substitute for nitrate salt heat storage; however, nitrate heat storage is the only large-scale commercial technology today.
- *Reactors*. The reactors (SFRs, FHRs, MSRs, or HTGRs) heat cold nitrate salt and produce hot nitrate salt with base-load operation. They are decoupled from the power block or hydrogen production.
- *High-temperature electrolysis*. The hydrogen production systems obtain heat from the hot salt tanks and electricity from the grid to produce electricity.
- *Heat-to-electricity storage*. Very low-cost electricity is bought from the grid and converted into high-temperature stored heat.

- *Steam plant*. The steam system produces electricity with heat from hot salt and returning salt to the cold salt tank.
- *Gas turbines*. Simple gas turbines burning natural gas and in the future hydrogen to produce peak electricity. Hot exhaust from the gas turbines is used to heat cold salt to produce hot salt. If heat from the hot salt tank is used for electricity production, the gas turbines are operating as GTCC systems with the high efficiency associated with these systems. In this mode, the gas turbines are operating as thermodynamic topping cycles with very high efficiency.

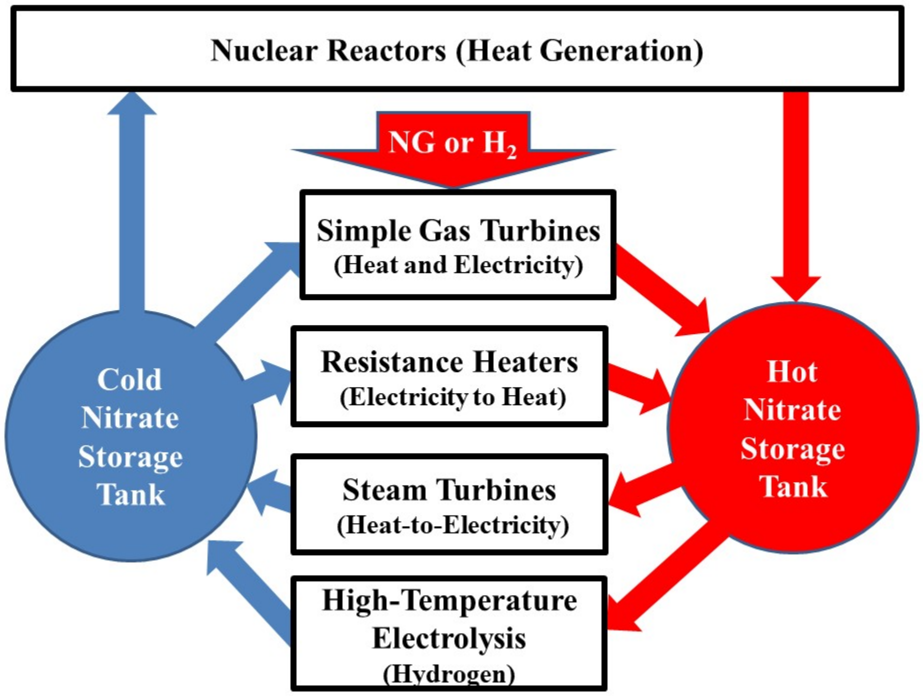


Figure 6.2. Electricity and hydrogen production with nitrate-salt heat storage.

The gas turbine, salt heat storage, and steam plants are off-the-shelf technologies. Multiple GenIV reactor types can couple to the system. The size and numbers of reactors, heat storage tanks, gas turbines and other components is based on market requirements. The system has the capability to buy and sell electricity.

Last, hydrogen on a large-scale is stored in underground locations like natural gas. This is a low-cost technology that has been used for decades. This storage has been used by the refinery and chemical industry to match hydrogen production with demand. However, more recently there is ongoing work to produce hydrogen for peak electricity production.

6.3 Thermochemical Heat Storage Using Hydrogen

Work is underway (Appendix C, Couture and Sullivan) on a variety of thermochemical heat storage technologies based on hydrides. Heat is generated at high temperatures by the chemical reaction of hydrogen with various compounds ($CaSi_2$/TiFe). To recharge the heat storage medium, heat is applied to the hydride to decompose it yielding hydrogen. There are wide variety of hydrides to choose between depending upon the heat source temperature to decompose the hydride. Most of the work today is associated with developing heat storage systems for CSP. These are isothermal heat storage systems and thus do not loose heat during storage. Such systems are at an earlier stage of development than the sensible heat storage systems discussed earlier.

All of these systems require hydrogen storage at low temperature. The choices include lower-temperature hydrides, tanks, and bulk geological heat storage. In this context, a hydrogen economy with pipeline hydrogen and low-cost bulk storage systems would have a beneficial cost impact on total system costs. These systems have higher performance but are at an earlier stage of development than sensible heat storage technologies. Many of the questions on economics are associated with how to transfer hydrogen in and heat out when discharging.

7. DISCUSSIONS ON PATH FORWARD

The workshop held two panel discussions on the path forward. The first panel (Shannon Bragg-Sitton [chair], INL; Marcus Nichol, Nuclear Energy Institute; Charles Forsberg, MIT; Wayne Moe, INL; and Ugi Otgonbaatar, Exelon) discussed the regulatory challenges for heat storage. The electricity market has multiple regulators including the Federal Energy Regulatory Commission, Public Service Commissions, Independent System Operators (grid operators) and the U.S. Nuclear Regulatory Commission (NRC). Some of the perspectives are described herein.

Marcus Nichol (NEI) emphasized the need to develop the business case—what are returns on investment and or the payback requirements. Except in regulated markets, a 20-year payback is unlikely to be viable. System size makes a difference—a 100 MWh heat storage system is not a significant source of revenue relative to a 3000 MWh storage system. The revenue will depend upon the market and could be some combination of arbitrage, capacity/auxiliary services and avoided transmission/distribution expansion. On the cost side, what are the system costs and opportunity costs—what other revenue could have been earned if low-price electricity was used for some other purpose such as hydrogen production. What are the risks including (1) new competitors for the same services (such as batteries) (2) changes in market rules that impact revenue and regulatory risks in terms of schedule and cost?

This leads to the question of whether there is a viable commercialization strategy. Where is the technology in the spectrum of development (e.g., fundamental research and development, proof of concept, viability validation)? Are their developers/suppliers, i.e., companies that are willing to price a product for the market, guarantee performance, and provide a warranty for the work? What is the demonstration plan, i.e., who is taking the risk, e.g., lab demonstration of tech, DOE partnership for first commercial demonstration? (JUMP program is a good idea here [Appendix C, Bragg-Sitton]. Who are the first customers, e.g., have the need and can take the risk? It might be easier for a regulated utility first, even though the intended customers are in the deregulated market).

These factors lead to the recommendation that an independent organization (e.g., EPRI, INL, etc.) perform a study to determine the revenue potential of heat storage based upon a broad range of existing and potential market rules. The study should also determine revenue resilience based upon the amount of storage a market can support.

Ugi Otgonbaatar (Exelon) discussed the importance as well as caution regarding interpretation of the 2018 FERC guidelines on energy storage (electricity, heat, other) [Appendix C, Otgonbaatar]. There is also the energy storage sector beyond the meter (ice storage, heat, automobiles) where the market impacts are not well understood that will impact grid storage options.

Charles Forsberg (MIT) observed that coupling heat storage to nuclear reactors creates a new type of generating system—a large nuclear power station capable of buying and selling electricity while providing assured generating capacity significantly above the base-load capacity of the nuclear reactor. None of the existing technologies has this set of the capabilities. It has the potential to fundamentally improve the performance electricity grid—particularly in a world with carbon constraints. However, it also raises concerns in competitive markets about market manipulation. Such a system will change the market. At the same time, there are several competing heat storage technologies. The costs and performance of these technologies will not be really understood until they are tested at scale.

These factors lead to the recommendation (Forsberg 2019b) for a joint federal-private demonstration program to demonstrate several of these heat storage technologies at significant scale. The program would be similar to that used to demonstrate early reactors where on the average the federal government and utility each paid half the costs. The utility choses the technology and manages the project. Such a program would demonstrate not only the technology but also address the multiple institutional challenges. Regulators (FREC, PUCs, ISO, NRC) have issued policy statements supporting energy storage—but until there is an application to build a real heat storage facility there is no experience in how those rules would be interpreted. Because large-scale storage is required for a low-carbon grid and has the potential to lower the cost of electricity, there are large incentives for the federal government to support such demonstration projects. Storage has the potential to boost plant revenue for the utility; thus, there are large incentives to consider storage at nuclear power plants. Joint demonstration projects provide the mechanisms to reduce the technical, financial, and regulatory risks for the first-of-a-kind projects.

Audience discussions also included the question of the smart grid and the ability to control demand (hot water heaters on utility control, variable electricity rates with time, etc.). Most but not all of these options depend upon electricity rate decisions by local Public Service Commissions and thus will be highly variable.

The second panel focused on (1) what is the commercial path to large scale deployment and (2) how can we integrate Nuclear and CSP heat storage research, development and demonstration to accelerate progress.

Avi Schultz (DOE/EERE) observed that large-scale deployment of heat storage for CSP plants started in 2010. We are early in the deployment of this class of technologies. There are large incentives for more sharing of information as plants are built to avoid repeating the same mistakes and provide feedback from real-world experience for new projects. EERE is working with industry to develop methods to share information and accelerate progress with commercial deployment.

Josh Walter (TerraPower) observed that in today's market, the economics only make sense if have revenue from arbitrage and capacity payments. Capacity payments only exist in some markets. The markets and market rules are changing rapidly making it difficult to predict future revenue streams.

There were general discussions on two general challenges. The first is the market is coming for large-scale storage, but the timing is uncertain that impacts investment decisions. Second, the clear need for a more coordinated research, development and demonstration effort between the nuclear, solar thermal and fossil energy communities.

8. OBSERVATIONS AND CONCLUSIONS

The choice of heat storage technology depends upon the operating temperatures of the reactor and the specific electricity market. Heat storage would not have been an economic option five years ago. It is the changes in the electricity markets that makes heat storage coupled to nuclear and fossil plants economically viable in some markets today and likely viable in many more markets in the future. It is unlikely that any single technology will dominate the market because there are multiple markets. Significant scale up and demonstration plants will be required to determine the most economic technologies. Because the incentives for such systems have only recently existed, we are early in the development of these systems with many unknowns about the economically optimum systems.

The economics are strongly dependent upon the market—particularly the number of hours of low-price electricity. Almost all economic analysis is based on two sources of revenue: (1) hours of high prices and hours of low prices based on the reactor diverting heat to storage at times of low electricity prices for sale of electricity at times of high prices and (2) capacity payments for assured generating capacity. However, for most of these systems there is a third major potential source of revenue—buy electricity at times of low prices, convert that electricity to heat, store the heat, and use that heat for peak electricity production. The added capital cost to take advantage of this revenue stream is the addition of electric resistance heaters and incremental heat storage—no addition to the peak generating capacity. This source of revenue may substantially improve the economics of such systems relative to system such as batteries. It is the basis of the Siemens hot-rock storage system but has not been deployed in CSP systems or received much attention.

Several recommendations follow from the workshop.

- *Integrating research, development, and demonstration programs for nuclear, solar thermal, and fossil.* Most heat storage technologies are applicable to any heat storage technology. This creates large incentives for joint development on heat storage technologies to accelerate deployment of these technologies.
- *Large-scale federal-private demonstrations of heat storage technologies for light water reactors*. Large-scale heat storage may enable a nuclear power plant to buy electricity and sell electricity with assured peak generating capacity significantly above baseload generating capability. This combination of capabilities has not previously existed in a single power station and has the potential to reduce electricity costs, improve grid reliability and increase plant revenue. However, there are a wide variety of technical and institutional questions that can only be answered by demonstrating these technologies at scale. The federal government and private industry should jointly fund several large heat-storage demonstration projects to address the technical and institutional challenges. Joint funding reduces the risks for first movers.
- *New nuclear plant architecture*. Heat storage enables an alternative nuclear power plant design (Figure 8.1) where the nuclear reactor is separated from the power block. In its simplest form with nitrate salt hot-and-cold storage tanks, the nuclear reactor heats cold salt from one tank and delivers hot salt to the other tank. The power block and industrial customers take hot salt, extract the heat, and return cold salt. Because the power block is isolated from the reactor, it can be operated without consideration of the reactor conditions. The reactor design, licensing, construction and safety is separated from the power system with the potential for major reductions in cost because it is not tightly coupled to the customer. This fundamentally different architecture should be fully examined as a method to reduce costs but also enable nuclear energy to provide the three services of fossil fuels: energy source, energy storage and assured electric generating capacity.

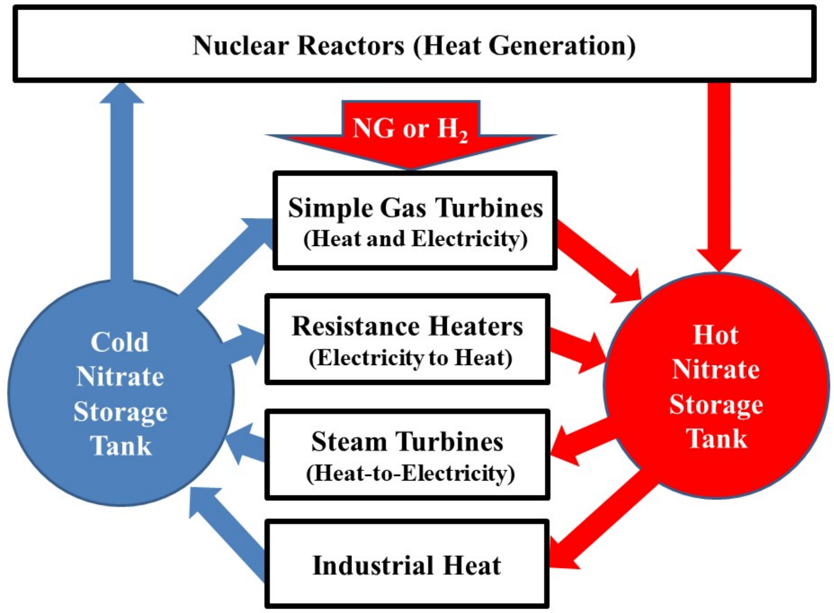


Figure 8.1. Alternative nuclear plant architecture.

9. REFERENCES

C. Abel, *Integrating Thermal Energy Storage and Nuclear Reactors: A Technical and Policy Study*, Ph.D. Thesis, Department of Nuclear Engineering, Georgia Institute of Technology, May 2018.

Abengoa Solar, 2013. *Advance Baseload Molten Salt Tower, Sunshot CSP Program Review*, DOE/GO-102013-3924, Phoenix, Arizona (2013).

K. J. Albrecht and C. K. Ho. "Design and operating considerations for a shell-and-plate, moving packed bed, particle-to-sCO2 heat exchanger", Solar Energy, 178, 331-340 (2019), https://doi.org/10.1016/j.solener.2018.11.065.

C. Andreades, R. O. Scarlat, L. Dempsey, and P. F. Peterson, "Reheating Air-Brayton Combined Cycle Power Conversion Design and Performance Under Normal Ambient Conditions", J. of Eng. for Gas Turbines and Power, 136, (June 2014).

C. Andreades et al., "Design Summary of the Mark-I Pebble-Bed, Fluoride-salt-cooled, High-Temperature Reactor Commercial Power Plant", *Nuclear Technology*, 195, 223-238, (Sept. 2016).

F. Bertrand, G. Mauger, M. Bensalah, P. Gauthe, "Transient behavior of ASTRID with a gas power conversion system," *Nuclear Engineering and Design*, *308*, 20-29 (2016).

H. Bindra, et al., "Thermal Analysis and Exergy Evaluation of Packed Bed Thermal Storage Systems." *Applied Thermal Engineering* **52**, 255-263 (2013).

H. Bindra, J. Edwards, D. Gould, *Methods and Systems for Thermal Energy Storage and Recovery*, U.S. Patent Application No. 62/339,576 (International Patent Application No. PCT/US2017/033566) (2017).

J. Birnbaum, M. Eck, M. Fichtner, T. Hirsc, D. Lehmann and G. Zimmermann, "A Direct Steam Generation Solar Power Plant With Integrated Thermal Storage," *Journal of Solar Energy Engineering*, **132** (*3)*, p. 31014 (2010).

S. Bisett, A. Laportin and E. Schneider, "Steam Accumulator Storage Integration into a Nuclear Power Plant," *Transactions of the American Nuclear Society*, San Francisco. June 11-15, 2017.

R. Boardman, Evaluation of Non-electric Market Options for a light-water reactor in the Midwest, Light Water Reactor Sustainability Market Study, (March 2019).

Bright Energy, 2019. https://www.brightes.com/.

T. A. Buscheck, et al. "Integrating CO_2 Storage with Geothermal Resources for Dispatchable Renewable Electricity", *Energy Procedia*, **63**, 7619-7630 (2014).

T. A. Buscheck, "Earth Battery," *Mechanical Engineering*, **137**, (December 3015) https://www.google.com/?gws_rd=ssl#q=Earth+Battery+ASME+Mechanical+Engineering+Magazine.

T. A. Buscheck, J. M. Bielicki, T. A. Edmunds, Y. Hao, Y. Sun, J. M. Randolph, and M. O. Sarr. "Multifluid Geo-energy Systems: Using Geologic CO_2 Storage for Geothermal Energy Production and Grid-scale Energy Storage in Sedimentary Basins", *Geosphere*, **12** (3), (2016) doi:10.1130/GES01207.1.

T. A. Buscheck, J. M. Bielicki, J. B. Randolph. CO_2 Earth Storage: Enhanced Geothermal Energy and Water Recovery and Energy Storage (2017) *Energy Procedia*.

H. Chen, Y. L. Ding, T. Peters, and F. Berger, 2007, *A method of storing energy and a cryogenic energy storage system,* WO 2007/096656.

P. Denholm et al., *The Potential for Battery Energy Storage to Provide Peaking Capacity in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-74184, 2019. https://www.nrel.gov/docs/fy19osti/74184.pdf.

W. Ding, A. Bonk, and T. Bauer, "Corrosion behavior of metallic alloys in molten chloride salts for thermal energy storage in concentrated solar power plants: A review." Front. Chem. Sci. Eng. 12 (3): 564. (September 2018). https://doi.org/10.1007/s11705-018-1720-0.

Y. L. Ding, Y. Li, Y. Jin, D. Li, G. Leng, F. Ye, Z. Sun, H. Cao, and G. Qiao, *A Peak-shaving Method for Nuclear Power Plants Through Integration with Cryogenic Energy Storage*., (2013) CN201310279616.2.

Y. L. Ding, Y. Li, and J. Radcliffe, "Liquid Air Energy Storage." *Storing Energy*, Trevor Letcher eds., Elsevier BV, (2016) ISBN 9780128034408.

J. H. Edwards, D. Franken, H. Bindra, and P. Sabharwall, "Packed Bed Thermal Storage for Compact Light-Water Cooled Small Modular Reactors", *Transactions of the American Nuclear Society Meeting,* **115**, Las Vegas, NV (November 6-10, 2016).

J. H. Edwards, H. Bindra, and P. Sabharwall, "Exergy Analysis of Thermal Energy Storage Options with Nuclear Power Plants," *Annals of Nuclear Energy*, **96**, 104-111 (2016).

K. Federsel, J. Wortmann and M. Ladenberger, "High-Temperature and Corrosion Behavior of Nitrate Nitrite Molten Salt Mixtures Regarding Their Application in Concentrated Solar Power Plants," *Energy Procedia* **69**, pp. 618–625 (2015).

R. L. Fitzhugh, J. D. Richards, J. M. Schaumann, and M. J. Memmott, "Preliminary Design of a Thermal Energy Storage System for a Light Water reactor," *International Congress on Advanced Nuclear Power Plants (ICAPP 2016),* San Francisco (April 17-20, 2016).

S. Fleischer, *Thermal Energy Storage Using Phase Change Materials*. Springer. (2015).

K. Frick, J. M. Doster and S. M. Bragg-Sitton, "Control Strategies for Coupling Thermal Energy Storage Systems with Small Modular Reactors", *Trans. American Nuclear Society*, San Francisco (June 11-15, 2017).

K. Frick, J. M. Doster and S. M. Bragg-Sitton, "Design of a Sensible Heat Peaking Unit for Small Modular Reactors", *Trans. American Nuclear Society*, Washington D.C. (October 29-November 7, 2017).

C. W. Forsberg, "Gigawatt-Year Nuclear-Geothermal Energy Storage for Light-Water and High-Temperature Reactors, *Proc. of International Congress on Advanced Nuclear Power Plants (ICAPP 2012),* (June 24-28, 2012).

C. W. Forsberg. "Hybrid Systems to Address Seasonal Mismatches between Electricity Production and Demand in Nuclear Renewable Electricity Grids," *Energy Policy*, **62**, 333-341 (2013).

C. Forsberg and P. F. Peterson, "Basis for Fluoride-Salt-Cooled High-Temperature Reactors with Nuclear Air-Brayton Combined Cycles and Firebrick Resistance-Heated Energy Storage", *Nuclear Technology*, 196, 13-31, (October 2016).

C. W. Forsberg, D. Curtis, and D. Stack, "Light-water Reactors with Crushed-Rock Thermal Storage for Industrial Heat and High-Value Electricity," *Nuclear Technology*, **198**, (April 2017) http://dx.doi.org/10.1080/00295450.2017.1294426.

C. Forsberg et al. *Light Water Reactor Heat Storage for Peak Power and Increased Revenue: Focused Workshop on Near-Term Options*, MIT-ANP-TR-170, July 2017, http://energy.mit.edu/2017-canes-light-water-reactor-heat-storage-for-peak-power-and-increased-revenue.

C. W. Forsberg, D. Stack, D. Curtis, G. Haratyk and N. A. Sepulveda, "Converting Excess Low-Priced Electricity into High-Temperature Stored Heat for Industry and High-Value Electricity Production," *Electricity Journal* (July 2017).

C. W. Forsberg. et al, *MIT-Japan Study: Future of Nuclear Power in a Low-Carbon World: The Need for Dispatchable Energy*, MIT-ANP-TR-171, Center for Advanced Nuclear Energy (CANES), Massachusetts Institute of Technology, September 2017, http://energy.mit.edu/wp-content/uploads/2017/12/MIT-Japan-Study-Future-of-Nuclear-Power-in-a-Low-Carbon-World-The-Need-for-Dispatchable-Energy.pdf.

C. Forsberg and P. F. Peterson, "Nuclear Combined Cycle Gas Turbines for Variable Electricity and Industrial Steam with Extended Firebrick Heat Storage", *Transactions American Nuclear Society*; Washington D.C., October 29-November 2, 2017

C. W. FORSBERG, S. BRICK, S. and G. HARATYK, "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Base-Load Reactor Operation, *Electricity Journal,* **31**, 23-31,(April 2018) https://doi.org/10.1016/j.tej.2018.03.008

C. W. FORSBERG, "Sodium-Steel Heat Storage for Variable Energy Output from Nuclear and Solar Power Systems," *Transactions of the 2018 American Nuclear Society Winter Meeting,* Orlando, Florida. (11-15 November 2018).

C. Forsberg and P. Sabharwall. *Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Operations*, ANP-TR-181, Massachusetts Institute of Technology, INL/EXT-18-51329, Idaho National Laboratory (2018)

C. W. Forsberg, "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology*, (March 2019) https://doi.org/10.1080/00295450.2018.1518555

C. W. Forsberg, "Commentary: Nuclear Energy for Economic Variable Electricity: Replacing the Role of Fossil Fuels", *Nuclear Technology*, **205**, iii-iv, (March 2019b) DOI:10.1080/00295450.2018.1523623

C. W. Forsberg, "A Modular High-Temperature Gas-Cooled Reactor (MHTGR) With Decreased Power Density and In-Core Stored Heat for Variable Electricity and Industrial Heat, *Trans. 2019 American Nuclear Society Annual Meeting*, Minneapolis, Minnesota (June 9-13, 2019)

C. W. Forsberg, H. Gougar AND P. Sabharwall, *Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Workshop Proceedings*, ANP-TR-185, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology, INL/EXT-19-54909, Idaho National Laboratory (July 2019).

C. W. Forsberg, E. Baglietto, M. Bucci and R. G. Ballinger, "Flibe Fusion Blankets and Flibe Fluoride-salt-cooled High-Temperature Reactors: Opportunities for Synergistic Development Strategies", *Transactions American Nuclear Society Winter Meeting*, Washington D.C., (November 17-21, 2019).

A. Gil, et al., "State of the Art on High Temperature Thermal Energy Storage for Power Generation. Part 1—Concepts, Materials, and Modelization," *Renewable and Sustainable Energy Reviews* 14.1, pp. 31–35 (2010).

P. V. Gilli, and K. Fritz, "Nuclear Power Plants with Integrated Steam Accumulators for Load Peaking" *IAEA Symposium on Economic Integration of Nuclear Power Stations in Electric Power Systems*, Vienna, WB-KE-2015 (October 5-9, 1970).

P. V. Gilli, and G. Beckman, "Steam Storage Adds Peaking Electricity Capacity to Nuclear Plants," *Energy International*. (August 1973).

M. Haider et al., University of Vienna, (2019) https://www.iet.tuwien.ac.at/forschungsbereich_thermodynamik_und_waermetechnik/forschungsgebiete/regenerative_energiesysteme/regenerative_energiesysteme/ht_waermespeicher/

T. Hirsch, J. Feldhoff, K. Hennecke and R. Pitz-Paal, "Advancements in the Field of Direct Steam Generation in Linear Solar Concentrators—A Review," *Heat Transfer Engineering*, **35** (*3*), pp. 258–271 (2014).

W. Han, J. Hongguang, S. Jianfeng; L. Rumou; and W. Zhifeng, "Design of the First Chinese 1 MW Solar-Power Tower Demonstration Plant." *Int. J. Green Energy*. Vol. 6, no. 5, pp. 414–425 (October 2009).

A. L. Harvy, "The Latest in Thermal Energy Storage", *Power*, **161** (*7*), 50-52 (July 2017).

Highview Power Storage, *Liquid Air Energy Storage (LAES)*. (2019) http://www.highview-power.com/

C. K. Ho, "A Review of High-Temperature Particle Receivers for Concentrating Solar Power", *Applied Thermal Energy*, 109 (2016)

C. K. Ho et al, *Highlights of the high-temperature falling particle receiver project: 2012 – 2016,* AIP Conference Proceedings **1850**, 030027, (27 June 2017), https://doi.org/10.1063/1.4984370

INPI, Bulletin officiel de la propriété industrielle, Brevets d'invention, n°18/24, June 15, 2018.

S. Khare, M. Dell'Amico, C. Knight, and S. McGarry, "Selection of Materials for High Temperature Latent Heat Energy Storage", Solar Energy Materials and Solar Cells, 107, 20-27, (2012) https://doi.org/10.1016/j.solmat.2012.07.020

M. Kulhanek, C. W. Forsberg, and M. J. Driscoll. *Nuclear Geothermal Heat Storage: Choosing the Geothermal Heat Transfer Fluid*, MIT-NES-TR-016, Massachusetts Institute of Technology, Cambridge, Massachusetts (January 2012)

S. Kuravi, et al, "Thermal Energy Storage Technologies and Systems for Concentrating Solar Power Plants (Review)," *Progress in Energy and Combustion Science*, **39**, 285-319 (2013)

D. Laing, C. Bahl, T. Bauer, D. Lehmann and W. Steinmann, "Thermal energy storage for direct steam generation," *Solar Energy*, **85** (*4*), pp. 627–633 (2011).

R. E. Lane, III. *Modeling and Integration of Steam Accumulators in Nuclear Steam Supply Systems*, MS Thesis, University of Texas at Austin (December 2016).

A. LaPotin and E. Schneider, "An Economic Model of a Steam Accumulator Storage System for Nuclear Power Plants", *Transactions of the American Nuclear Society*. (November 2016).

Y. Lee, C. Forsberg, M. Driscoll, and B. Sapie, "Options for Nuclear Geothermal Gigawatt-Year Peak Electricity Storage Systems, *Proc. of ICAPP'10*, San Diego (June 13-17, 2010)

Y. Lee, *Conceptual Design of Nuclear-Geothermal Energy Storage Systems for Variable Electricity Production*, MS Thesis, Department of Nuclear Science and Engineering, Massachusetts Institute of Technology (June 2011).

Y. Li, H. Cao, S. Wang, D. Li, X. Wang, and Y. Ding, "Load shifting of nuclear power plants using cryogenic energy storage technology." *Applied Energy,* **113** p. 1710–1716 (2014).

D. Liu et al. "Progress in Thermochemical Energy Storage for Concentrated Solar Power: A Review", Int. J. Energy Res., 2018, 42, 4546, https://doi.org/10.1002/er.4183

W. N. Mann. *Construction of Hybrid Nuclear Thermal Energy Storage Systems under Electric Market Uncertainty*, MS Thesis, University of Texas at Austin (2017)

G. Mauger, N. Tauveron, F. Bentivoglio, A. Ruby, "On the dynamic modeling of Brayton cycle power conversion systems with the CATHARE-3 code," *Energy*, 168, 1002-1016 (2019).

M. Medrano, A. Gil, I. Martorell, X. Potau and L. F. Cabeza, "State of the art on high-temperature thermal energy storage for power generation. Part 2—Case studies," *Renewable and Sustainable Energy Reviews*, **14** (*1*), pp. 56–72 (2010)

M. Mehos et al., *Concentrated Solar Power Gen3 Demonstration Roadmap*, National Renewable Energy Laboratory, NREL/TP-5500-67464, (January 2017) https://www.nrel.gov/docs/fy17osti/67464.pdf

G. Mohan, *Development of High-Temperature Sensible Thermal Energy Storage Systems for Advanced Concentrated Solar Power Generation*, Ph.D. Thesis, Australian National University (June 2018).

G. Mohan, M Venkataraman, J. Gomez-Vidal and J. Coventry, 2018. "Assessment of a Novel Ternary Eutectic Chloride Salt for Next Generation High-Temperature Sensible Heat Storage," *Energy Conversion and Management* **167**, 156–164 (2018).

K Mongird, Energy Storage Technology and Cost Characterization Report, Pacific Northwest National Laboratory, PNNL-28866 (July 2019).

National Renwable Energy Laboratory, 2017. "Concentrating Solar Power Projects." [Online]. Available: https://www.nrel.gov/csp/solarpaces/index.cfm

K. Niedermeier, J. Flesch, L. Marocco, and T. Wetzel, "Assessment of Thermal Energy Storage Options in a Sodium-based CSP plant". *Applied Thermal Engineering,* **107**, 386–397 (2016) http://dx.doi.org/10.1016/j.applthermaleng.2016.06.152.

H. Moon and S. J. Zarrouk. "Efficiency of Geothermal Power Plants: a Worldwide Review," *Proc. New Zealand Geothermal Workshop,* Auckland, New Zealand. (November 19-21, 2012).

R. I. Olivares, "The Thermal Stability of Molten Nitrite/Nitrates Salt for Solar Thermal Energy Storage in Different Atmospheres," *Solar Energy* 86.9, pp. 2576–2583 (2012).

D. Proctor, "Volcanic Rock Offers New Take on Energy Storage", *Power Magazine*, **163**(8), 11-13 (August 2019) https://view.imirus.com/427/document/13193/1.

K. Schwaiger et al., 2015. "Fluidized bed steam generators for direct particle absorption CSP-plants", *International Conference on Concentrating Solar Power and Chemical Energy Systems*, 2015.

SolarPACES, *Energy Procedia* **69,** 1421 – 1430 (2014).

Siemens Gamesa Renewable Energy, Same Force New Rules, Introducing Electric Thermal Energy Storage (ETES) (2019), https://www.siemensgamesa.com/-/media/siemensgamesa/downloads/en/products-and-services/hybrid-power-and-storage/etes/siemens-gamesa-storage-etes-storage-brochure-en.pdf, https://www.siemensgamesa.com/en-int/newsroom/2019/06/190612-siemens-gamesa-inauguration-energy-system-thermal.

Solar Reserve, 2019, https://www.solarreserve.com/en/index.html.

W. D. Steinmann and M. Eck, "Buffer storage for direct steam generation," *Solar Energy*, **80** (*10*), pp. 1277–1282 (2006).

D. C. Stack, D. Curtis, and C. Forsberg, "Performance of Firebrick Resistance-Heated Energy Storage for Industrial Heat Applications and Round-Trip Electricity Storage", *Applied Energy,* 242, 782-796 (2019) https://doi.org/10.1016/j.apenergy.2019.03.100.

Ushak, S., A. G. Fernandez and M. Gradeda. "Using Molten Salts and Other Liquid Sensible Storage Media in Thermal Energy Storage (TES) Systems," *Advances in Thermal Energy Storage Systems*, pp. 49–63 (2015).

Westinghouse Electric Company LLC, 2016, *Nuclear Energy Storage*.

G. Wilson, S. Sahoo, P. Sabharwal and H. Bindra. "Packed Bed Thermal Storage for LWRs", Chapter 7 in *Storage and Hybridization of Nuclear Energy,* Edited by H. Bindra and S. Revankar, Elsevier Inc. (2019), https://doi.org/10.1016/B978-0-12-813975-2.00007-7

X. L. Yan and H. Sato, "HTGR and Renewable Hybrid Energy System for Grid Stability – an Assessment of Performance, Economics, and CO_2 Reductions," *IAEA Technical Meeting on Nuclear-Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration*, Vienna, Austria, October 22.-25, 2018.

B. Zohuri and P. McDaniel, *Advanced Smaller Modular Reactors: An Innovative Approach to Nuclear Power* 1st Edition, Springer 2019, https://www.springer.com/us/book/9783030236816

B. Zohuri and P. McDaniel, *Combined Cycle Driven Efficiency for Next Generation Nuclear Power Plants: An Innovative Design Approach, 2nd ed*., Springer, 2018, https://www.springer.com/gp/book/9783319705507

B. Zohuri, P. McDaniel, and C. R. De Oliveria, "Advanced Nuclear Open Air-Brayton Cycles for Highly Efficient Power Conversion", *Nuclear Technology*, **192** (1), 48-60, (2015), http://dx.doi.org/10.13182/NT14-42

S. Zunft, S. Freund, and E. M. Schlichtenmayer, "Large-Scale Electricity Storage with Adiabatic CAES – The Adele-Ing Project", *Energy Storage Global Conference*, Paris. (November 19-21, 2014).

Appendix A
Workshop Agenda

Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors
Changing Markets, Technology, Nuclear-Renewable Integration and Synergisms with Solar Thermal Power Systems

July 23-24, 2019
Idaho State University
Bennion Student Union Building, 1784 Science Center Drive, Idaho Falls Idaho

Tuesday, July 23, 2019

7:15	Morning Refreshments	
8:15	Welcome	Pete Wells, Idaho National Laboratory Hans Gougar, Idaho National Laboratory

Economics, Regulation, and Programs for Heat Storage

8:30	Changing Electricity Markets with the Need for Dispatchable Electricity	Charles Forsberg, Massachusetts Institute of Technology
9:00	Utility Perspectives on Heat Storage: Economics, Markets and Regulation (FERC and NRC)	Otgonbaatar Uuganbayar (Ugi), Exelon
9:30	EPRI Programs on Storage	Andrew Sowder, Electric Power Research Institute
10:00	Coffee Break	
10:30	National Program for Heat Storage in Concentrated Solar Power	Avi Shultz, Department of Energy
11:00	Nuclear JUMP Initiative	Shannon Bragg-Sitton, Idaho National Laboratory
11:30	Panel: What are the Regulatory (Federal Energy Regulatory Commission, PUCs, ISO, Nuclear Reactor Commission, etc.) and other Barriers to Large-Scale Heat Storage?	Panel Members: • Shannon Bragg-Sitton, Idaho National Laboratory • Marcus Nichol, Nuclear Energy Institute • Charles Forsberg, Massachusetts Institute of Technology • Otgonbaatar Uuganbayar (Ugi), Exelon • Wayne Moe, Idaho National Laboratory
12:30	Lunch	Discussions Among Participants

Heat Storage Technology Options for GenIV Reactors

1:30	Nitrate Salt Heat Storage	Bruce Kelly, Solar Dynamics
2:00	High Temperature (600°C) Concrete Storage and Pumped Heat Variant	Kevin Pykkonen, Bright Energy Storage Technologies
2:30	Westinghouse Heat Storage Studies	Cory Stansbury, Westinghouse
3:00	Coffee Break	
3:30	Heat Storage for Sodium-Cooled Reactor Systems	Gedeon Mauger, CEA France
4:00	Hot Sand Heat Storage	Cliff Ho, Sandia National Laboratories
4:30	TerraPower Integrated Energy System Architecture with Storage	Josh Walter, TerraPower
5:00	Break - set up posters	
5:10 – 8:30	Reception – Poster Session, Dinner, and Speaker	

Thank you to our generous sponsors Exelon and MIT.

Wednesday, July 24, 2019

7:15	Morning Refreshments	

Other Technologies for Heat Storage and Grid Integration

8:00	Status of Chloride-Salt Heat Storage	Craig Turchi, National Renewable Energy Laboratory
8:30	Thermochemical Energy Storage for CSP and Nuclear Power Management	Jamison Couture, Brayton Energy Shaun Sullivan, Brayton Energy
9:00	Brayton Power Cycles with Peaking Capability and Storage	Bahman Zohuri, University of New Mexico
9:30	Hydrogen Integration: Storable Product	Tyler Westover (INL)
	Potential User Case for Hydrogen Storage	Scott Barney
	Cast Iron Storage for Heat Storage in Na, Salt, Pb, and He Cooled Reactors	Charles Forsberg (MIT)
10:15	Coffee Break	
10:30	Chemical Heat Pumps	Vivek Utgikar, University of Idaho

Path Forward

11:15	Break	
11:30	Bag Lunch (Discussions Among Participants)	
12:00	Panel: What is the Commercial Path to Large-Scale Deployment? How can we Integrate Nuclear and CSP Heat Storage Research, Development, and Demonstration to Accelerate Progress?	Panel Members: • Hans Gougar, Idaho National Laboratory • Avi Schultz, Department of Energy • Josh Walter, TerraPower • Andrew Sowder, Electric Power Research Institute

Thank you to our generous sponsors Exelon and MIT.

Appendix B
Participant List

	Heat Storage Workshop	July 23-24, 2019
	Name	**Company**
1	Abraham Shultz	DOE - Solar
2	Amey Shigrekar	University of Idaho
3	Andrew Sowder	Electric Power Research Institute
4	Avi Schultz	DOE
5	Bahman Zohuri	University of New Mexico
6	Benjamin Leibowicz	University of Texas at Austin
7	Bernard McGrail	Pacific Northwest National Lab
8	Brendan Ward	Kansas State University
9	Bruce Kelly	Solar Dynamics
10	Charles Forsberg	Massachusetts Institute of Technology
11	Clifford Ho	Sandia National Laboratories
12	Colleen Nehl	Booz Allen Hamilton
13	Cory Stansbury	Westinghouse Electric Company
14	Craig Turchi	National Renewable Energy Laboratory
15	Cristian Rabiti	Idaho National Laboratory
16	Daniel MIkkelson	NC State University
17	Darryl Gordon	Framatome
18	Dayna Daubaras	Idaho National Lab
19	Elizabeth Worsham	North Carolina State University
20	Gédéon Mauger	CEA
21	Hans Gougar	Idaho National Laboratory
22	Jackie Stokes	Idaho National Laboratory
23	Jacob McMurray	Oak Ridge National Laboratory
24	Jamison Couture	Brayton Energy
25	Jinsuo Zhang	Virginia Tech
26	Jodi Vollmer	Idaho National Laboratory
27	Joshua Walter	TerraPower, LLC
28	Kevin Pykkonen	Bright Energy Storage Technologies
29	Konor Frick	Idaho National Laboratory
30	Lori Braase	Idaho National Lab
31	Malcolm Handley	Strong Atomics
32	Marcus Nichol	Nuclear Energy Institute
33	Patrick McDaniel	University of New Mexico
34	Pete Wells	Idaho National Laboratory
35	Piyush Sabharwall	INL
36	Richard Boardman	INL
37	Richard Christensen	Univeristy of Idaho
38	Richard Vilim	ANL
39	Robert Corbin	TerraPower
40	Robert Varrin, Jr.	VRD
41	Sarah Roberts	INL
42	Scott Barney	Millard County, Economic Development
43	Shane Gallagher	University of California, Berkeley
44	Shannon Bragg-Sitton	Idaho National Laboratory
45	So-Bin Cho	INL
46	Tatsuro Kobayashi	TEPCO HD
47	Timothy Stack	Framatome
48	Tyler Westover	INL
49	Uuganbayar Otgonbaatar	Exelon

50	Vivek Utgikar	University of Idaho
51	Wayne Moe	INL
52	W Neal Mann	The University of Texas at Austin, Department of Mechanical Engineering
53	William Stewart	MIT

Appendix C
Presentations

Appendix C: Presentations

Table of Contents

Massachusetts Institute of Technology | Idaho National Laboratory | Exelon

Heat Storage for Gen IV Reactors for Variable Electricity from Base-load Reactors

Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

July 23, 2019: 8:15 am to 5:00 pm (plus dinner)
July 24, 2019: 8:30 to 12:00 Noon

Idaho Falls, Idaho

Massachusetts Institute of Technology

Role of Heat Storage in Changing Electricity Markets with the Need for Dispatchable Electricity

Charles W. Forsberg
Massachusetts Institute of Technology
Email: cforsber@mit.edu

Massachusetts Institute of Technology

Electricity Markets are Changing

Addition of Wind and Solar

Goal of Low-Carbon Energy System

Massachusetts Institute of Technology

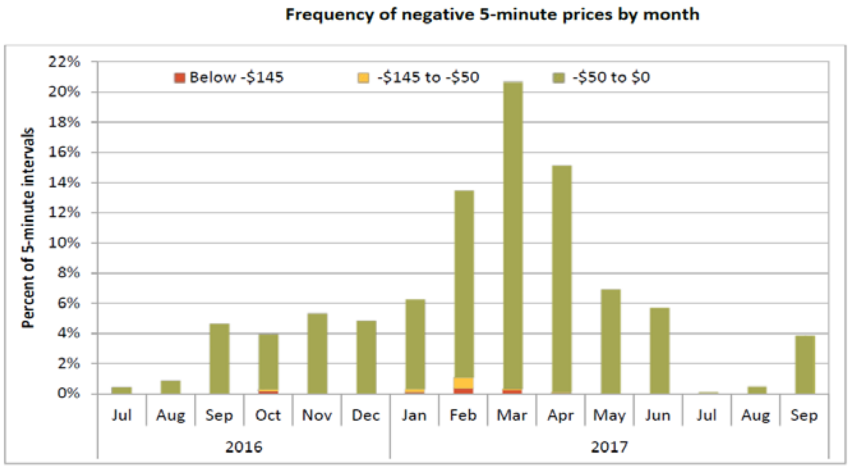
3

Large-Scale Solar or Wind Causes Price Collapse and Higher Prices at Other Times

Impact of Added Solar PV on California Wholesale Prices: Value of Wind and Solar Decrease With Scale

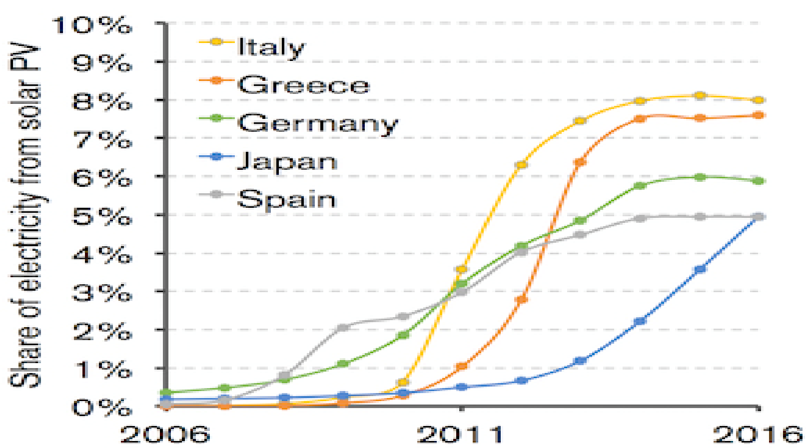
4

Seasonal Mismatch Between Demand and Wind/Solar
California Negative Wholesale Prices by Month



End of Subsidies and Technology Modifications will Convert Negative-Price to Zero-Price Electricity over Time

Electricity Price (Revenue) Collapse Limits Non-Dispatchable Wind and Solar Without Storage
Saturate Market Even If Large Subsides



Massachusetts Institute of Technology

Varum Sivaram,, "A Tale of Two Technologies", THE BREAKTHROUGH JOURNAL, NO. 8 / WINTER 2018.

Low Levelized-Cost-of-Electricity (Lazard 2017) Does Not Imply Large Market Share

Technology	Energy Form	LCOE: $/MWh(e)	Dispatch	Low-Carbon
Solar PV: Thin Film Utility	Electricity	43–48	No	Yes
Solar Thermal Tower with Storage	Heat	98–181	Yes	Yes
Wind	Electricity	30–60	No	Yes
Natural Gas Peaking	Heat	156–210	Yes	No
Natural Gas Combined Cycle	Heat	42–78	Yes	No
Nuclear	Heat	112–183	Yes	Yes

Dispatchability Is as Important as LCOE

7

Low-Carbon Energy Sources Have Different Economic Characteristics Than Fossil Fuels

Massachusetts Institute of Technology

8

No Change In Energy Policy for 300,000 Years, Throw a Little Carbon on the Fire

Cooking Fire

Natural-Gas Combined Cycle

Low-Capital-Cost Power Systems, Labor & Money in Collecting Fuel: Wood or Natural Gas: Economic at Part Load

Fossil Fuels Are Hard to Replace Because They Provide Three Services

- Source of energy
- Low-cost energy storage
- Low-cost dispatchable energy

Low-Carbon System Economics:
High Capital Cost and Low Operating Cost

Operate At Half Capacity Doubles Energy Costs




Produce Electricity | **Produce Heat**

Massachusetts Institute of Technology

11

Rethinking Energy System Design for Heat Generating Technologies in a Low Carbon World

Nuclear (Fission), Concentrated Solar, Geothermal, Fossil Fuel With Carbon Capture and Fusion (Future)

Massachusetts Institute of Technology

12

What a Low-Carbon Electricity System Needs

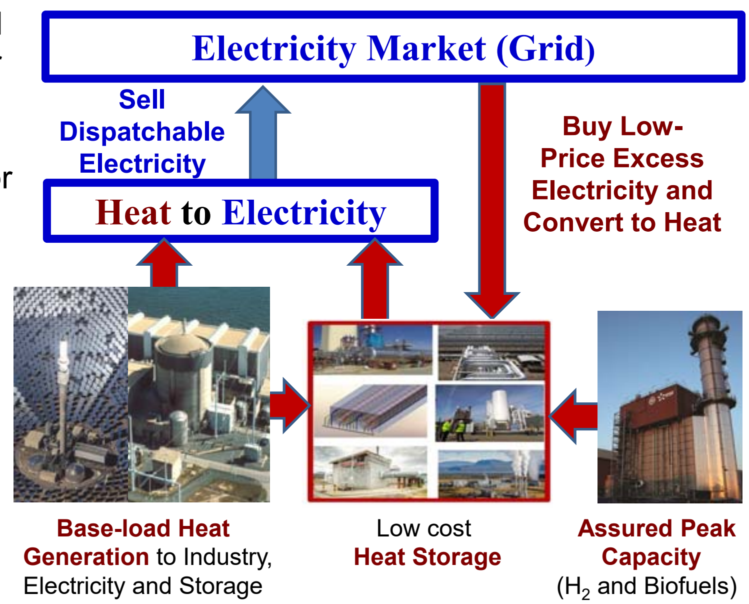
- Sell dispatchable electricity
  - Low cost
  - Assured generating capacity for peak loads
- Buy very-low-price electricity from wind and solar PV at times of excess production: Sets a higher minimum price that improve economics
- Operate nuclear reactors and other heat-generating technologies at base-load to minimize costs

Replace the Storage, Dispatchability and Production Characteristics of Fossil Fuels

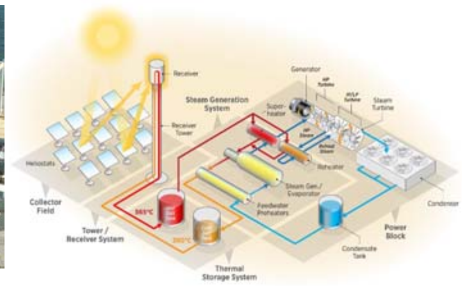
13

Require a New System Design

- Base-load nuclear or CSP
- Heat storage for peak electricity
- Low-price electricity to heat storage
- Backup furnace: assured peak capacity



System Design Applicable to All Heat-Generating Technologies

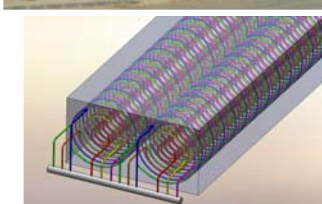


Nuclear Power System **NREL CSP System**

Massachusetts Institute of Technology

15

Low-Cost Heat Storage Couples to Nuclear: Same Technologies as Concentrated Solar Power



Steam Accumulators

Sensible Heat (Oil, salt, etc.)

Cryogenic Air

Hot Cement

Geothermal (Seasonal)

Hot Rock

16

Heat Storage Is Cheaper than Electricity Storage (Batteries, Pumped Hydro, etc.)

- DOE heat storage goal: $15/kwh(t)
- Battery goal $150/kWh(e), double if include electronics
- **Difference is raw materials cost**

Gigawatt-Hour Heat Storage Technologies	Temperature Limits (°C)
Pressurized Water	<300
Geothermal	<300
Counter Current Sat Steam	<300
Cryogenic Air	<1600
Concrete	>600
Crushed Rock	800
Sand	>1000
Oil	<400
Cast Iron	700/900
Nitrate Salt	<650
Chloride Salt	<1000
Graphite	>1600

17

Power System Coolant Temperatures Define Allowable Storage Materials

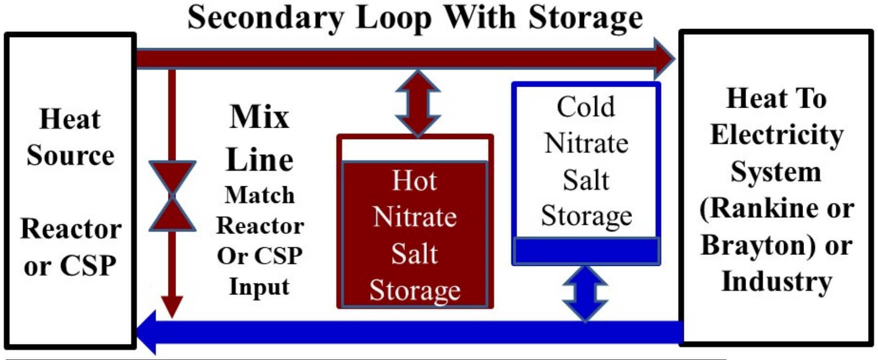
Coolant	Nominal Inlet Temperature (°C)	Nominal Exit Temperature (°C)
NP: Water	270	290
NP: Sodium	450	550
NP: Helium	350	750
NP: Salt	600	700
CSP: Nitrate	290	565
CSP: Chloride	500	725
CSP: Sodium	500	750
CSP: Sand	575	775

Massachusetts Institute of Technology

18

Storage Temperature Range Can be Decoupled from Nuclear /CSP System

- Some reactors have small delta T across core
- Large delta T reduce storage costs



Massachusetts Institute of Technology

19

Two Strategies for Peak Power

Heat from Reactor/CSP and Heat Storage

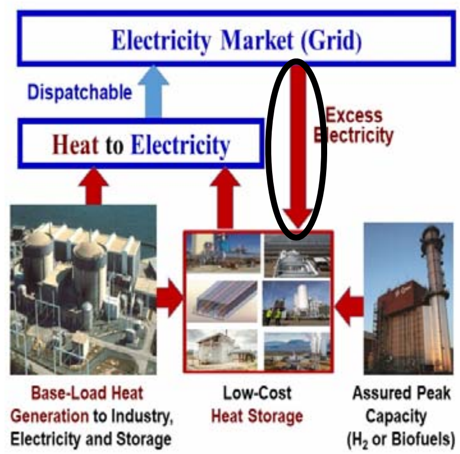
- Oversize Main Turbo-Generator
  - Fast response from operating turbine
  - Peak power capacity limited
  - Turbine efficiency highest at only one power level
  - Low-cost option
- Separate Peaking Turbo-Generator
  - Peaking turbine can be sized to any market
  - Return condenser water to main turbine

Massachusetts Institute of Technology

20

If Heat Storage, Buy Low-Price Electricity and Convert to Heat for Later Use

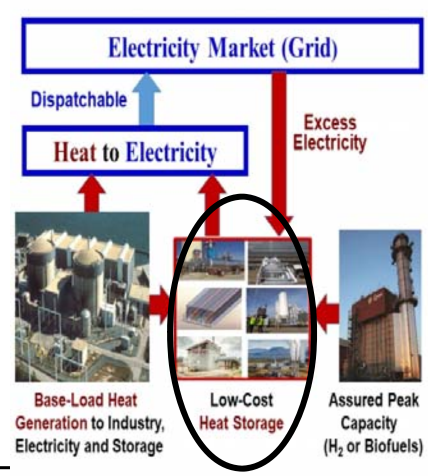
- When low-prices
  - Nuclear generator and grid electricity to heat storage
  - Electric resistance heaters
- Low-cost storage option
  - Same equipment (grid connections, transformers, switchgear) to buy and sell electricity
  - Own storage system and electricity peaking capability
  - Incremental addition to heat storage capacity



Improves Nuclear, Wind and Solar Economics 21

This System Can Address the Weekday-Weekend Market Challenge

- Low-carbon systems will have excess low-price electricity on weekends: <u>low electricity demand</u>
- Only added cost for weekend-to-weekday storage is <u>incrementally larger heat storage</u>: very low cost



Massachusetts Institute of Technology

22

If Heat Storage, Option to Buy Steam Generator for <u>Assured Peak Power</u>

- All storage devices can become depleted but need for assured peak power
- Burns (1) natural gas or (2) low-carbon biofuels and hydrogen
- Low-cost option
  - Use storage electricity peaking capability (turbine generator)
  - Half to third the cost of backup gas turbine for assured capacity

Seldom Used & Low-Carbon Fuel Options

23

Can Nuclear with Heat Storage Compete with Natural-Gas Peaking Plants?

Technology	Energy Form	LCOE: $/MWh(e)	Dispatch	Low-Carbon
Natural Gas Peaking	Heat	156–210	Yes	No
Natural Gas Combined Cycle	Heat	42–78	Yes	No
Nuclear	Heat	112–183	Yes	Yes

- Natural gas peaking plants expensive: High maintenance cost with very high temperature machine plus low capacity factor
- Nuclear with heat storage to replace peaking gas turbine
  - Sell peak power—same as NG peaking plant
  - Assured peak generating capability—same as NG peaking plant
  - Buy low-price electricity for heat storage and peak power—Added revenue

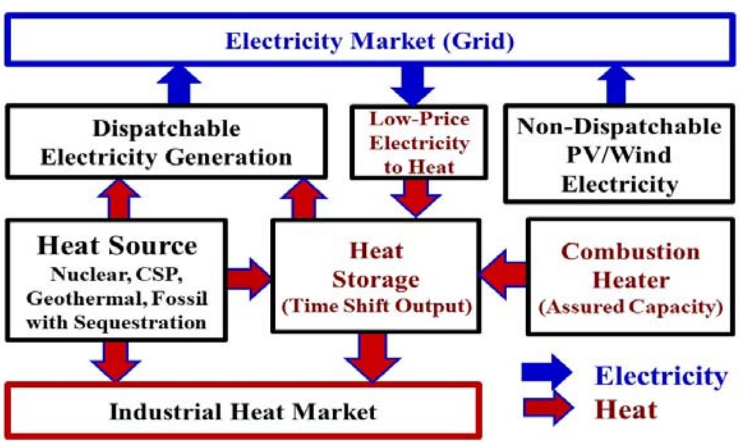
Massachusetts Institute of Technology

24

Conclusions

- Electricity market is changing: Volatile prices
  - Deployment of non-dispatchable wind and solar PV
  - Goals of low-carbon economy
- Low-carbon world requires a replacement for fossil fuels as (1) Energy source, (2) Storable energy and (3) Dispatchable energy
- **Require heat storage on the gigawatt-hour scale**
  - **No market 5 years ago, market rapidly growing**
  - **Same challenges for all heat generating technologies**
  - **Enabling technology for economic larger-scale use of nuclear, wind and solar**

Questions



Massachusetts Institute of Technology

26

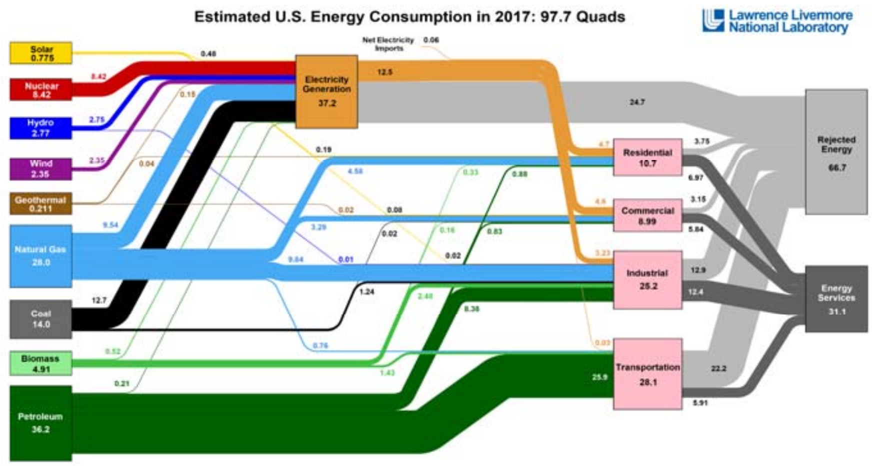
References

1. C. W. Forsberg, "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology* March 2019. https://doi.org/10.1080/00295450.2018.1518555
2. C. Forsberg and P. Sabharwall, *Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Operations*, ANP-TR-181, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology, INL/EXT-18-51329, Idaho National Laboratory
3. Charles Forsberg, Stephen Brick, and Geoffrey Haratyk, "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Base-Load Reactor Operation, *Electricity Journal,* **31**, 23-31, April 2018, https://doi.org/10.1016/j.tej.2018.03.008
4. The Future of Nuclear Energy in a Carbon Constrained World, Massachusetts Institute of Technology, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf
5. C. Forsberg, K. Dawson, N. Sepulveda, and M. Corradini, *Implications of Carbon Constraints on (1) the Electricity Generating Mix for the United States, China, France and the United Kingdom and (1) Future Nuclear System Requirements*, MIT-ANP-TR-184 (March 2019)
6. Charles W. Forsberg (March 2019): Commentary: Nuclear Energy for Economic Variable Electricity: Replacing the Role of Fossil Fuels, *Nuclear Technology*, **205**, iii-iv, DOI:10.1080/00295450.2018.1523623

Take Away Messages

- Restrictions on carbon emissions and the addition of wind and solar PV change the electricity market
  - Volatile electricity prices including zero and negative priced electricity (low marginal cost wind and solar)
  - Need economic assured peak generating capacity
- Require a system solution: Nuclear co-generation (electricity and heat) with large-scale heat storage and assured peak electricity generating capacity
  - Buy electricity at times of low prices
  - Sell electricity at times of high prices
  - Operate power systems at full capacity
- Same storage/power system technologies for CSP

The Characteristics of Fossil Fuels Enable Separate Energy Supply Chains for Electricity, Industry and Transportation



In a Low-Carbon World, Need to Integrate Separate Energy Supply Chains to Minimize Costs

29

NREL Summary Descriptions

Technology	Storage Media	Receiver Outlet Temp (C)	Hot Storage Temp (C)	Cold Storage Temp (C)
CSP Parabolic Trough	Na/K nitrate “solar salt”	390	385	295
CSP Molten-Salt Tower	Na/K nitrate “solar salt”	565	565	290
Gen3 CSP Chloride Salt Tower	Mg/K/Na chloride	725	720	500
Gen3 CSP Sodium Receiver + Chloride-salt TES	Mg/K/Na chloride	750	720	500
Gen CSP Particle Tower	Sand		775	575

Massachusetts Institute of Technology

Added Information

Three Electricity Generating System Options for a Low-Carbon World that Meet the Three Requirements:

Electricity Generation
Energy Storage
Assured Peak Generating Capacity

Nuclear Energy with Heat Storage and Backup Furnace (Biofuels, Hydrogen, etc.)

Heat Generation to Electricity and Storage

Heat Storage

Backup Boiler for Depleted Storage

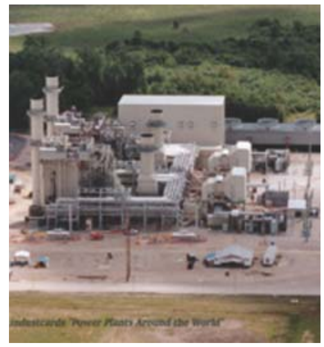
Concentrated Solar Power (CSP) has Same System Design

Wind / Solar PV System With Electricity Storage and Backup Gas Turbine

Generation

McCrary Battery Storage Demonstration

Electricity Storage



Backup GT for Depleted Storage

Seasonal Solar & Wind Input Requires Significant Operation of Gas Turbine Backup (Biofuels and H_2)

33

Fossil Plant with Carbon Capture and Sequestration

Petra Nova (Joint venture): NGR Energy and JX Nippon Oil and Gas Exploration

- Post combustion capture CO_2
- 240 MW
  - Added to Unit 8 (654 MW)
  - 37% of Unit 8 emissions
- 90% CO_2 capture

Massachusetts Institute of Technology

34

Comparison of the Three Energy Options

Some Mixture Likely Where Choices Depend upon Location

Option/ Characteristic	Nuclear* with Storage + Fuel	Wind/Solar PV* With Storage + Fuel	Fossil with Carbon Sequestration
1. Base-load Fuel cost	Low	~0	High
2. GW_{total}/GW_{peak}	1	>2	1
3. Low-carbon fuel (H_2, biofuels, etc.)	Low	High	None
4. Location Dependent	No	Yes	Yes

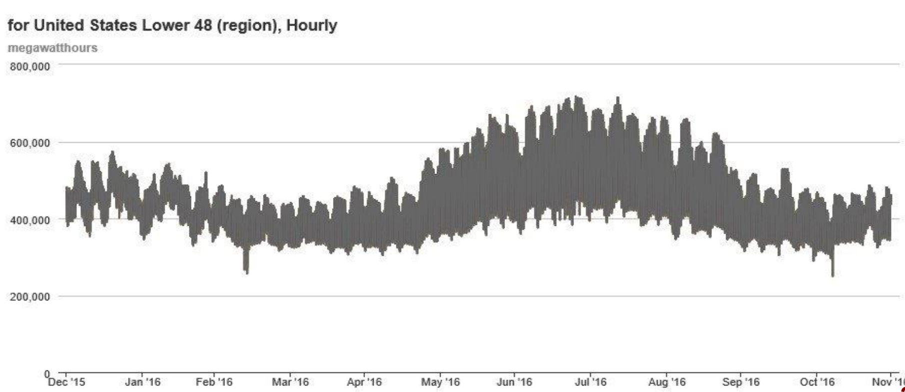
Numbered Notes below coupled to characteristics
2. GW(e) nameplate rating divided by GW(e) assured peaking capacity. Wind and solar PV total generating capacity equals Wind/Solar PV + battery + gas turbine but if extended low wind/solar conditions, the only assured capacity is the gas turbine.
3. Low-carbon fuel required for assured peaking capacity when storage is depleted. For nuclear this peaking capacity above base-load nuclear. For wind/solar this is total power because no assured base-load capability from wind and solar.
4. No location dependency for nuclear. Wind/Solar depend upon local wind and solar conditions. Fossil depend upon sequestration sites.
*Concentrated Solar Power systems have some of the characteristics of nuclear systems and some of the characteristics of solar PV

Massachusetts Institute of Technology

35

Lowest Cost System Depends upon (1) System Option Cost and (2) Best Match Between Production and Demand

- Mismatch between full production and electricity demand implies more storage and higher costs; Nuclear with storage has the closest match



36

Most Economic Nuclear System Depends upon Three Factors

- Markets. Market with wind or solar will have different nuclear heat storage requirements because of different storage times (daily versus multiday cycles).
- Storage technology. Preferred storage technology depends upon market and reactor choice
- Reactor choice. Higher temperature reactor implies lower heat-storage costs
  - If sensible heat storage, double hot-to-cold temperature swing reduces heat storage system in half per MWh (heat)
  - Heat-to-electricity efficiency depends upon temperature. If 50% more efficient, smaller heat storage system per MWh (electricity)

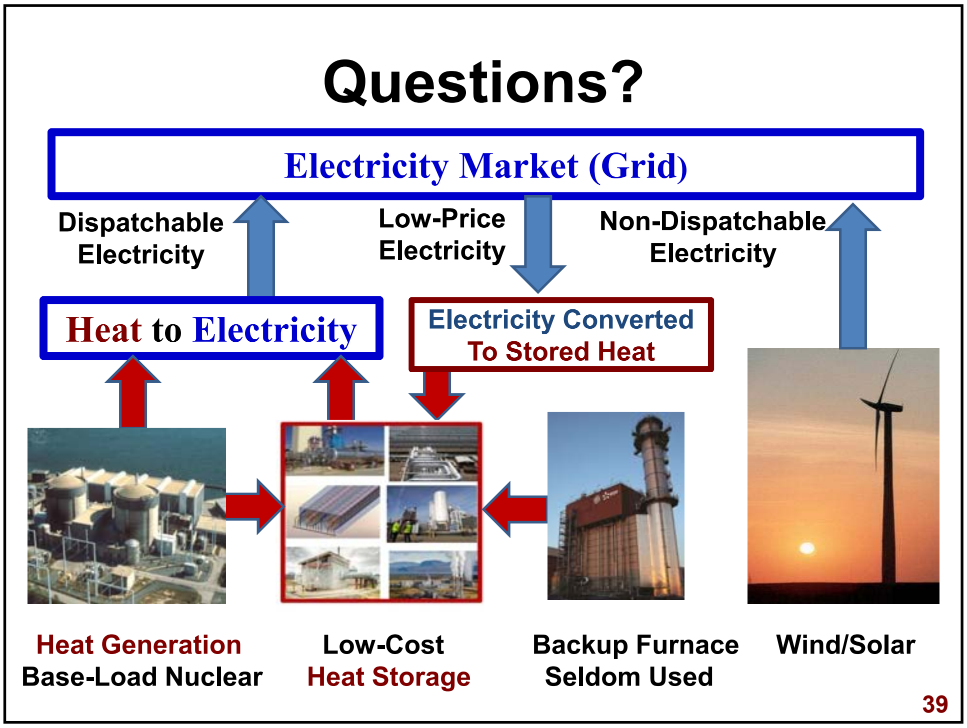
Massachusetts Institute of Technology

37

Same Nuclear System for Co-Generation
Produce Variable Heat and Electricity

- Industrial heat demand twice total electricity output of the United States
  - Electricity costs 4 to 6 times the cost of heat
  - Expensive to “electrify” industry by converting electricity to heat
- Large incentives for nuclear cogeneration
  - Existing fossil cogeneration plants sometimes vary production to maximize electricity sales when prices are high. Low-cost way for nuclear co-generation added assured peak generating capacity
  - Storable manufactured fuels (hydrogen, biofuels) have massive heat and electricity inputs. Incentives to vary production with electricity prices that couples utility and transportation energy markets
- Co-generation enables optimization of combined electricity, industrial, and transportation energy markets to minimize total costs

38


Questions?
Electricity Market (Grid)
Dispatchable Electricity
Low-Price Electricity
Non-Dispatchable Electricity
Heat to Electricity
Electricity Converted To Stored Heat
Heat Generation Base-Load Nuclear
Low-Cost Heat Storage
Backup Furnace Seldom Used
Wind/Solar
39

Energy Storage Technologies for Operating Nuclear Power Plants

Heat Storage for Gen IV Reactors for Variable Electrify from Base-Load Reactors

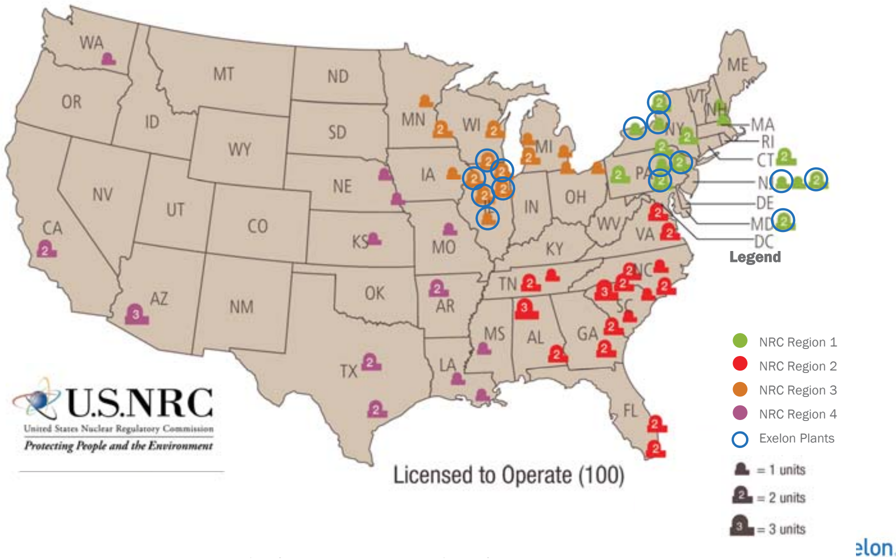
July 23-24, 2019

Exelon.

Exelon overview

Exelon.

Exelon nuclear plants are located in competitive electricity market regions



elon.

Nuclear plant profitability has decreased, due to a confluence of factors

Natural gas prices (which fuels marginal generators in many regions) have dropped by more than 50%

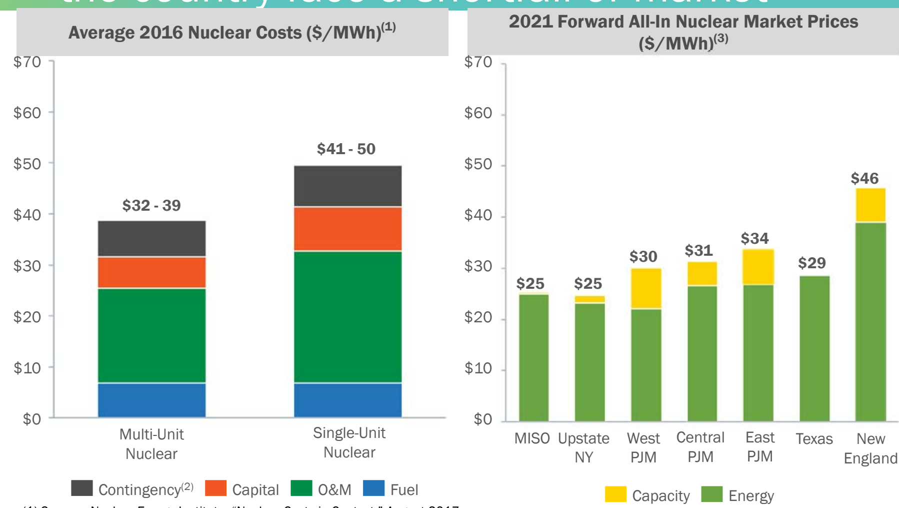
Load growth is down due to both the economy and increased energy efficiency programs

Renewables penetration has suppressed wholesale energy prices in some regions

Across the U.S. nuclear fleet, operating costs have increased (albeit with reductions in recent years)

Exelon.

Merchant nuclear plants in all regions of the country face a shortfall of market



(1) Source: Nuclear Energy Institute, "Nuclear Costs in Context," August 2017
(2) Contingency (or risk) is calculated as 10% of total costs plus $4/MWh
(3) Based on 6/4/2018 NYMEX forward energy prices for relevant hub less 2015-2017 average basis differential to nuclear plants

Exelon.

Closing nuclear plants is detrimental to achieving carbon reductions goals

Between 2013 and 2014, **four nuclear plants that generated more electricity than all solar electricity produced in the U.S.** in 2014 were prematurely closed. Their closure resulted in the **carbon dioxide equivalent of adding three million new cars on the road**.

If all at-risk reactors close, the US will **lose the power equivalent of five times all solar power generated** in 2015, and emissions will rise, adding the carbon dioxide-equivalent of **13 million new cars on the road**.

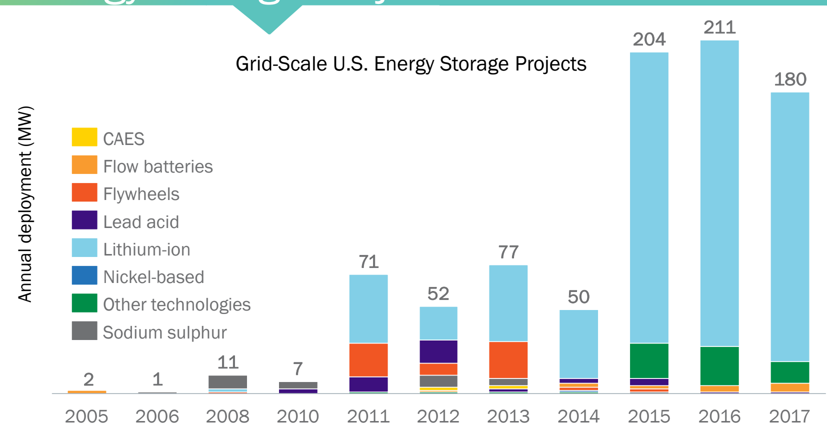
Nuclear plants generally employ **400 – 700 workers each**, at salaries that are more than **30% higher than typical wages** in their areas.

*EnvironmentalProgress.org

Exelon.

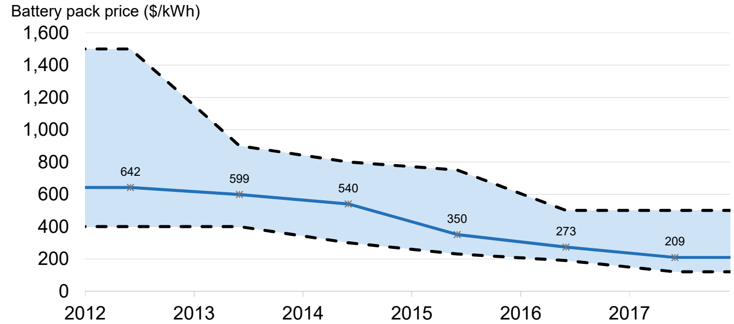
Energy storage technologies and deployment

Lithium-Ion Batteries Dominate U.S. Energy Storage Projects



- As of May 2018, the cumulative capacity of grid-scale energy storage deployed in the U.S. was 955 MW. (Scope: grid-scale systems have > 500 kW or > 500 kWh / system)
- Over 90% of the energy storage projects deployed in the U.S. in 2017 used Li-ion batteries.
- Wholesale market rules determine battery installation opportunities for grid-scale systems, such as the 2015 deployment of Li-ion battery energy storage projects to serve the frequency regulation market in PJM.

Li-ion battery pack prices are dropping



- Reported battery pack purchase prices ranged between $120/kWh and $500/kWh in 2017, primarily due to differences in order volume.
- High-volume orders from EV manufacturers obtained the lowest prices, and the volume-weighted average of Li-ion battery pack prices was $209/kWh.
- Fully-installed costs for a battery energy storage system ranged from $400 - $1400 / kWh in 2017.

FERC Order 841 on Energy Storage

FERC Order 841 sets tariff rules for wholesale market participation of energy storage resources

Timeline	**Nov. 2016** **Rulemaking issued for Order 841**	**Feb. 2018** **FERC Order 841 approved**	**Feb. 2019** **Tariff rules due from RTOs/ISOs**	**Feb. 2020** **Implementation of new tariff rules expected**

FERC Order 841 Content

FERC Order 841 directs wholesale market operators to devise new tariffs that will:

- Allow energy storage resources to participate in wholesale market as **both a buyer and a seller of electricity**
- Establish a minimum size, not to exceed 100 kW, for energy storage resources to participate in RTO/ISO markets
- Allow storage to provide **energy**, **capacity** and **ancillary services** (including black-start and reactive power services)

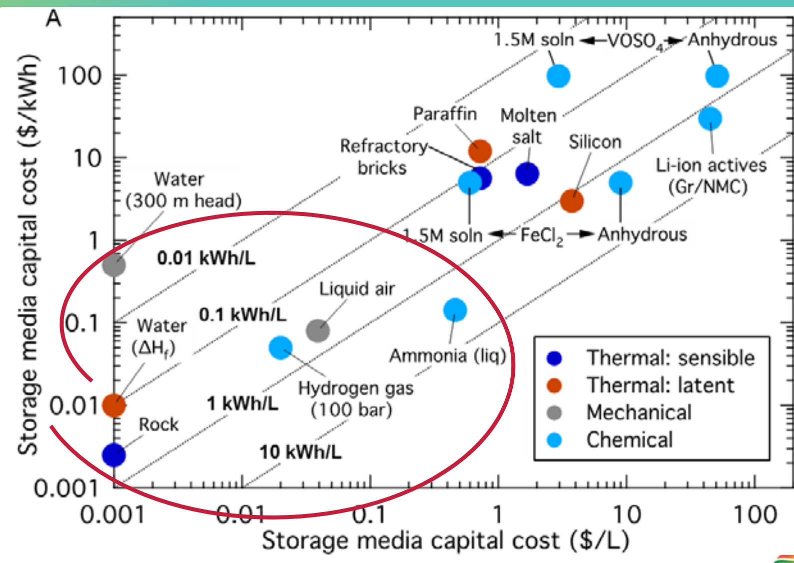
Context

- California (CAISO) already allows energy storage to participate in wholesale power markets
- California is also moving towards implementing rules to govern “revenue stacking” for energy storage projects that provide multiple energy services
- PJM has hosted working groups towards developing rules for energy storage participation

Implications

- FERC Order 841 will reduce barriers and encourage a level playing field for energy storage resources to participate in inter-state wholesale electricity markets
- As markets mature, energy storage will compete against conventional peaking plants

Other storage options are possible



Exelon.

Thermal Energy Storage

Cost effective avoidance of plant cycling in future high renewable power systems

Andrew Sowder, Technical Executive

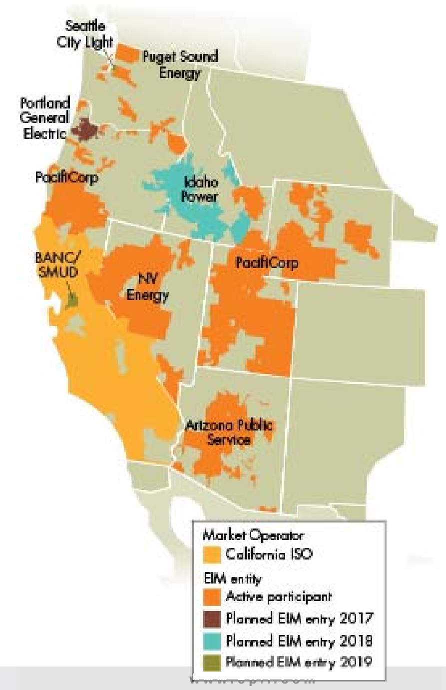
July 23, 2019

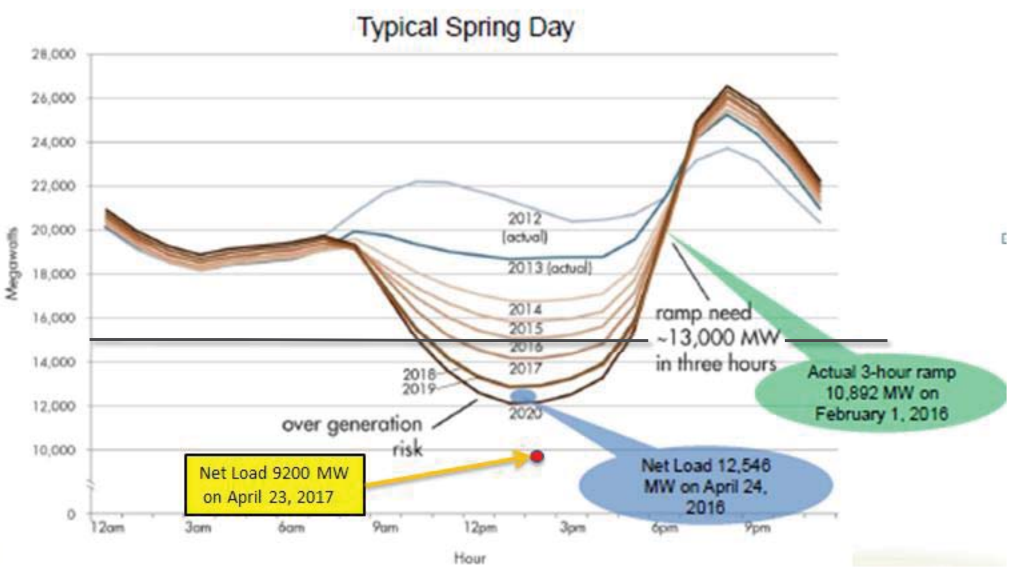
MIT/INL/Exelon Workshop: Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors

Idaho Falls, ID

ELECTRIC POWER RESEARCH INSTITUTE

Over-Generation Driving Need for Flexible Operations
Example: CAISO





Source: CAISO

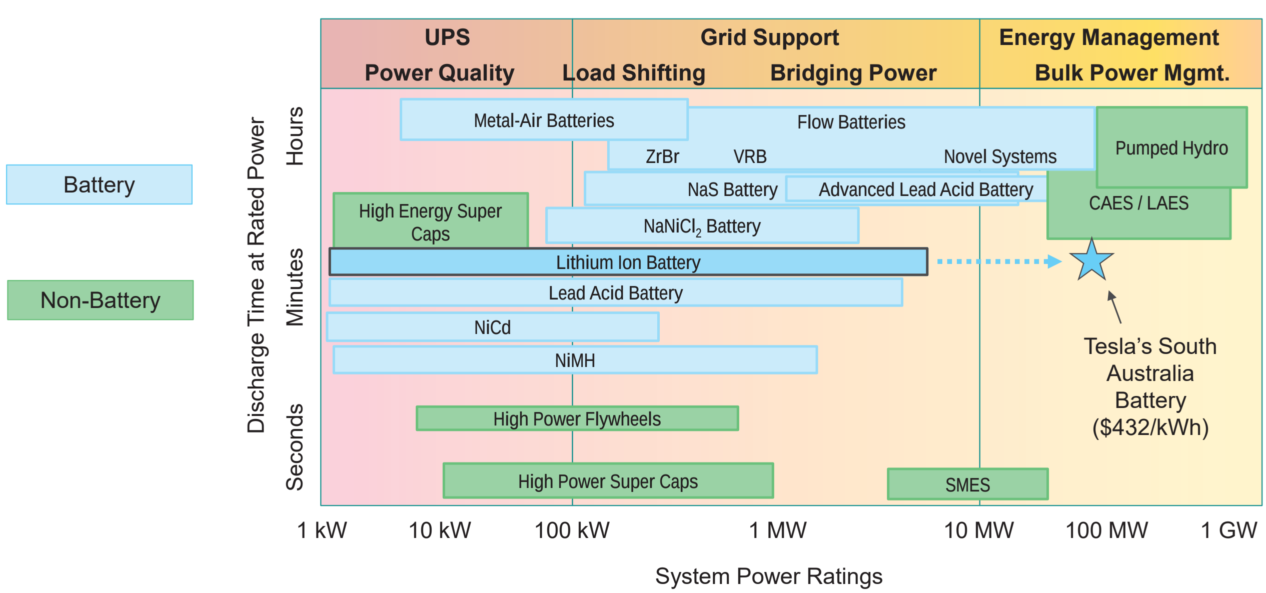
Increasing Demand for Flexible Generation Assets

- Cycling of fossil and nuclear units comes at a cost
- R&D now focusing on reducing minimum loads and improving ramp rates in fossil plants and preparing baseload nuclear plants for flex-ops
- If energy can be stored at scale:
  - Plants can operate during low/negative pricing periods <u>without</u> power exports
  - Battery technology can be used, however the cost of storage can be prohibitive at **$1400 – $2300/kW** for a 4-hour system installed today*
  - Due to high cost relative to incremental value makes battery technology more challenging at longer durations (e.g +10 hour storage)

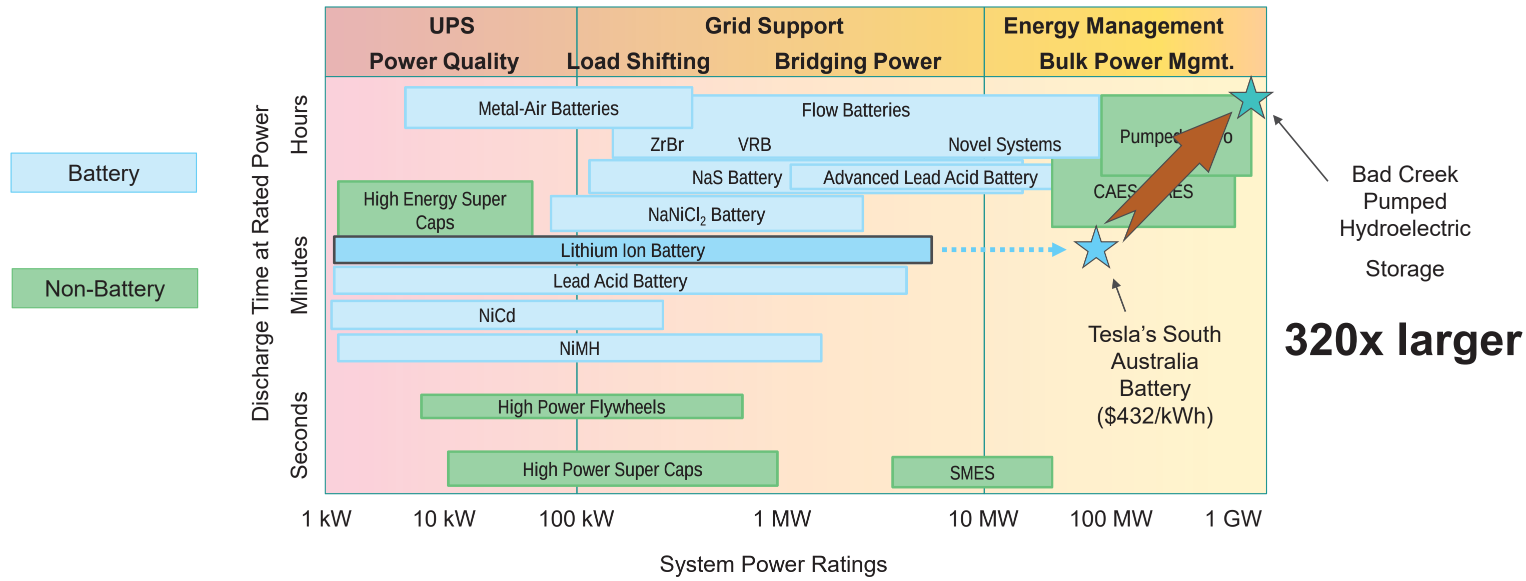
**Energy Storage Cost Analysis: 2017 Methods and Results. EPRI, Palo Alto, CA: 2017. [3002010963](3002010963).*

Non-battery bulk energy storage may deliver lower cost options

Energy Storage Options – Power Rating vs. Discharge Duration

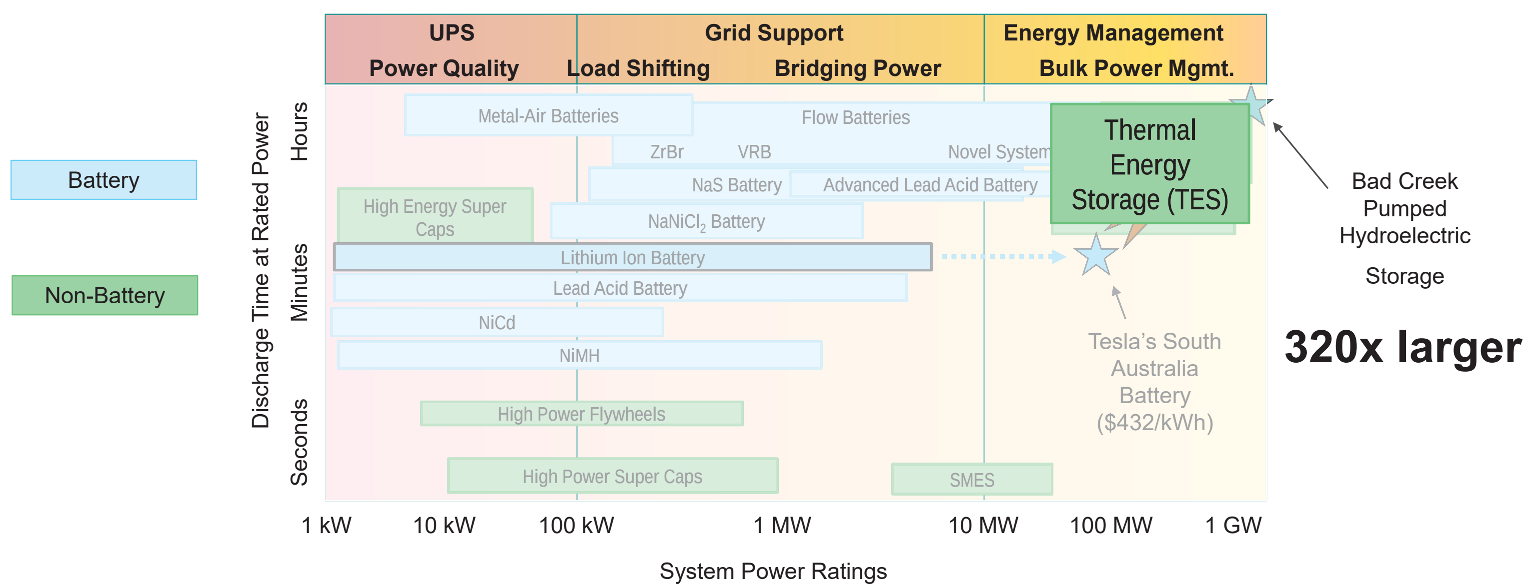


Energy Storage Options – Power Rating vs. Discharge Duration



Can a different type of bulk energy storage be cheaper than a battery?

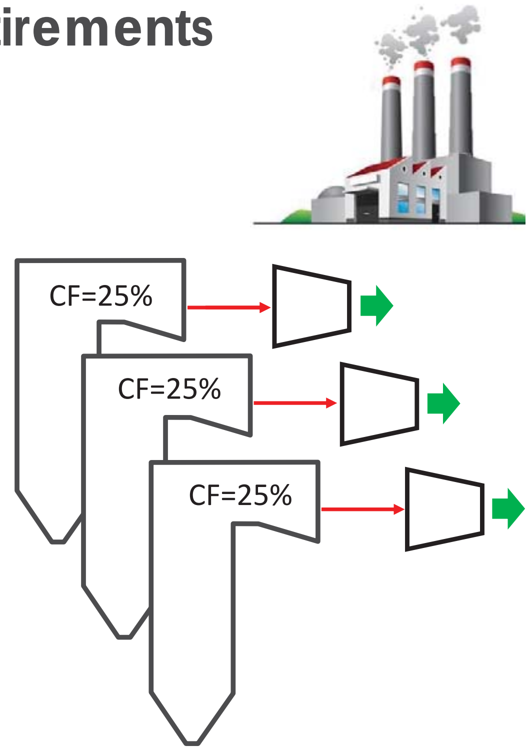
Energy Storage Options – Power Rating vs. Discharge Duration



Can a different type of bulk energy storage be cheaper than a battery?

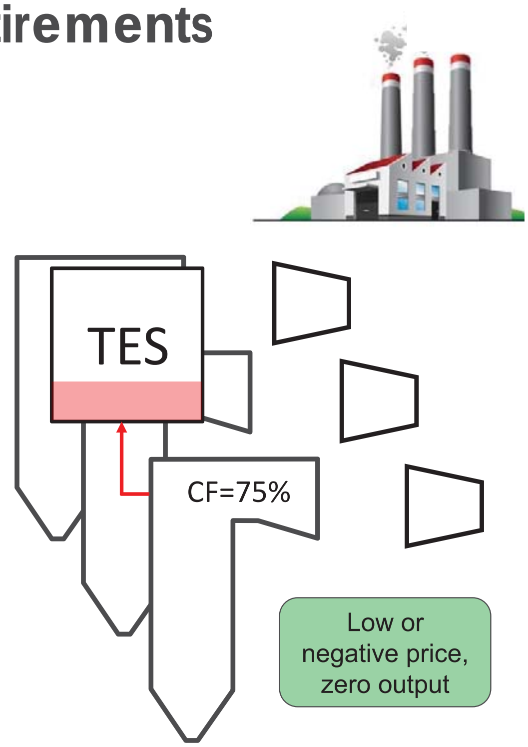
TES Deployment to Stave Off Fossil Retirements

- Consider a power facility with three units (of varying vintage) operating at low capacity factor and two of which are scheduled to be retired
- Renewable intermittency results in:
  - Boilers incur frequent starts and stops
  - Rapid ramping requirements
  - Overall low capacity factors
  - Higher O&M costs
  - Increased emissions per MWh exported



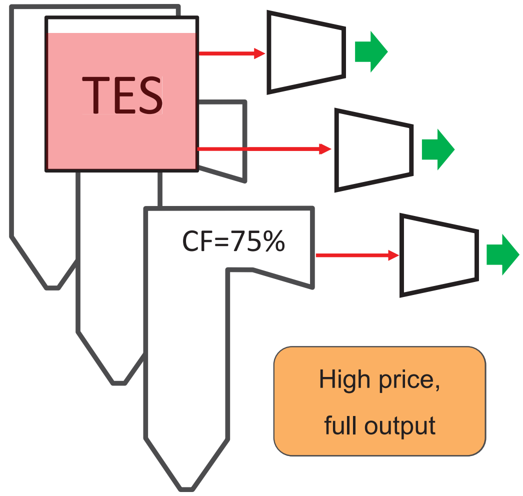
TES Deployment to Stave Off Fossil Retirements

- By providing steam to TES during periods of low grid prices, the unit could remain operational, avoiding shutdown and restart



TES Deployment to Stave Off Fossil Retirements

- By providing steam to TES during periods of low grid prices, the unit could remain operational, avoiding shutdown and restart
- When energy prices increase, steam from the boiler can be diverted to the unit steam turbine AND the TES units can provide steam to the turbine-generators of the units with retired boilers
- All three units generate power when needed



Thermal Energy Storage Materials

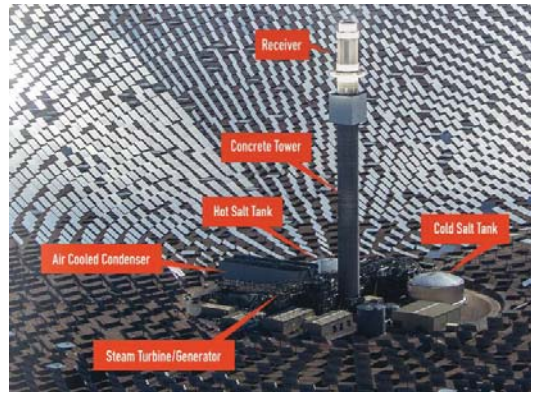
- Low cost materials critical for long duration
- Three categories:

Sensible Heat	Latent Heat	Heat of Reaction
molten salts (nitrate, fluoride, and chloride), oil, water, glycol, concrete, rocks, sand, ceramics	steam accumulators, water/ice, hydrocarbon waxes, aluminum and magnesium alloys, elemental silicon, sulfur	thermochemical endothermic and exothermic reactions hydration/dehydration, carbonate CaO, MgO & CO_2 metal oxides/hydroxide

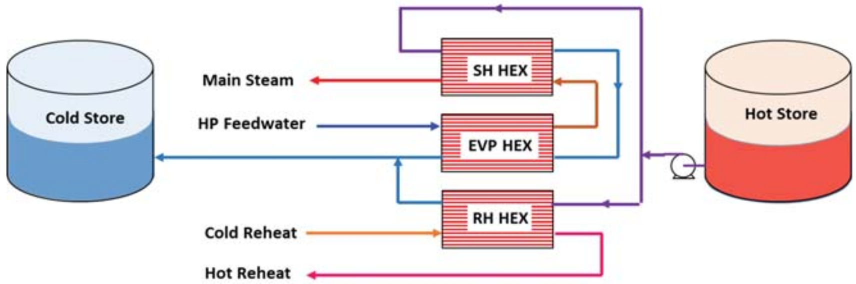
- Many applications:
  - Direct thermal (store heat from power plant)
  - Resistive heating (low cost AC-AC storage, limited RTE)
  - Pumped heat energy storage (AC-AC storage)
  - Adiabatic compressed air, liquid air (compression heat, cold)

TES: Molten Salt (commercial)

- Developed for power-tower type concentrating solar plants (CSP)
- Heat transfer via "solar salt" between solar receiver and steam-Rankine cycle
- Two-tank system at Crescent Dunes
  - Operating 290°C to 565°C
  - 10 hours of storage at 110 MWe
- Salt cost: **$950/tonne**
- Commercially available now



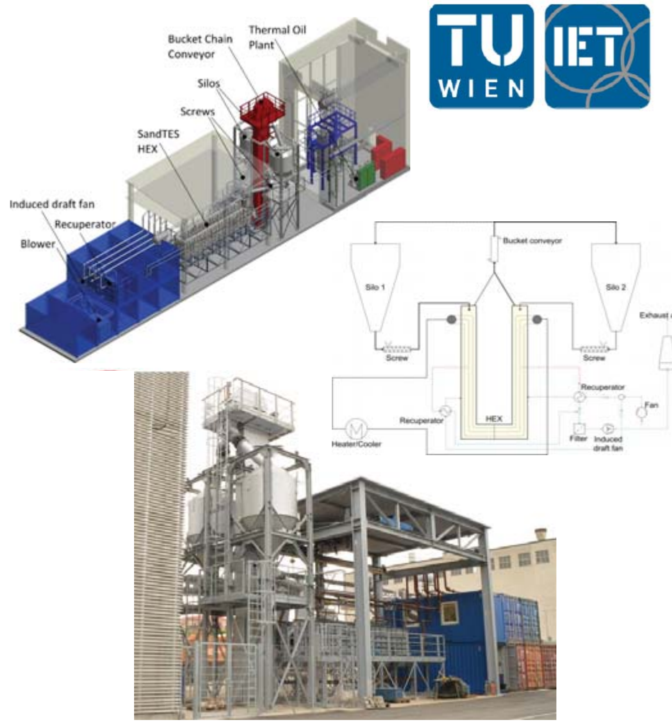
Crescent Dunes CSP, Tonopah NV (SolarReserve)



Molten salt discharging operation

TES: SandTES (development)

- Developed by Technical University of Vienna (TUW)
- Ultra low-cost material with high availability: **$46/tonne**
- Heat transferred to and from sand in counter-current bubbling bed heat exchanger
- Sand stored at temperature in large silos to enable high storage capacity and minimize heat losses
- Pilot plant operational in late 2017

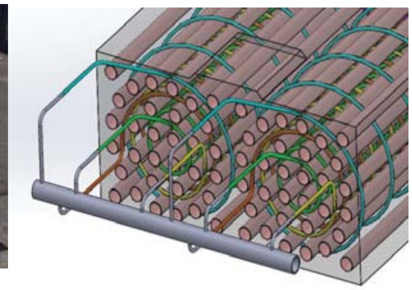


280 kWth pilot plant (courtesy of TUW)

TES: Concrete (development)

Bright Energy

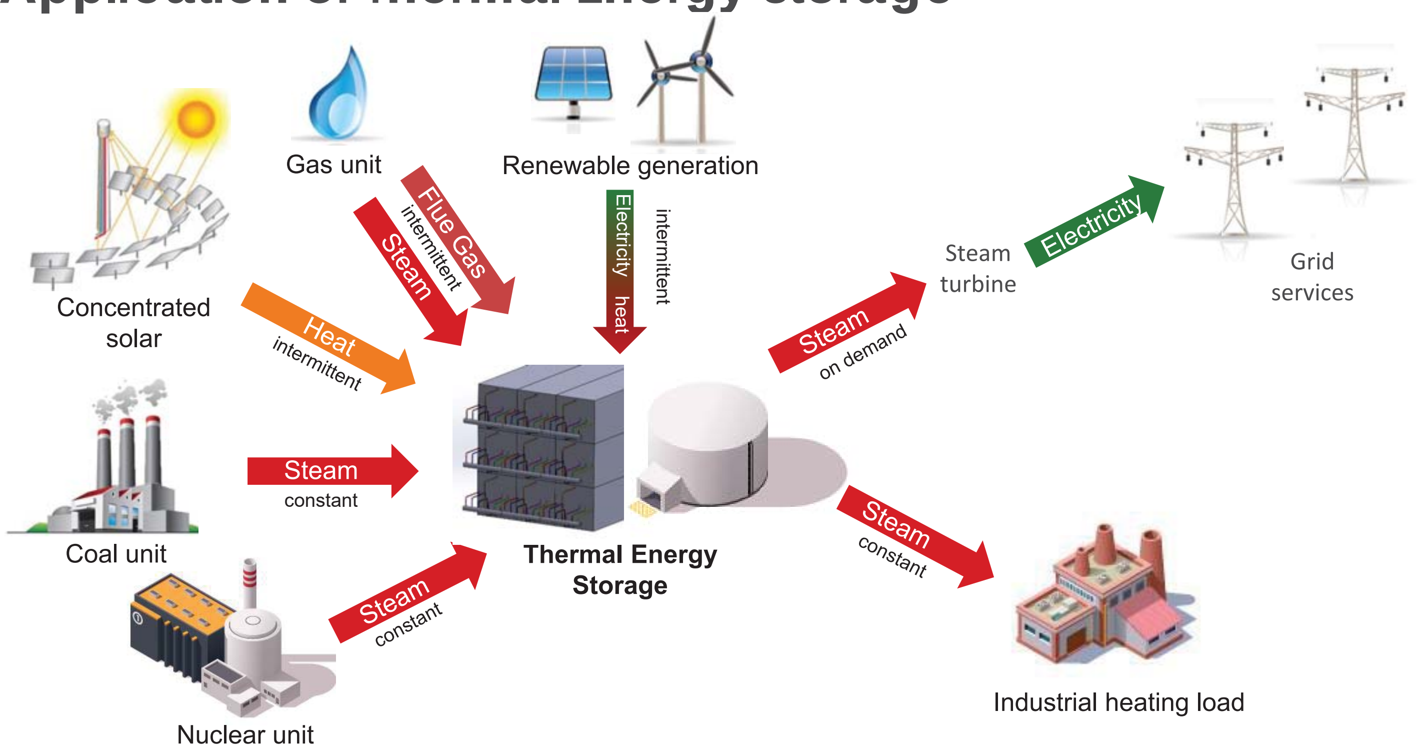
- Solid 'thermocline' structure used to store thermal energy
- Low-cost material **$68/tonne**
- Modular system 12.5 m (41 ft)



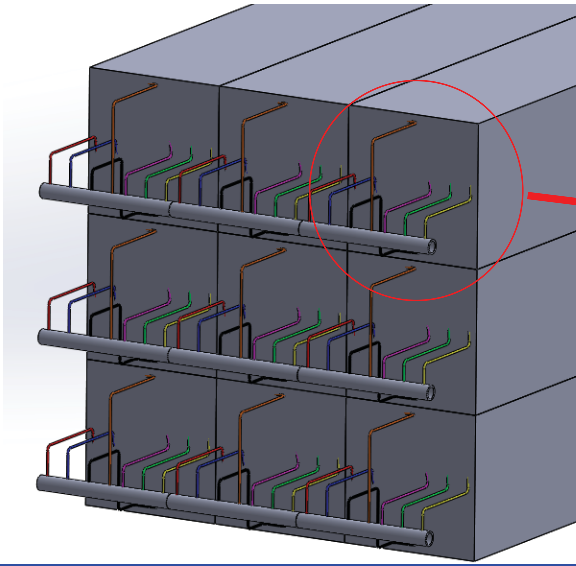
- Steam tubes embedded into concrete monoliths as coils
- Conductive heat transfer
- No moving parts

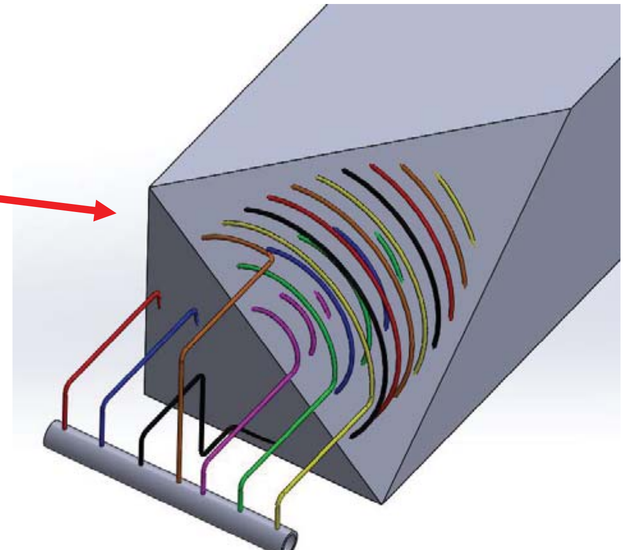
Images courtesy of Bright Energy Storage Technologies

Application of Thermal Energy Storage



Steam-only Concrete TES (Nuclear/Fossil)





Steam in – steam out design can be applied to many thermal sources.

Initial Conclusions from EPRI Analysis

- TES effective round-trip efficiency can be high as the thermal energy was never converted to power before discharge
- Capital cost is on the order of **$100/kWh,** i.e., 3 to 4 times less than Li-ion batteries today
- TES can also be applied to natural gas combined cycles and nuclear power plants

Additional research needed to validate technology and costs

EPRI R&D and Programs Relevant to Thermal Storage

- Flexible Power Operations program for current nuclear fleet
- Advanced reactor strategic program to support and prepare for next generation of nuclear energy technology
- 10-MWh concrete thermal energy storage pilot for a field demonstration of a low-cost, long-duration, flexible energy storage system for
  - Cross-cutting technology applicable to any thermal power plant
  - Improved plant flexibility and increased capacity
- Enhancing current economic models to capture energy storage
- Hydrogen as an energy carrier and an energy storage medium
- Deep decarbonization of industrial economies
- Integration of power sector with broader energy sector (incl. transportation, heating, process heat)

Together…Shaping the Future of Electricity

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE

Concentrating Solar Thermal Power Research and Development Overview

Dr. Avi Shultz, Program Manager

Thermal Energy Storage Workshop

Idaho Falls, ID

July 23, 2019

energy.gov/solar-office

SETO overview

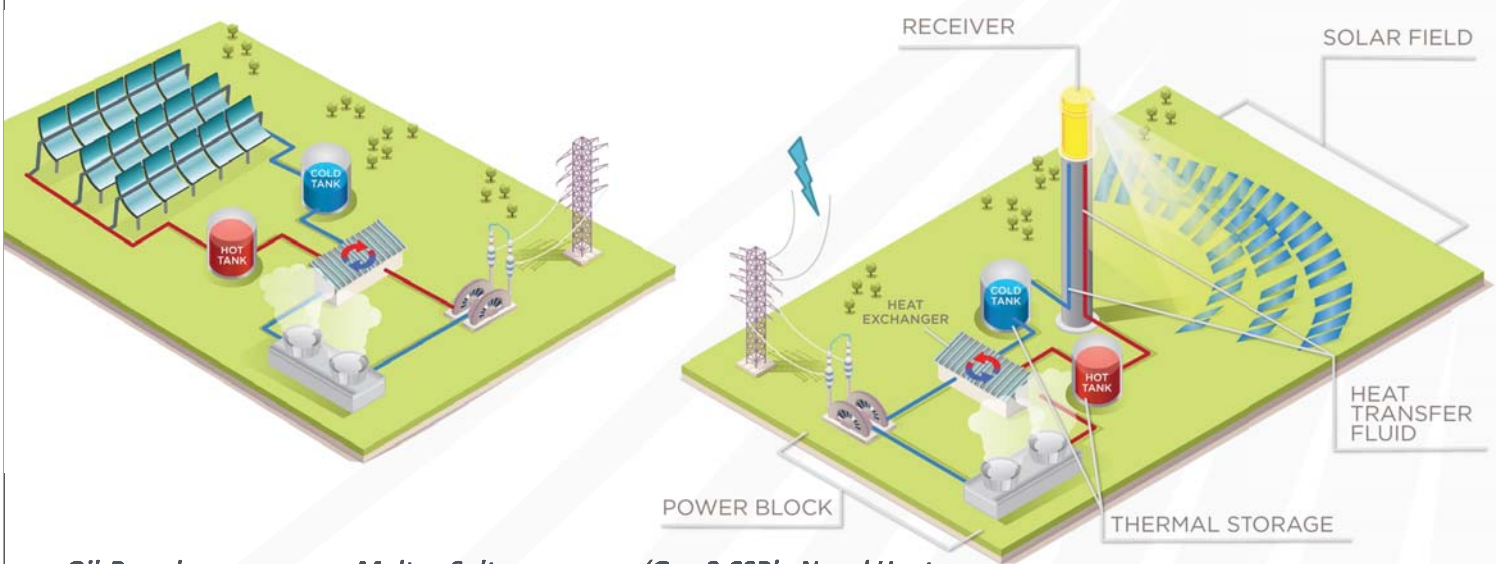
WHAT WE DO

The U.S. Department of Energy's Solar Energy Technologies Office supports early-stage research and development of solar technologies while focusing on **grid reliability**, **resilience**, and **security**.

HOW WE DO IT

The office uses a competitive solicitation process to addresses critical research gaps, ensuring the solar industry has the technological foundations needed to **lower solar electricity costs**, **ease grid integration**, and **enhance the use and storage of solar energy**.

CSP with Storage is Solar Energy On-Demand



Oil-Based Troughs with steam rankine cycle (~400 °C) → *Molten Salt Towers with steam rankine cycle (~565 °C)* → *'Gen 3 CSP': Novel Heat Transfer Media with advanced power cycle (>700 °C) @ 5¢/kWh*

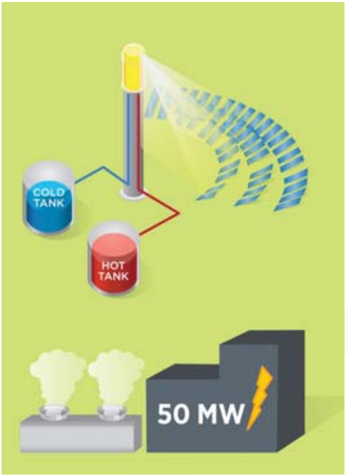
energy.gov/solar-office

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

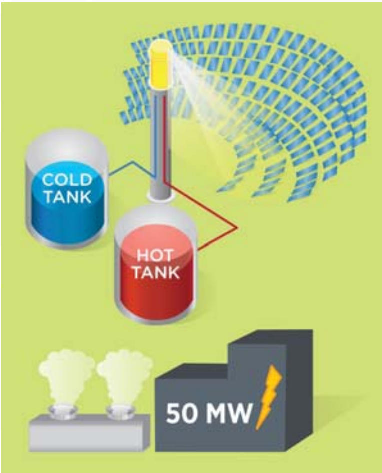
3

CSP: Flexible Designs for an Evolving Grid

'Peaker'
(≤6 hours of storage)



'Baseload'
(≥12 hours of storage)

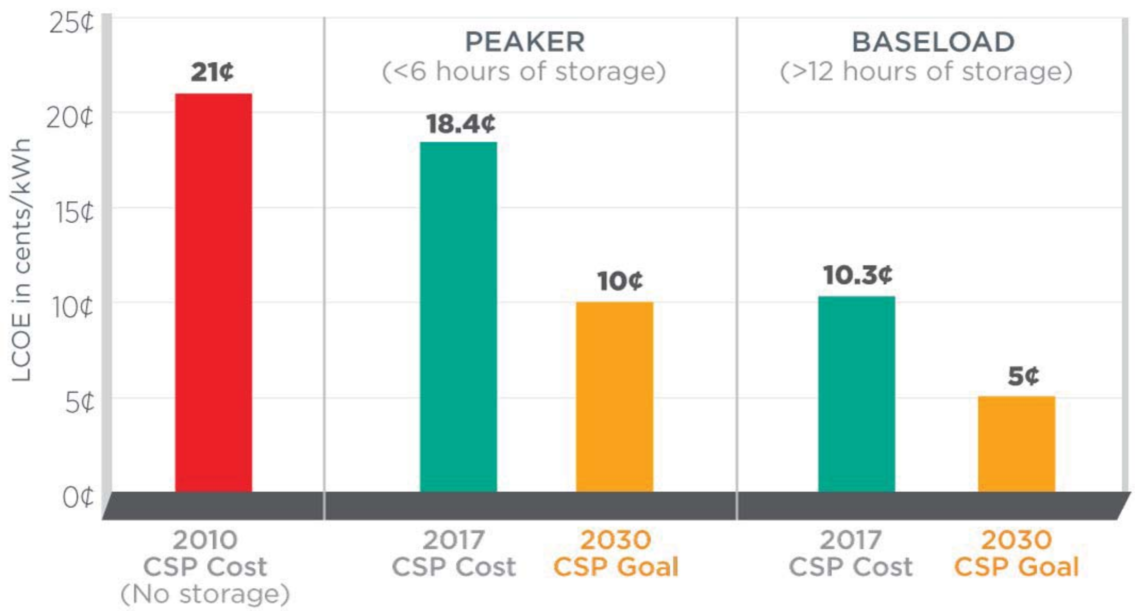


By choosing the size of the solar field and thermal energy storage, the same CSP technology can be configured to meet evolving demands of the grid

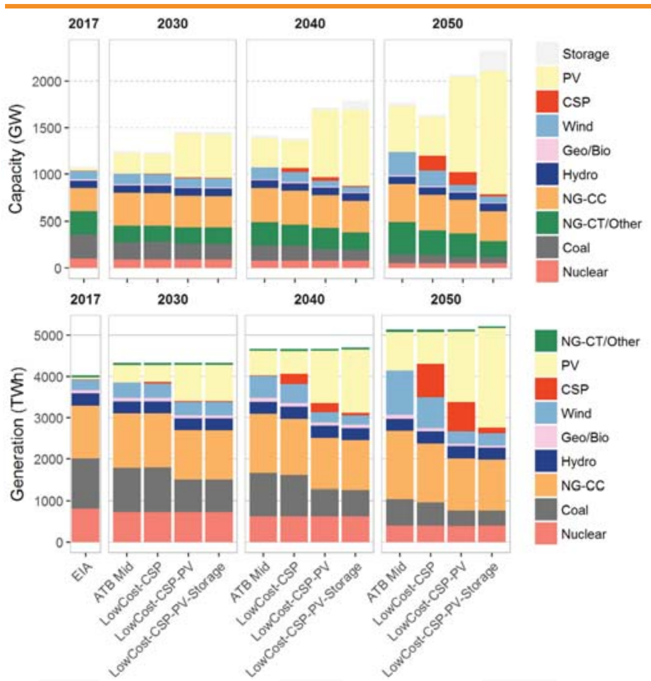
energy.gov/solar-office

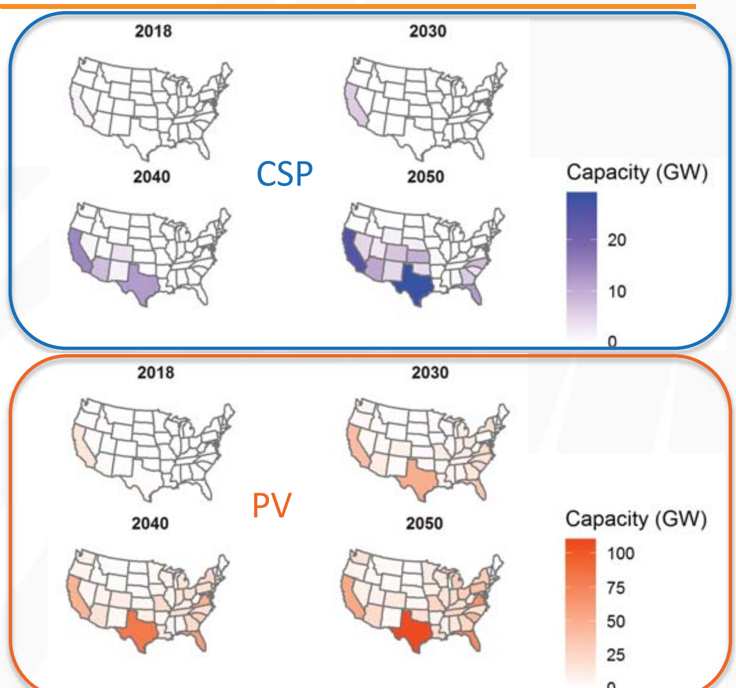
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

2030 DOE Levelized Cost of Electricity Targets



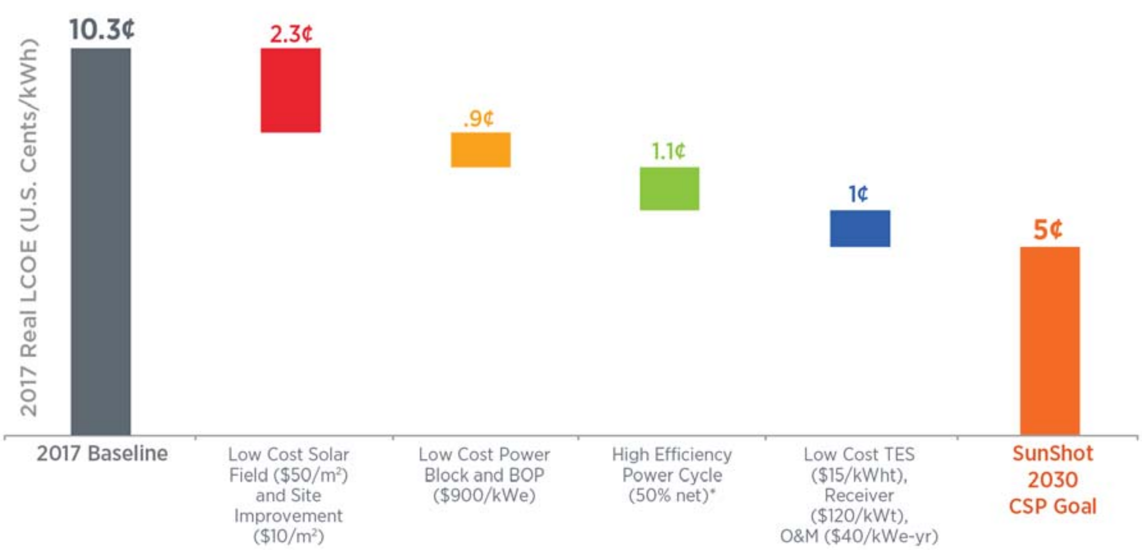
Potential CSP Deployment in the US if DOE CSP and PV 2030 Cost Targets are Achieved





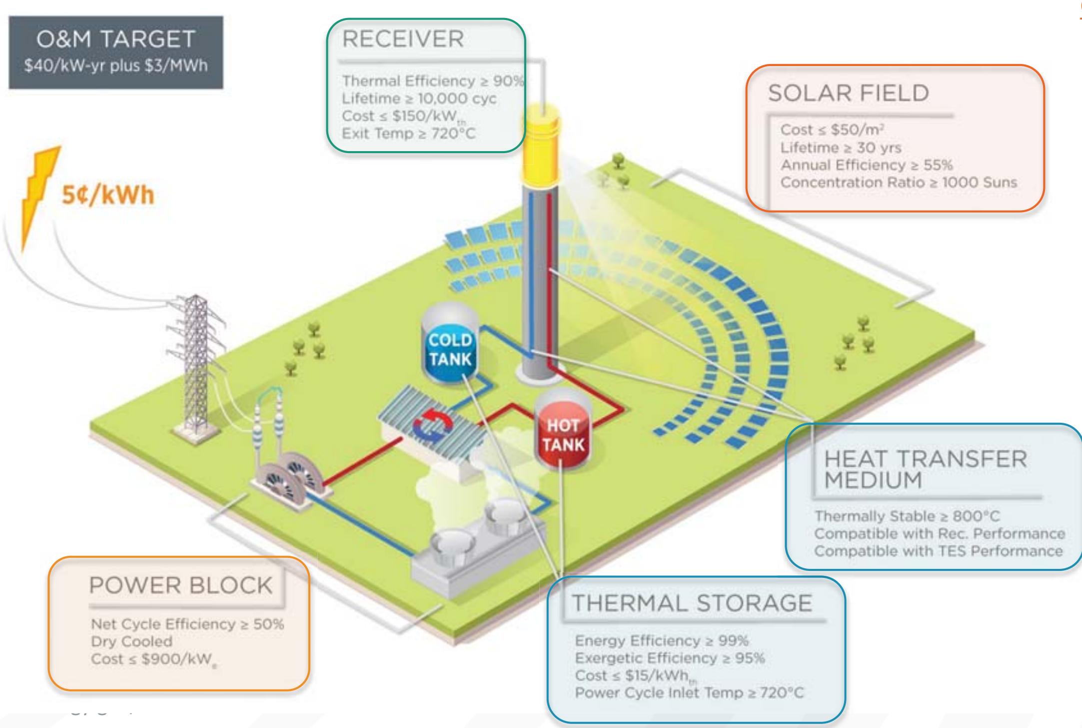
Murphy, et al. **2019**, NREL/TP-6A20-71912

A Pathway to 5 Cents per KWh for Baseload CSP



*Assumes a gross to net conversion factor of 0.9

CSP Program Technical Targets



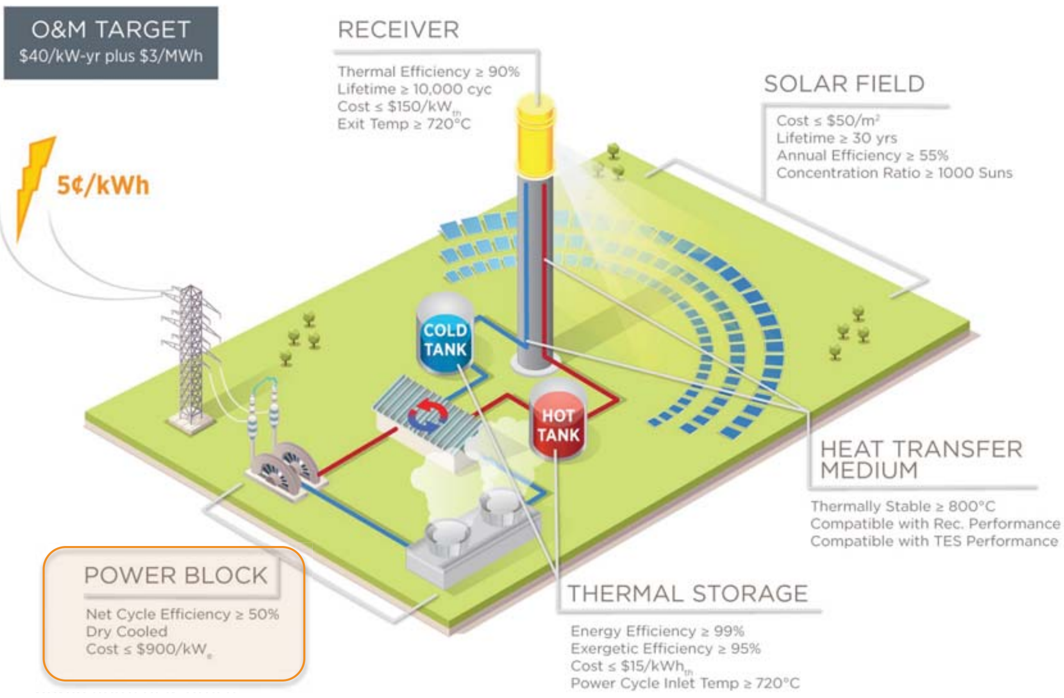
Collector Field
- Optical Physics
- Structural design and dynamics
- Manufacturing and automation
- Sensors and control

Receivers
- Optical properties
- Coatings
- High temperature materials
- Chemistry
- Heat Transfer, Fluid Mechanics

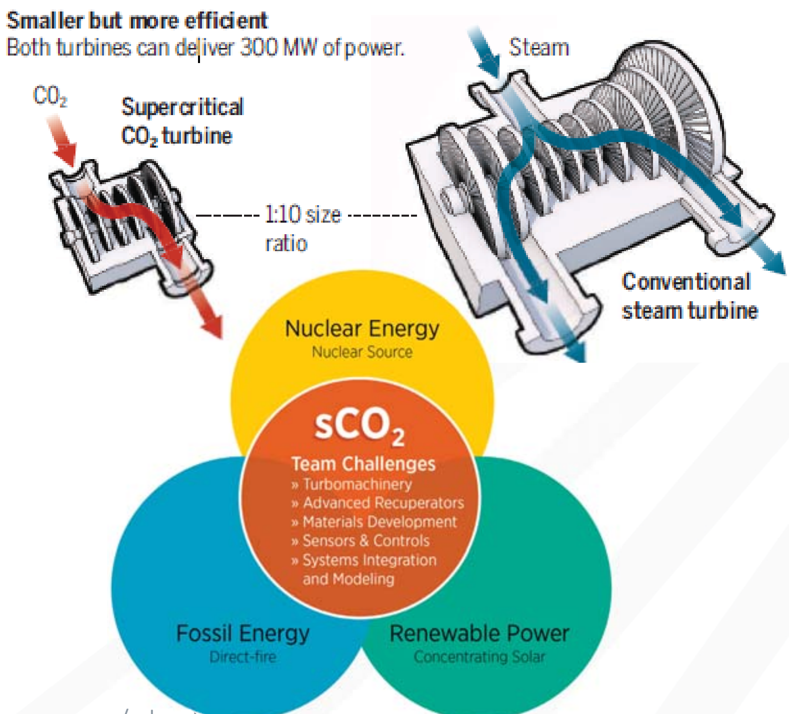
TES and HTF
- Chemistry
- High temperature materials
- Materials Science
- Heat Transfer, Fluid Mechanics

Power Block
- High temperature materials
- Turbomachinery
- Manufacturing and automation
- Sensors and control

CSP Program Technical Targets



Next Generation CSP will Leverage Next Generation Power Cycles



Advantages of the sCO_2 Brayton Cycle:

- Higher Efficiency (50% ~720 C)
- Compact Components
- Smaller Turbine Footprint (by a factor > 10)
- Reduced Power Block Costs
- Amenable to Dry Cooling
- Scalability (Sub 100 MW)
- Operational Simplicity (No Phase Change)

CSP Specific R&D Challenges

- Higher Temperature Thermal Transport System
- Expanding Temperature Change (Sensible TES)
- Ambient Temperature Variability (Dry Cooling)
- Variable Solar Resource

Irwin, Le Moullec. "Turbines can use CO_2 to cut CO_2." *Science* 356.6340 (2017): 805-806.

Next Generation CSP will Leverage Next Generation Power Cycles

Supercritical CO_2: a dense, compressible fluid

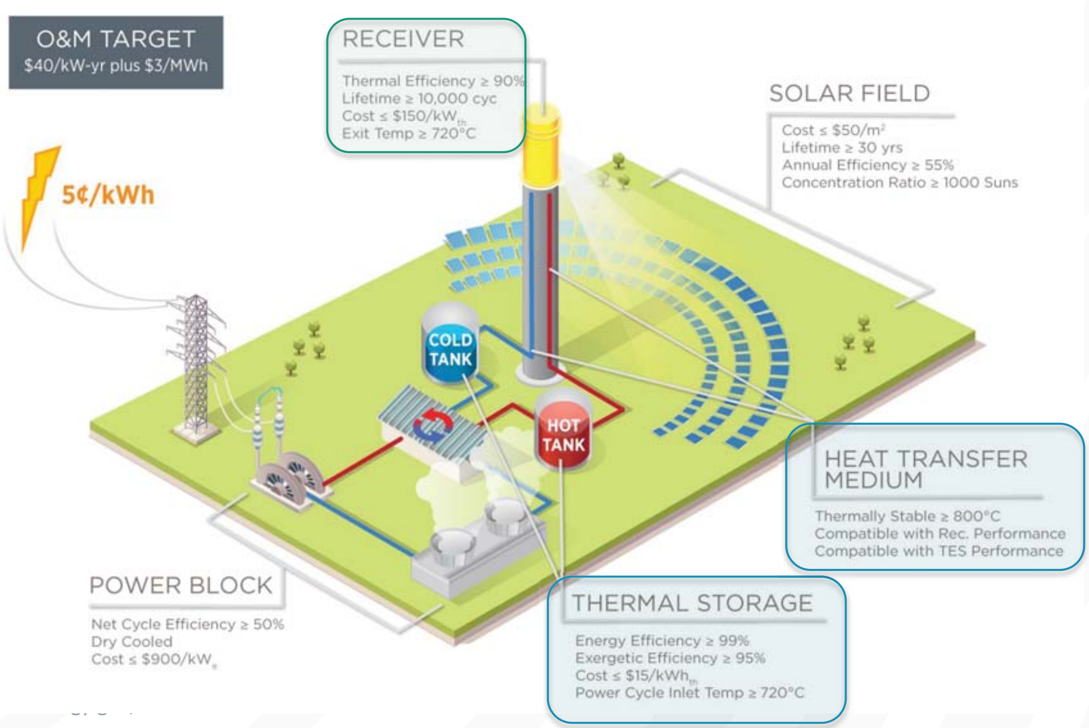
- Compact turbomachinery
- Good compatibility with dry cooling
- Fewer loss mechanisms and parasitics

10 MW_e STEP Test Facility

- $100 M Program managed by FE begun in 2017
- Awarded to Gas Technology Institute, facility located at Southwest Research Institute
- Capable of testing all components of Cycle Integrated with controls & instrumentation
- Resolve issues common to multiple potential heat sources
- Reconfigurable facility capable of 700 °C and 300 bar operation

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

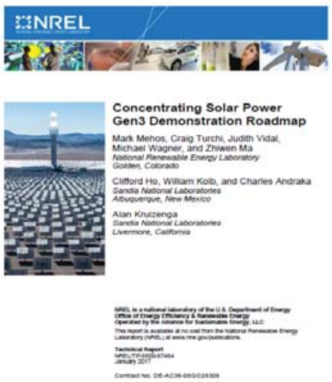
CSP Program Technical Targets



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

Gen3 CSP: Raising the Temperature of Solar Thermal Systems

$$\eta = 1 - \frac{T_C}{T_H}$$


NREL

Concentrating Solar Power Gen3 Demonstration Roadmap

Mark Mehos, Craig Turchi, Judith Vidal, Michael Wagner, and Zhiwen Ma
National Renewable Energy Laboratory
Golden, Colorado

Clifford Ho, William Kolb, and Charles Andraka
Sandia National Laboratories
Albuquerque, New Mexico

Alan Kruizenga
Sandia National Laboratories
Livermore, California

http://www.nrel.gov/docs/fy17osti/67464.pdf

Gen3 CSP Topic 1 Awardees

Sandia National Laboratories

DOE Award (P1-2): $9,464,755

NREL NATIONAL RENEWABLE ENERGY LABORATORY

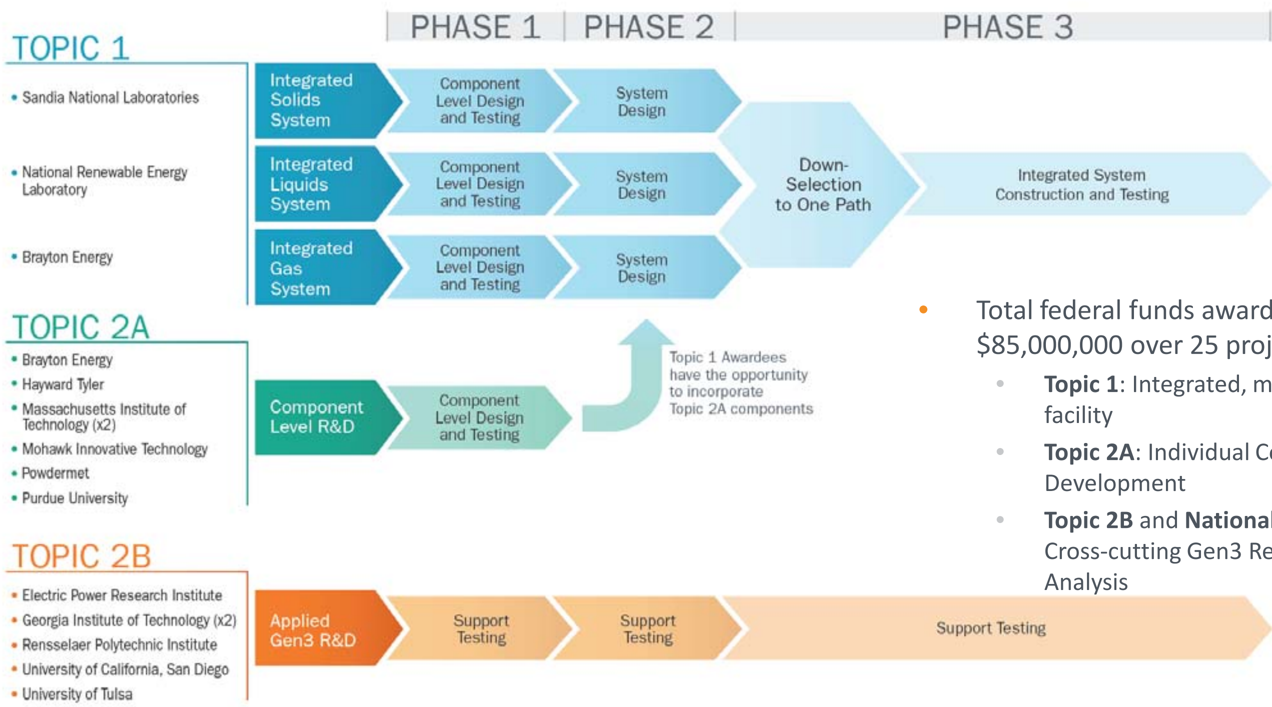
DOE Award (P1-2): $7,035,309

BraytonEnergy

DOE Award (P1-2): $7,570,647

COLLECTOR FIELD	RECEIVER	THERMAL TRANSPORT	THERMAL STORAGE	HEAT TRANSFER MEDIA	HEAT EXCHANGE	POWER CYCLE
SOLID MEDIA	• Thermal Efficiency: • Particle Loss • Flow Velocity Control and Monitoring	• Reliability • Mechanical and Thermal Efficiency • Scalability • Insulation	• Charging and Discharging Particle loss, Efficiency, Scalability	• Particle Attrition • Optimized Performance Character	• Low Cycle Fatigue • Particle Mass Flow Control • Ramp Rates & Transients	
MOLTEN SALT	• Thermal Conductivity • Thermal Stability • Tube Strength and Durability	• Pipe Material Compatibility • Freeze Recovery • Pumps Valves Seals • Leak Detect	• Corrosion Behavior • Chemistry Monitoring and control • Tank Cost	• Characterize Material Properties • Cost / Supply Chain	• Material Compatibility w/ salt & CO_2 • Freeze Protection • Thermal Ramp Rates	
GAS	• High Pressure Fatigue • Absorptivity Control and Thermal Loss Management	• Recirculator Cost & Operating Power • Large Pipes High Cost	• Storage Concept not Determined	• Low Thermal Conductivity • Low Heat Capacity	• Requires High Area • Multiple Heat Exchangers • Cascading Temperature	

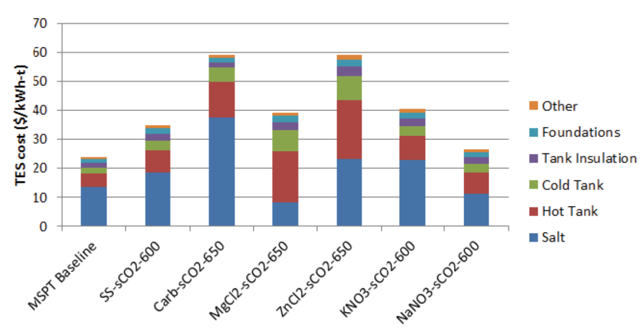
Gen3 CSP Awardees

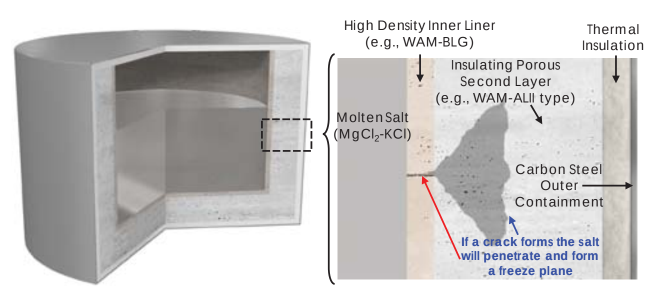


- Total federal funds awarded in 2018: $85,000,000 over 25 projects in 3 Topics:
  - **Topic 1**: Integrated, multi-MW test facility
  - **Topic 2A**: Individual Component Development
  - **Topic 2B** and **National Lab Support**: Cross-cutting Gen3 Research and Analysis

Thermal Energy Storage R&D: Components

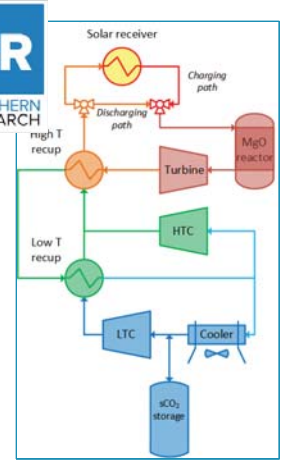
TOPIC	PRIME	PI	FOA
Advanced Hot Media Insulation	**SolarReserve**	Bill Gould	**Tech-to-Market (2017)**
	MIT	Asegun Henry	**Gen3 CSP Systems (2018)**
	UCSD	Jian Luo	**SETO FY18 FOA – SIPS**
Hot Salt Pumps	**Powdermet**	Joseph Hensel	**Gen3 CSP Systems (2018)**
	Hayward Tyler	Benjamin Hardy	**Gen3 CSP Systems (2018)**
	MIT	Asegun Henry	**Gen3 CSP Systems (2018)**
Integrated Heat Pump	**NREL**	Joshua McTigue	**SETO FY19-21 Labcall**

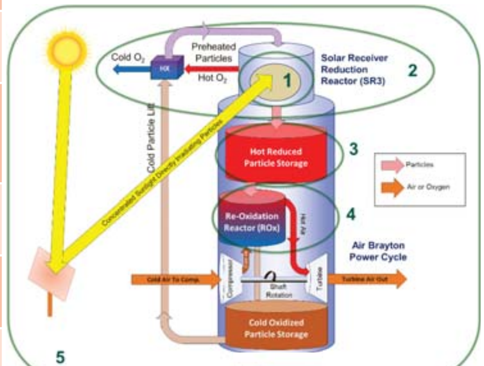




Thermal Energy Storage R&D: Thermochemical

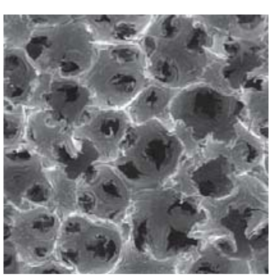
TOPIC	PRIME	PI	FOA
Metal Oxides	Sandia NL	James Miller / Andrea Ambrosini	ELEMENTS (2014)
	Colorado School of Mines	Greg Jackson	ELEMENTS (2014)
Metal Hydrides	Savannah River NL	Ragaiy Zidan	SunShot Lab R&D (2013)
	Brayton Energy	Shaun Sullivan	APOLLO (2015)
Metal Sulfides	Los Alamos NL	Steve Obrey	SuNLaMP (2015)
Metal Carbonates	Southern Research	Andrew Muto	ELEMENTS (2014), APOLLO (2015)
	Echogen	Tim Held	Tech-to-Market (2017)
Ammonia	UCLA	Adrienne Lavine	ELEMENTS (2014)
	Sandia NL	Andrea Ambrosini	FY19-21 Labcall



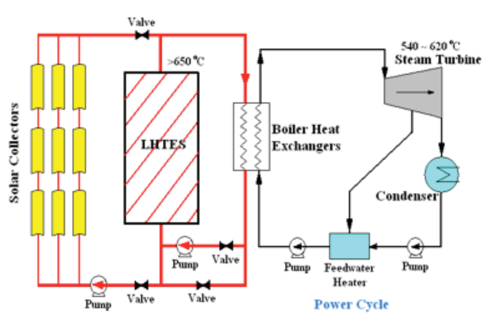


Thermal Energy Storage R&D: Phase Change Materials

Argonne NATIONAL LABORATORY

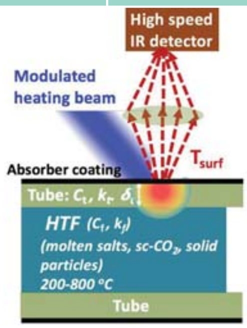


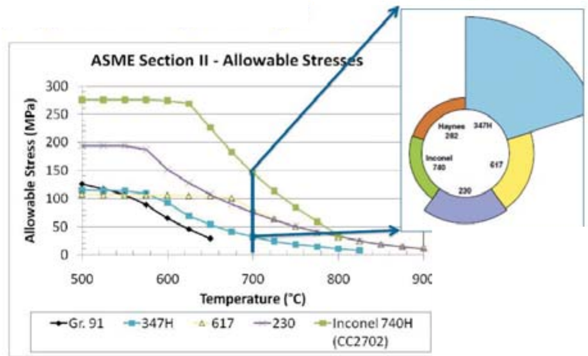
- PI: Dileep Singh
- Developed change materials (PCMs) in combination with new, high thermal conductivity graphite foams funded through **SunShot Lab R&D (2012)** and **APOLLO (2015)**
- Currently being developed into **Gen3 CSP** indirect TES system with Brayton Energy



Thermal Energy Storage R&D: Thermal / Materials Characterization

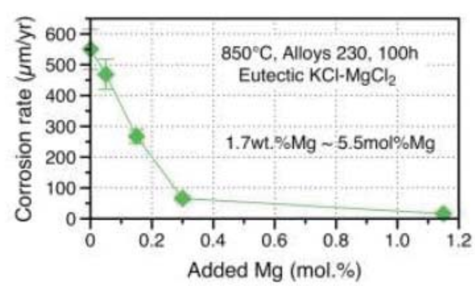
TOPIC	PRIME	PI	FOA
Thermophys. Prop. Of Particles	**Sandia NL**	Kevin Albrecht	**Gen3 Lab Support**
	Georgia Tech	Peter Loutzenhiser	**Gen3 CSP Systems (2018)**
	U. Tulsa	Todd Otanicar	**Gen3 CSP Systems (2018)**
Thermophys. Charactericration	**UCSD**	Renkun Chen	**Gen3 CSP Systems (2018)**
	Georgia Tech	Shannon Yee	**Gen3 CSP Systems (2018)**
Low-Cost Ni-Alloy Mfg	**EPRI**	John Shingledecker	**Gen3 CSP Systems (2018)**
	Oak Ridge NL	G. Muralidharan	**FY19-21 Labcall**





Thermal Energy Storage R&D: Thermo-physical and -chemical Characterization of Chloride Salts

Topic	PRIME	PI	FOA
Thermo-physical and chemical characterization	**NREL**	Judith Vidal	Gen3 Lab Support (2018)
	Oak Ridge NL	Kevin Robb	Gen3 Lab Support (2018)
Corrosion Characterization	**Oak Ridge NL**	Bruce Pint	Gen3 Lab Support (2018)
	Oak Ridge NL	Gabriel Veith	Gen3 Lab Support (2018)
	Rensselear Polytechnic Institute	Emily Liu	Gen3 CSP Systems (2018)
Corrosion Mitigation	**Savannah River NL**	Brenda Garcia-Diaz	Gen3 Lab Support (2018)
	U. Arizona	Dominic Gervaiso	SETO FY18 FOA
	Purdue University	Kenneth Sandhage	SETO FY18 FOA - SIPS
	Virginia Tech	Ranga Pitchumani	SETO FY18 FOA - SIPS



If salt chemistry – O_2, H_2O content – can be controlled, corrosion can be managed

SETO's FY19 Funding Opportunity Announcement was issued on March 26, 2019

Achieving SETO's priorities across the solar energy technology landscape requires sustained, multifaceted innovation. For our FY19 Funding Program, the office intends to support high-impact, early-stage research in the following areas:

- **Topic 1: Photovoltaics Research and Development**
- **Topic 2: Concentrating Solar-Thermal Power Research and Development**
- **Topic 3: Balance of Systems Soft Costs Reduction**
- **Topic 4: Innovations in Manufacturing: Hardware Incubator**
- **Topic 5: Advanced Solar Systems Integration Technologies**

Topic 2 – Concentrating Solar-Thermal Power Research and Development

Topic 2.1: Firm Thermal Energy Storage ($11 million)
Concepts that expand the dispatchability and availability of CSP plants to provide value to grid operators. Thermal energy storage (TES) systems of interest include:

- Long-term TES systems that store energy for weekly or seasonal dispatch
- Pumped heat electricity storage for CSP and concepts that enable charging of TES via off-peak grid electricity
- Commercializing TES through projects that pursue near-term market adoption

Topic 2.2: Materials and Manufacturing ($11 million)
Solutions that reduce the cost of manufacturing CSP components, encourage the commercialization of new CSP technologies, and support the development of an agile, U.S.-based CSP manufacturing sector.

Topic 2.3: Autonomous CSP Collector Field ($11 million)
Solutions that enable a solar field that can fully operate without any human input, reducing costs and maximizing thermal energy collection efficiency.

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

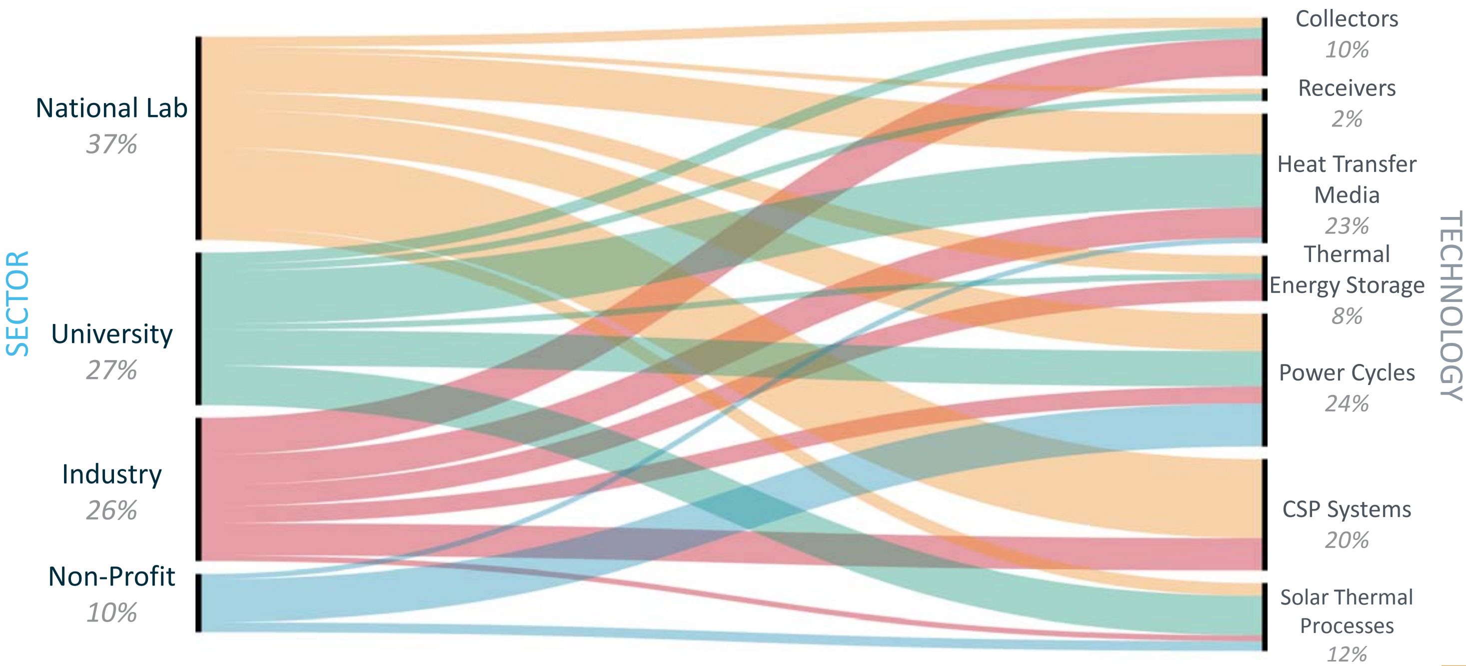
Questions?

Avi Shultz

avi.shultz@ee.doe.gov
Program Manager, CSP

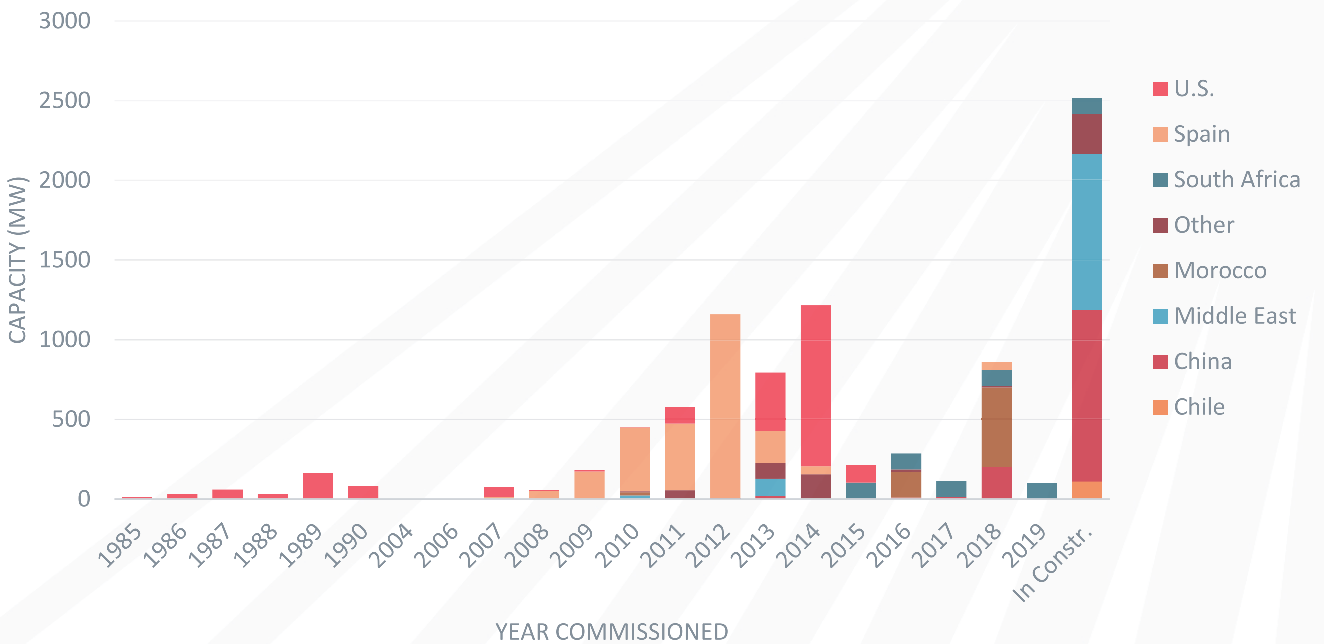
energy.gov/solar-office

CSP Awardee Breakdown by Funding



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

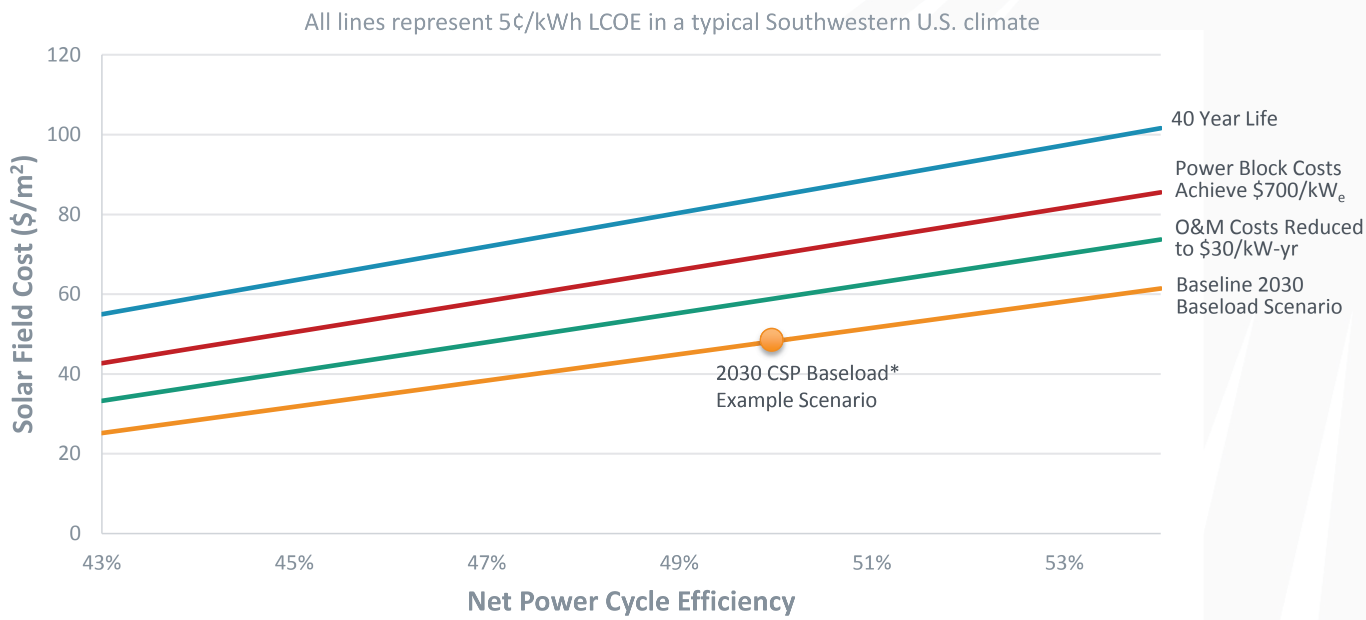
CSP is Being Deployed Worldwide



energy.gov/solar-office

ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

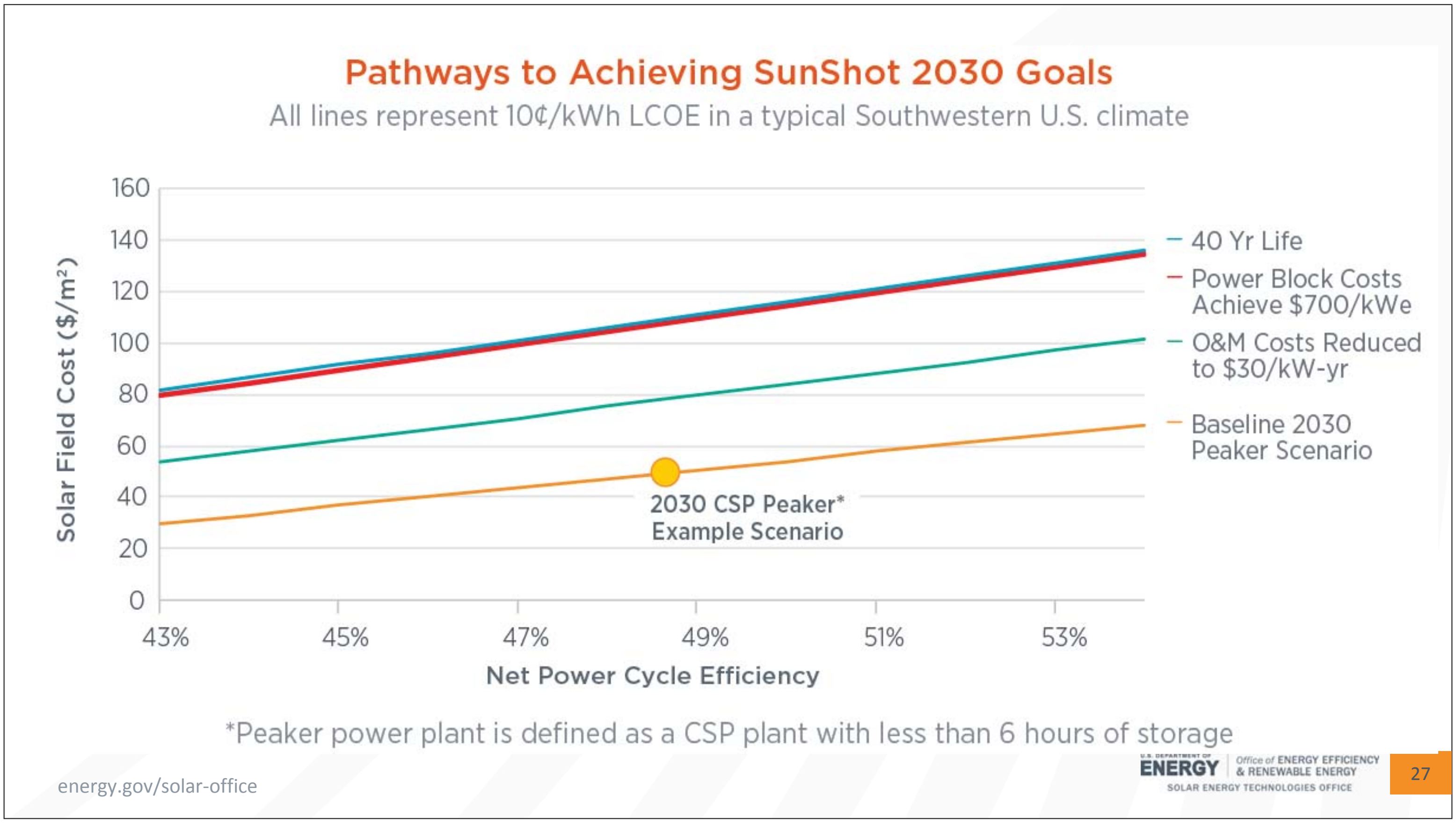
Pathways to Achieving SunShot 2030 Goals



*Baseload power plant is defined as a CSP plant with greater than or equal to 12 hours of storage

energy.gov/solar-office

ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE



SETO sCO_2 Power Cycle Portfolio by Category

CATEGORY	PROJECT TITLE	PRIME
Turbomachinery	Compression System Design and Testing for sCO_2 CSP Operation	GE
	Development of an Integrally-Geared sCO_2 Compander	Southwest Research Institute
	Development of High Efficiency Expander and 1 MW Test Loop	Southwest Research Institute
	Physics-Based Reliability Models for sc-CO_2 Turbomachinery Components	GE
	Process Gas Lubricated Bearings in Oil-Free Drivetrains	GE
	High-Temperature Dry-Gas Seal Development and Testing	Southwest Research Institute
Materials	Lifetime Model Development for Supercritical CO_2 CSP Systems	Oak Ridge NL
	sCO_2 Corrosion and Compatibility with Materials	UW-Madison
Other Components	Development and Testing of a Switched-Bed Regenerator	UW-Madison
	sCO_2 Power Cycle with Integrated Thermochemical Energy Storage	Echogen Power Systems
	High-Efficiency Hybrid Dry Cooler System for sCO_2 Power Cycles	Southwest Research Institute
	Additively Manufactured sCO_2 Power Cycle Heat Exchangers for CSP	GE
Technoeconomics	Cycle Modeling, Integration with CSP, and Technoeconomics	NREL
Primary Heat Exchanger	High Flux Microchannel Direct sCO_2 Receiver	Oregon State U.
	High-Temperature Particle Heat Exchanger for sCO_2 Power Cycles	Sandia NL
	Various Molten Salt-to-sCO_2 Heat Exchangers	Purdue / UC Davis / Comprex
	Fluidized Beds for Effective Particle Thermal Energy Transport	Colorado School of Mines

Gen3 Topic 2 and Lab Support Awards

CATEGORY	PRIME	PROJECT TITLE	PI	AWARD
Liquid (2A)	**Hayward Tyler**	Development of High Temperature Molten Salt Pump Technology for Gen3	Benjamin Hardy	$2,000,000
	MIT	High Temperature Pumps and Valves for Molten Salt	Asegun Henry	$1,932,414
	Powdermet, Inc	High Toughness Cermets for Molten Salt Pumps	Joseph Hensel	$1,326,384
	MIT	Ceramic Castable Cement Tanks and Piping for Molten Salt	Asegun Henry	$1,771,798
Liquid (2B and Lab Support)	**Purdue**	Robust High Temperature Heat Exchangers	Kenneth Sandhage	$1,960,745
	Rensselear Polytechnic Institute	Development of In-Situ Corrosion Kinetics and Salt Property Measurements of salts and containment materials	Li (Emily) Liu	$1,799,892
	Savannah River NL	Full Loop Thermodynamic Corrosion Inhibition and Sensing in Molten Chloride	Brenda Garcia-Diaz	$1,000,000
	NREL	Molten Chloride Thermophysical Properties, Chemical Optimization, and Purification	Judith Vidal	$1,000,000
	Oak Ridge National Lab	Enabling High-Temperature Molten Salt CSP through the Facility to Alleviate Salt Technology Risks (FASTR)	Kevin Robb	$4,300,000
	Oak Ridge National Lab	Progression to Compatibility Evaluations in Flowing Molten Salts	Bruce Pint	$1,000,000
	Oak Ridge National Lab	Comparison of Protecting Layer Performance for Corrosion Inhibition in Molten Chloride Salts through Interfacial Studies at the Molecular Scale	Sheng Dai	$955,000

energy.gov/solar-office

ENERGY | & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

29

Gen3 Topic 2 and Lab Support Awards

CATEGORY	PRIME	PROJECT TITLE	PI	Award
Particle (2B and Lab Support)	**Georgia Institute of Technology**	Advanced Characterization of Particulate Flows for CSP Applications	Peter Loutzenhiser	$1,352,195
	U. of Tulsa	GEN3D – Experimental and Numerical Development of GEN3 Durability Life Models	Todd Otanicar	$1,515,687
	Sandia National Labs	Characterization and Mitigation of Radiative, Convective, and Particle Losses in High-Temperature Particle Receivers	Cliff Ho	$1,031,070
	Sandia National Labs	Quantifying thermophysical properties and durability of particles and materials for direct and indirect heat transfer mechanisms	Kevin Albrecht	$445,000
Gas (2A)	**Brayton Energy**	Development of Integrated Thermal Energy Storage Heat Exchangers for CSP Applications	Jim Nash	$1,181,603
	Mohawk Innovative Technology, Inc	Oil-Free, High Temperature Heat Transfer Fluid Circulator	Hooshang Heshmat	$1,258,629
Gas (Lab Support)	**Idaho National Lab**	Creep-fatigue behavior and damage accumulation of a candidate structural material for a CSP thermal receiver	Michael McMurtrey	$1,000,000
Agnostic (2B and Lab Support)	**Georgia Institute of Technology**	Thermophysical Property Measurements of Heat Transfer Media and Containment Materials	Shannon Yee	$1,966,440
	UC San Diego	Non-contact thermophysical characterization of solids and fluids for CSP	Renkun Chen	$1,180,000
	EPRI	Improving Economics of Gen3 CSP System Components Through Fabrication and Application of High Temperature Ni-Based Alloys	John Shingledecker	$1,499,901
	Sandia National Labs	Design and Implementation of a 1-3 MWth sCO2 Support Loop for Maturation of Molten Salt, Particulate, and Gas phase Thermal Storage Primary Heat Exchangers	Matthew Carlson	$3,600,000

Joint Use Modular Plant Program Research, Development & Deployment Activities – Overview

Shannon Bragg-Sitton, Ph.D.
JUMP Program Director

Co-Director, INL Integrated Energy Systems Initiative

Lead, Nuclear-Renewable Integrated Energy Systems, DOE Office of Nuclear Energy

July 2019

www.inl.gov

Idaho National Laboratory

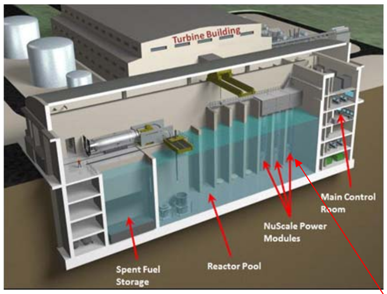
Idaho National Laboratory

Memorandum of Understanding (signed December 2018)

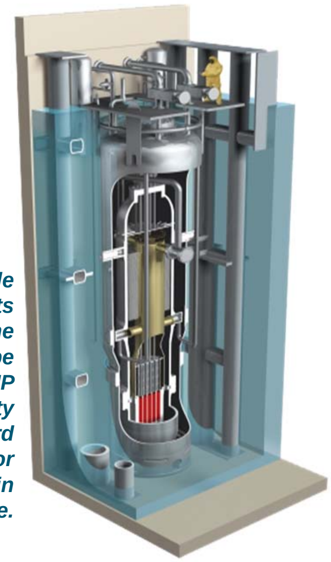
- Parties:
  - U.S. Department of Energy (DOE)
  - Utah Associated Municipal Power Systems (UAMPS)
  - Battelle Energy Alliance (BEA)
- Scope:
  - Contemplate the licensing, construction, and operation of a first-of-a-kind SMR at INL
  - One module would be dedicated to research, development, and demonstration (RD&D) under the JUMP program
  - One module would be used for power production to support INL energy needs (via Power Purchase Agreement [PPA])
  - Includes collaboration during pre-construction, construction, and licensing periods
- JUMP Agreement Scope
  - UAMPS to work with the U.S. Nuclear Regulatory Commission (NRC) to develop a licensing approach to include RD&D activities
  - Anticipated 15-yr term w/potential for 15-yr renewal

What is JUMP?

- Joint Use Modular Plant (JUMP) Program is a key aspect of the Carbon-Free Power Project (CFPP) that will build the first NuScale Nuclear Power Plant (operational late 2026)
- The JUMP Program would support research, development & demonstration (RD&D) activities *and* commercial use within a single multi-module nuclear plant, wherein a specific module is allocated to RD&D.



3D view of six NuScale modules

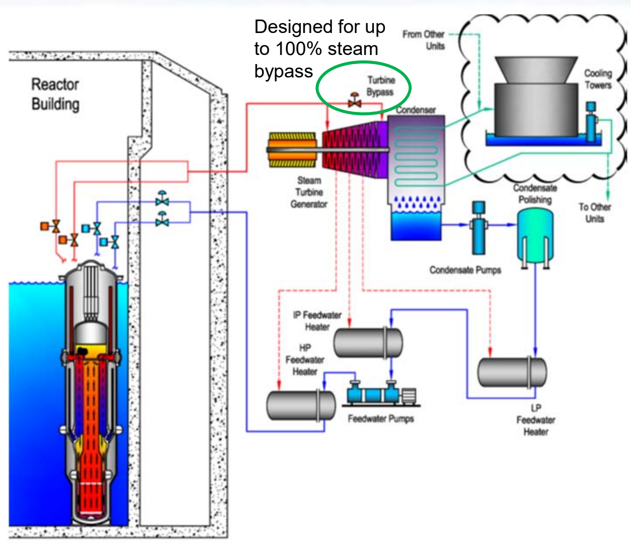


Single NuScale module within its operational bay – one bay would be dedicated to JUMP RD&D, with the ability to support a standard module initially or modified module in the future.

3

Constraints on JUMP RD&D

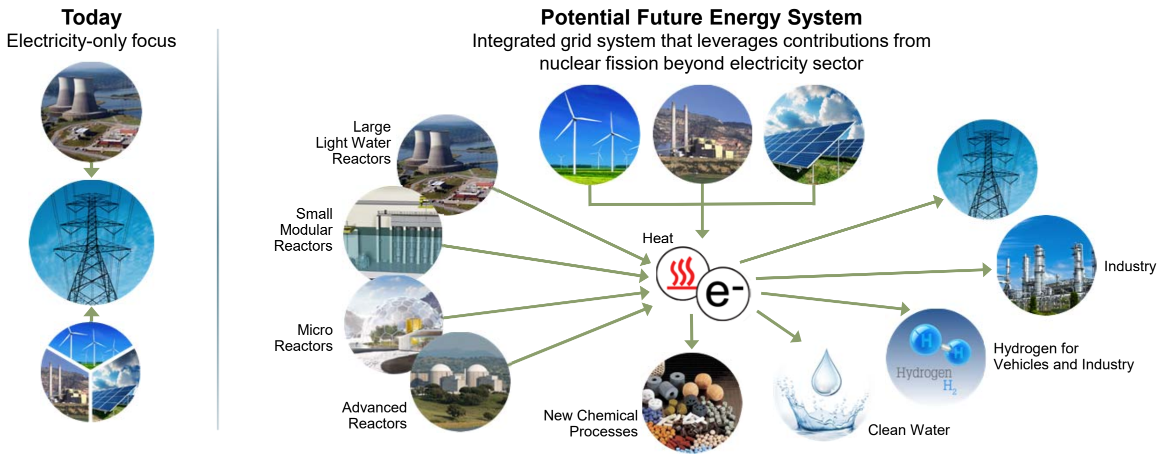
- Consider potential impacts on regulatory processes
- Should not require significant modification of the nuclear island within the standard plant design
  - Most RD&D projects are likely to require license amendment
  - Potential licensing impacts will be identified and evaluated
  - Alteration of the secondary side systems may require addition of a transition heat exchanger to decouple the RD&D components from the NuScale Power Module secondary coolant system
- Module must be able to return to standard electricity production service at the end of the contractual agreement



© NuScale Power, LLC

Key Research Priority: Integrated Energy Systems

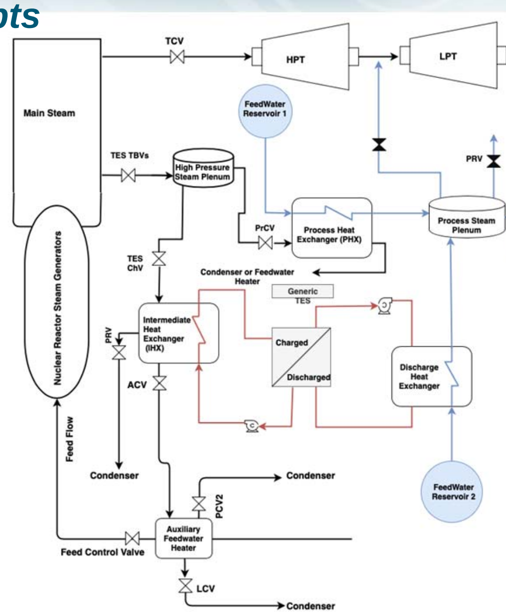
- Tighter coupling of nuclear plant output required to achieve highly efficient integrated energy systems
- JUMP provides opportunity to measure energy transport phenomena for non-steady-state process operations



Integrated Energy System Concepts

JUMP provides a platform for demonstration of:

- Coordinated operation with nearby renewable installations
- Front-end control approaches, communications standards, control reliability
- Data collection and analytics to maintain process stability
- Thermal and electrical energy delivery system effectiveness
- Multiple energy users/industrial applications:
  - Energy storage (electrical, thermal, chemical)
  - Industrial process pilot scale demonstration:
    - Hydrogen generation, desalination, carbon conversion, etc.
    - Verify process chemistry, operational stability
  - Grid emulation environment to replicate arbitrary grid conditions
- Demonstrate human factors aspects of integrated system operation
- Exercise new regulatory approaches

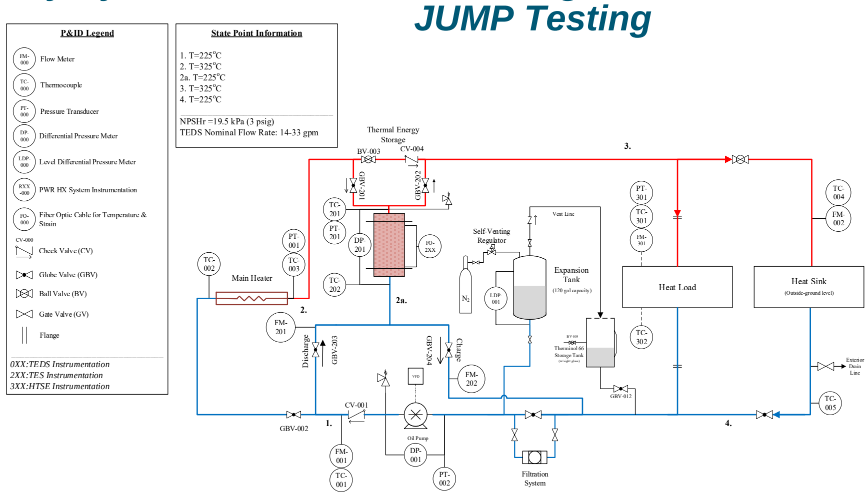


Example: Pre-conceptual integrated system design with steam offtake to thermal energy storage.

6

Thermal Energy Delivery System – Nonnuclear Testing to Precede JUMP Testing

- 200 kW Heater
- 200 kW-hr Thermocline
- Therminol-66 used as Heat Transfer Fluid
- Original Heat Load is High Temperature Electrolysis Experiment
- Design Pressure: 100 psig
- Design Temperature: 340 °C
- Maximum Operating Temperature: 325 °C
- Return Temperature: 225 °C
- Maximum Operating Pressure: 14 psig
- Design Flow Rate: 0.9 kg/sec (15 gpm)
- Flow Rate Range in TEDS: 0.8-2.1 kg/s (14-33 gpm)
- Nominal Pipe Size: 2 inch



Proposed RD&D for Innovative Technologies and Approaches

Advanced Instrumentation, Model Verification & Validation (V&V)*

- Test and demonstrate advanced instrumentation and sensor technologies in relevant reactor conditions
- Collect valuable data for system characterization, model development and V&V; reduce design conservatisms

Fuels and Materials Testing, Characterization*

- Provide prototypic commercial operating conditions
- Characterize materials as a function of design, fabrication methods, operating parameters, load cases
- Test advanced fuels under various operational conditions; leverage module ability to accept full assemblies
- Provide data to support licensing

Human Factors*

- Measure and evaluate human performance via a realistic operational environment
- Inform future control rooms and training simulator designs, increase reliability of safety critical systems, and increase operator awareness in unfamiliar operating environments

Cybersecurity

- Demonstrate operator situational awareness in cyber-attack scenarios
- Evaluate supply chain security

Regulatory Research

- Inform regulatory approach for fully digital I&C
- Exercise specialized licensing paths for non-traditional applications

Safeguards Research*

- The integration of features to support domestic/IAEA safeguards & security into the design process for a new or refurbished nuclear facility

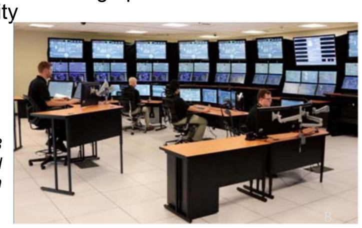


Image taken from June 2018 NuScale Power advanced technology presentation available at https://gain.inl.gov.

Advanced Instrumentation: In-core Instrumentation for Model Verification and Validation (V&V)

Opportunities

- Validation of core simulation tools for LWRs
  - Aligned with INL and NE Agenda and stakeholder needs
  - Demonstrated technological gap in DOE and nuclear industry capabilities
  - Benefit NuScale design optimization (reduce margins)
- Capitalize on JUMP module advanced features
  - Natural circulation cooling
  - Integrated Energy Systems
- Multi-scope validation:
  - Flow field thermo-hydraulics (core / bypass)
  - Fuel rod performance
  - Core / void region neutronics

Challenges

- Infrastructure requires installation of specifically designed / instrumented test rigs
  - Goals cannot be met with 'drop-in' test in current design provisions
- Design provisions for instrumented test port must be considered as part of licensing basis
  - Conceptual design preliminary estimate from NuScale is between $0.5M and $3M
- Complex test rigs require extensive demonstration of instrumentation performance
  - Out of pile test in relevant conditions (flow)
  - In-pile demonstration of sensor performance

Advanced Instrumentation: Demonstration of Advanced In-core Instrumentation

Opportunities

- JUMP provides a test bed for the demonstration of advanced core instrumentation in conditions relevant to LWRs
  - Unique opportunity to extend technology TRL with minimal risk to industry
- Existing design features may be sufficient to allow specific instrumentation test
  - In-core instrumentation system (ICIS)
- Advanced instrumentation development and demonstration could be leveraged from existing DOE activities
- V&V infrastructure (test port) can be shared

Challenges

- Design provisions for instrumented test port must be considered as part of licensing basis
- The demonstration of advanced instrumentation specific to JUMP objectives may require R&D and demonstration in irradiation facilities, adding cost and complexity to the project

Advanced Instrumentation: Structural Health Monitoring (SHM) of SMR Ex-vessel Components

Opportunities

- Validation of advanced SHM and maintenance processes (early fault detection) for LWRs
  - Aligned with INL and NE Agenda and stakeholder needs
  - Demonstrated technology gap in DOE and nuclear industry capabilities
  - Benefit SMR design optimization (reduce margins)
- Stepwise approach to advanced sensor technology development (Ex-vessel to in-vessel)
  - Distributed optical fiber sensing
  - Smart components (embedded sensors)

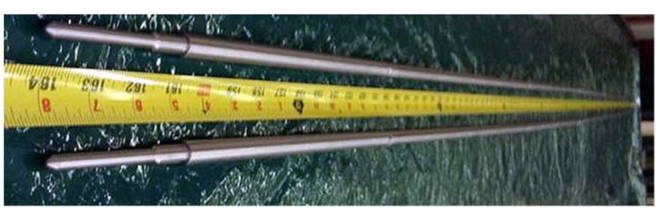
Challenges

- Limited relevance and complexity due to design integration in existing design (retro-fitting) for primary components (i.e., seismic isolators)
- The demonstration of advanced instrumentation specific to SHM may require R&D and demonstration in irradiation facilities, adding cost and complexity to the project

Fuels and Materials Testing, Characterization

- JUMP will provide prototypic commercial operating conditions for advanced fuels and materials
- Irradiation to allow characterization of materials as a function of design, fabrication methods, operating parameters, load cases
- Test advanced fuels under various operational conditions; leverage JUMP module ability to accept full assemblies
- Provide data to support licensing

Framatome's new chromium-coated zircaloy test fuel pins with new fuel pellets welded inside. https://www.energy.gov/ne/articles/new-accident-tolerant-fuel-framatome-being-tested-idaho-national-laboratory



Unfueled IronClad lead test rods are set for installation into Southern Nuclear's Hatch-1 reactor in Georgia. https://www.energy.gov/ne/articles/ges-nuclear-fuel-designs-ready-reactor-testing

12

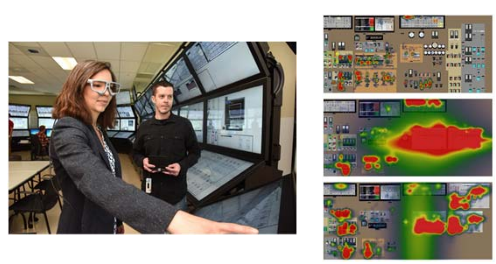
Fuels & Materials Motivation, Goals

- Uncertainty Quantification
  - Novel fabrication methods
  - Novel design
  - Operating parameters and load-cases not previously seen in standard LWR operation
- Provide prototypical environment for
  - Materials and components (non-fuel) testing for fatigue
  - Other materials degradation and water chemistry effects
- Collected data would be used to confirm actual load and operating parameters to verify operating margins and inform maintenance requirements, aiding in the reduction or elimination of over-conservatisms
- Provide data to support development of more accurate predictive models for materials degradation management

Human Factors Research

- Foundational research using the NuScale training simulator
  - Human-automation interaction
  - Evaluate new operational concepts
- Develop data collection methodology
  - Eye tracking
  - Electroencephalogram (EEG)
  - Physiological data
    - Heart rate
    - Galvanic Skin response
    - Blood Pressure
  - Logging human actions and plant response
    - Develop structure for automatically adding context to human actions for streamlined analysis

INL Human Systems Simulation Laboratory



Eye Tracking and Visualization of Control Board Evaluation Results

Human Factors Research

- Develop the tools and capability to collect and characterize human actions in an operating unit to support:
  - Human Reliability Analysis (HRA)
  - Human-system interface design
  - Operational concepts in advanced control rooms
- Apply the methods developed using the training simulator to facilitate
  - Long term data collection and storage
  - Advanced analytics

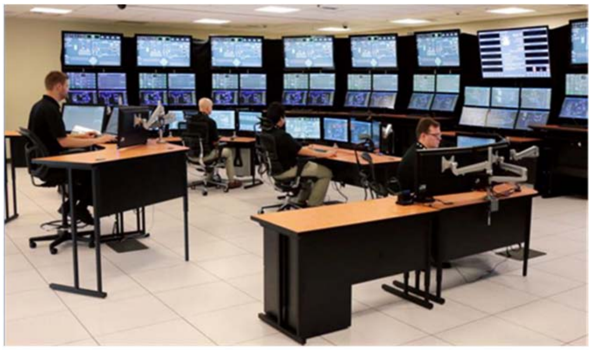


Image taken from June 2018 NuScale Power advanced technology presentation available at https://gain.inl.gov.

Safeguards Research Scope

- **Domestically**
  Within the United States, nuclear safeguards and security (S&S) requirements are well established and observed under relevant NRC/DOE rules and regulations.
- **Internationally**
  Under the United Nations' nuclear non-proliferation treaty (NPT), the IAEA is tasked with the mandate of ensuring that nuclear materials and related facilities are used only for their officially declared purpose. S&S measures vary by facility type.

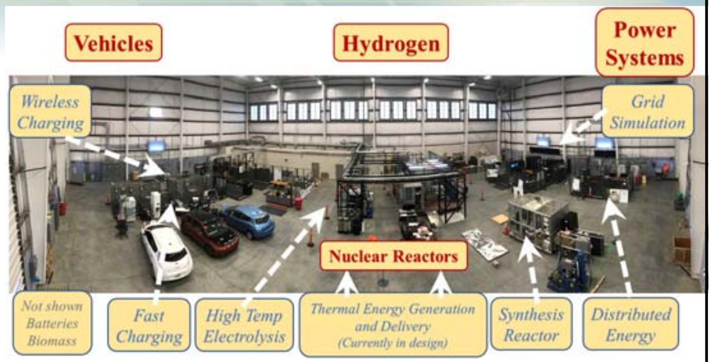
Key Goals

- ***Enable RD&D of new Safeguards & Security (S&S) systems***
  The multi-module SMR plant offers a first-of-its-kind platform to concurrently adopt emerging technologies into the S&S by-design (SSBD) methodology, permitting optimization of these systems into the early design of this new nuclear facility. This is of particular relevance once SMR vendors extend products and services into the international market.
- ***Provide technical assistance to the international community***
  It is envisioned that SMRs will be built in large numbers around the world. The optimization of S&S measures will assist the IAEA in carrying out its non-proliferation treaty (NPT) mission more effectively and efficiently.

Leveraging Relevant Facilities in the DOE Complex

- Systems Integration Laboratory
- Human Systems Simulation Laboratory
- Fuels and Materials Development and Testing
- High Temperature Test Laboratory (sensor development and testing)

INL Materials and Fuels Complex

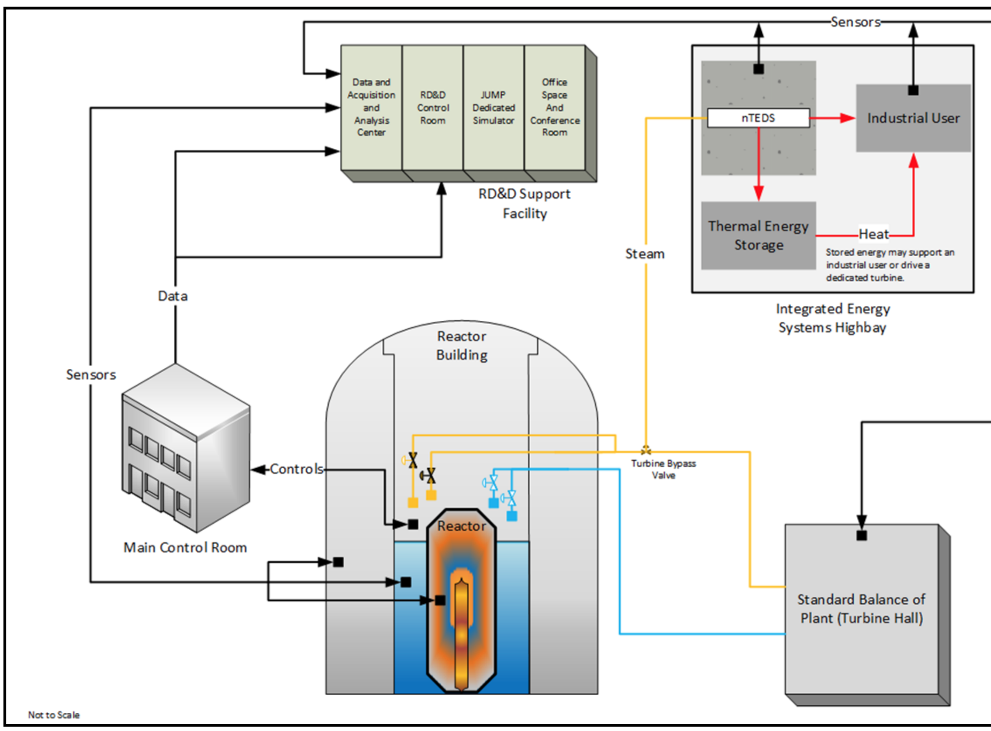


INL Systems Integration Laboratory

High Temperature Steam Electrolysis Test Platform

INL Human Systems Simulation Laboratory

Overview of the JUMP concept relative to the NuScale module in the UAMPS commercial facility

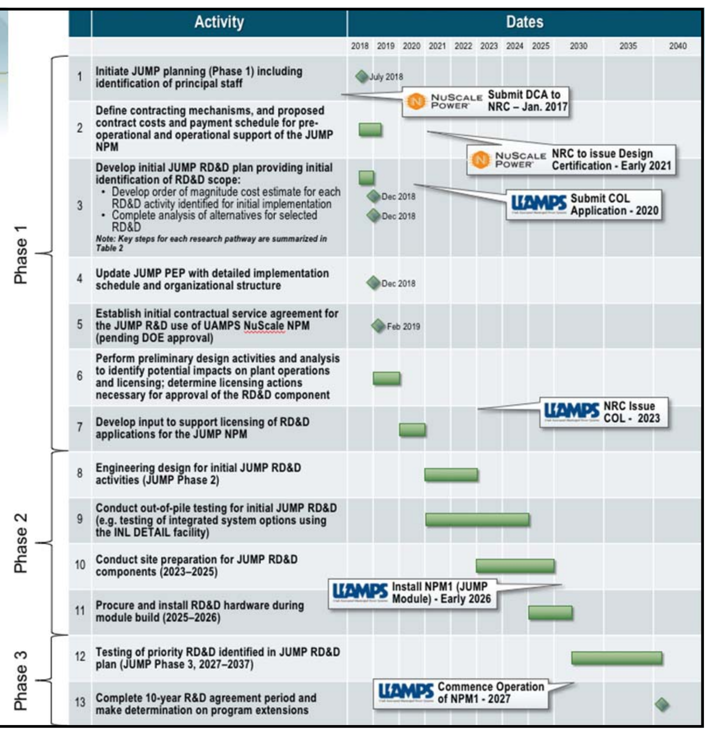


Process to Determine JUMP Research Prioritization

- Collect RD&D proposals in multiple focused brainstorming sessions with DOE programmatic leads and RD&D thought leaders
- Screen concepts for preliminary licensing feasibility with subject matter experts and plant designers
- Review programmatic and other stakeholder interests
  - Gauge overall support within DOE research programs
  - Obtain vendor (NuScale) input on RD&D concept and high-level design
  - Establish preliminary prioritization
- Assess complementary RD&D activities that can be coupled or conducted in parallel
- Evaluate alternatives available to achieve the desired RD&D results
- Develop order-of-magnitude cost estimates for high-priority activities
- Review concepts with DOE and other stakeholders – select options to proceed to detailed design

Schedule and Task Summary

- ***Phase 1 (2018–2021): Planning***
  - Develop detailed program plan, RD&D plan, schedule and budget, analysis of alternatives
  - Establish contractual agreements
  - Conduct preliminary JUMP RD&D hardware design activities
  - Assess licensing impacts and development of inputs to licensing (engage NRC staff)
- ***Phase 2 (2021–2026): Precursor Activities, Hardware Installation & Pre-Op RD&D***
  - Modeling, benchtop testing, and scaled non-nuclear demonstrations for the selected RD&D activities
  - Final design of JUMP hardware, infrastructure
  - NRC engagement; submit license amendments
  - Procure and install JUMP-related hardware and infrastructure
- ***Phase 3 (2027–2037): Post-Op JUMP RD&D***
  - Initial testing of hardware
  - Execute JUMP RD&D plan
  - Assess and plan for future use of JUMP




Questions?
Idaho National Laboratory
For more information, contact:
Shannon.Bragg-Sitton@inl.gov

Heat Storage for Gen IV Reactors

Nitrate Salt Heat Storage

Idaho State University
July 23, 2019
Bruce Kelly
SolarDynamics LLC
Bruce.Kelly@SolarDynLLC.com

This presentation was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy.

SolarDynamics

Nitrate Salt Thermal Storage

- Commercial projects
  - Solar parabolic trough and central receiver
  - Two-tank (hot tank and cold tank) designs
  - No thermocline systems have been built to date
- Nitrate salt
- Tank design basis
- Foundation design basis
- Experience from solar thermal projects

Commercial Solar Projects

SolarDynamics

Project		Capacity, MWe	Storage, hours	Project		Capacity, MWe	Storage, hours
Andasol-1	Trough	50	7.5	Khi Solar One	Tower	50	2
Andasol-2	Trough	50	7.5	La Africana	Trough	50	7.5
Andasol-3	Trough	50	7.5	La Dehesa	Trough	49.9	7.5
Arcosol 50 - Valle 1	Trough	49.9	7.5	La Florida	Trough	50	7.5
Arenales	Trough	50	7	Manchasol-1	Trough	49.9	7.5
Ashalim Trough	Trough	121	4.5	Manchasol-2	Trough	50	7.5
Aste 1A	Trough	50	8	NOOR I	Trough	160	3
Aste 1B	Trough	50	8	NOOR II	Trough	200	7
Astexol II	Trough	50	8	NOOR III	Tower	150	7
Bokpoort	Trough	55	9.3	Planta Solar 10	Tower	11.02	1
Casablanca	Trough	50	7.5	Planta Solar 20	Tower	20	1
Cerro Dominator	Tower	110	17.5	Solana Generating Station	Trough	280	6
Crescent Dunes	Tower	110	10	SunCan Dunhuang 10 MW Phase I	Tower	10	15
DEWA Tower Project	Tower	100	10	Termesol 50 - Valle 2	Trough	49.9	7.5
DEWA Trough Unit 1	Trough	200	10	Termosol 1	Trough	50	9
DEWA Trough Unit 2	Trough	200	10	Termosol 2	Trough	50	9
DEWA Trough Unit 3	Trough	200	10	Xina Solar One	Trough	100	5.5
Extresol-1	Trough	49.9	7.5	Shagaya	Trough	50	10
Extresol-2	Trough	49.9	7.5	Ilanga	Trough	100	5
Extresol-3	Trough	50	7.5	Supcon Delingha	Tower	10	2
Gemasolar Thermosolar Plant	Tower	19.9	15	Supcon Delingha	Tower	50	7
Kathu Solar Park	Trough	100	4.5	CGN Delingha	Trough	50	9
KaXu Solar One	Trough	100	2.5	Suncan Dunhuang	Tower	100	11

Commercial Solar Projects - Continued

SolarDynamics

- 250 MWe Solana project, with 6 storage units

SolarDynamics

Commercial Solar Projects

- Thermal storage tanks at the 110 MWe Crescent Dunes central receiver project

SolarDynamics

Nitrate Salt

- 60 weight percent $NaNO_3$ and 40 weight percent KNO_3
  - Not the eutectic (50 mole percent each), but less expensive
  - Freezing range of 220 to 240 °C
- Oxidizing material, but chemically stable
  - In air, as the ullage gas in the thermal storage tanks
  - In water, when exposed to leaks in the steam generator
- Very low vapor pressure; less than 20 Pa at 600 °C
- Upper temperature limit of ~ 600 °C
  - First equilibrium reaction: $NO_3 \leftrightarrow NO_2 + ½ O_2$
  - Second (quasi) equilibrium reaction: $NO_2 \leftrightarrow NO_{(g)} + O^-$
  - Oxide ions reacts to form nickel oxide, iron oxides, and soluble chromium oxides
  - At oxide concentrations above ~ 200 ppm, corrosion rates exceed commercially acceptable values

Tank Design Basis

SolarDynamics

- Large volumes (15,000 m^3) and low vapor pressures (10 Pa) lead to a flat bottom tank with a self-supporting dome roof as the lowest cost approach
- Necessarily requires the tank to be supported by, and to interact with, a foundation
- ‘Closest’ design code is American Petroleum Institute 650 - Welded Tanks for Oil Storage
- API 650 is limited to 260 °C
  - For higher temperatures, allowable material stresses are taken from ASME B&PV Code Section II - Materials
  - Combination of Codes must be approved by the local Authorized Inspector

Tank Design Basis - Continued

SolarDynamics

- Materials
  - Carbon steel for temperatures below 375 °C
    - Defined by corrosion rate and allowable long-term creep deformation
  - Type 304L stainless steel for temperatures between 375 °C and 538 °C
    - Ferritic materials (chrome-moly) offer acceptable corrosion resistance
    - However, the higher chrome alloys require post weld heat treatment
  - Type 347H stainless steel for temperatures above 538 °C
    - ‘H’ grade stainless steels (> 0.04 percent C) are required
    - However, the common types, such as 304H and 316H, can be permanently damaged by intergranular stress corrosion cracking
    - Stabilized stainless steels, including Type 321 and Type 347, are less susceptible to intergranular stress corrosion cracking

SolarDynamics

Tank Design Basis - Continued

- Requirements not specifically addressed in API 650 or ASME Section II
  - The tank must be preheated to 350 °C prior to filling with salt
  - The tank operates through daily pressure and temperature cycles
  - The low cycle fatigue life must be at least 10,000 cycles
  - The tank, when full, can either increase in temperature or decrease in temperature. Friction between the thin floor (6 to 8 mm) and the foundation places the floor into either tension or compression.
  - The EPC must specify weld filler materials, weld procedures, and post weld heat treatments
    - Post weld heat treatment of carbon steel is specified in Section VIII
    - Post weld heat treatment of stainless steel is optional in Section VIII; i.e., an EPC decision
    - Tricky decision for stabilized stainless steels

SolarDynamics

Tank Design Basis - Continued

- Tank inlet piping and eductor arrangements may not provide perfect mixing, particularly during trip conditions
- Foundation temperatures are high enough to produce soil desiccation and oxidation of organic material. To prevent excessive foundation settlement, cooling must be provided to limit soil temperatures to 75 °C.
- The EPC must develop
  - Tank specifications based on API 650, ASME Section II, Section VIII Division 1 (infinite fatigue life), Section VIII Division 2 (low cycle fatigue life), and modifications to the rules in API 650
  - CFD analyses of flow distributions during transient conditions, and the associated FEA analyses of the floor and wall stresses
  - Operating procedures consistent with a 30-year fatigue life
- The storage system, particularly the hot tank, is neither isobaric nor isothermal

SolarDynamics

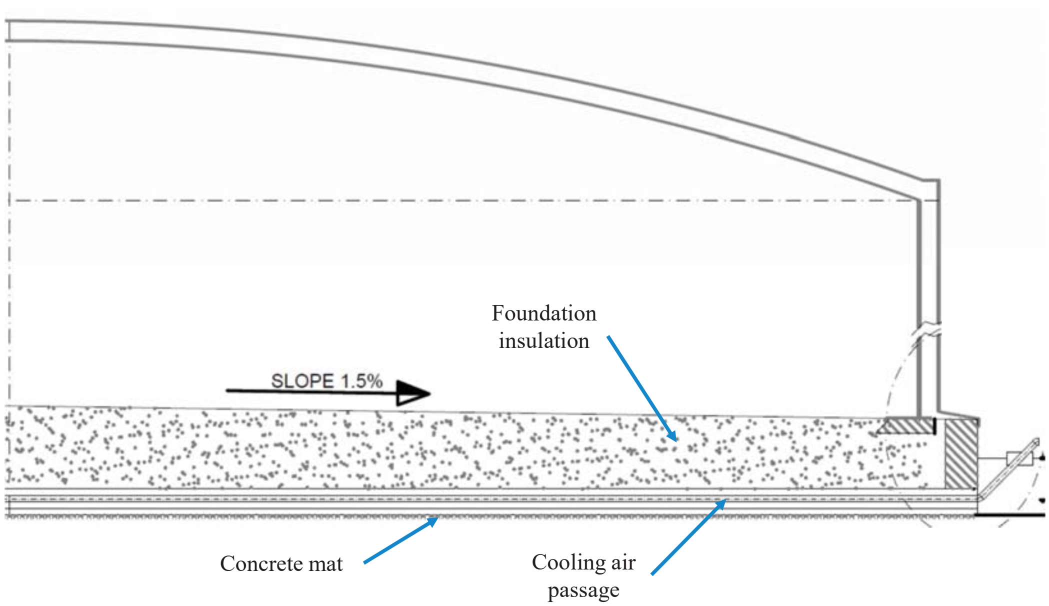
Foundation Design Basis

- Concrete base slab
- Forced convection air cooling of the concrete
- Rigid perimeter ring wall of a refractory material (cast or bricks) to accommodate the concentrated vertical loads from the wall and the roof. Expanded clay as the sole foundation material has repeatedly been shown not to work.
- Expanded glass as the primary insulation material
- Contiguous drip pan to isolate the foundation from a salt leak
  - Salt has a higher thermal conductivity than the insulation
  - Foundation thermal losses will markedly increase due to salt contamination
- Sand layer to reduce friction forces between bottom of the tank and the foundation
  - Reduce the potential for buckling of the thin floor plates

SolarDynamics

Foundation Design Basis - Continued

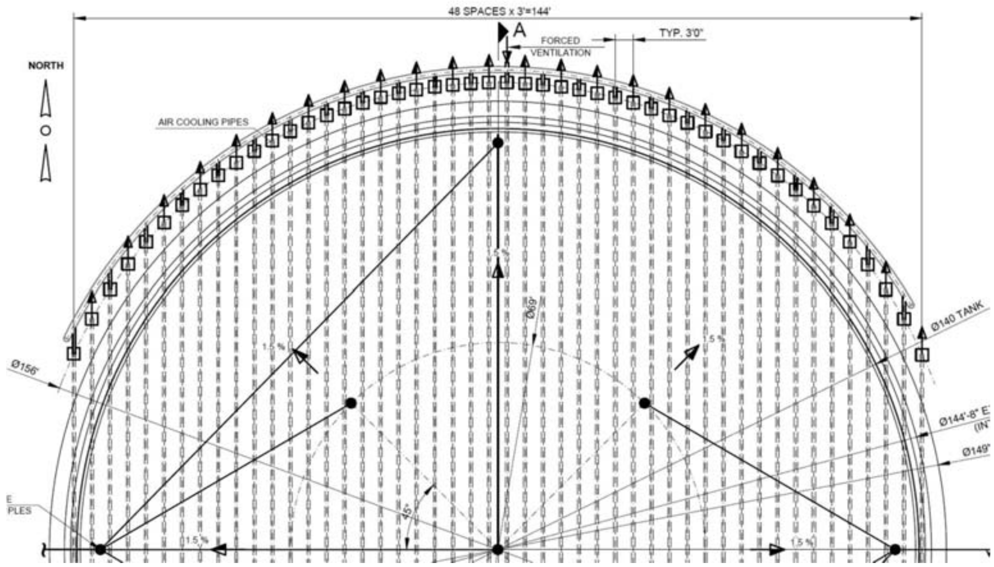
- Cooling air ducts in a (somewhat non-representative) tank foundation



Foundation Design Basis - Continued

SolarDynamics

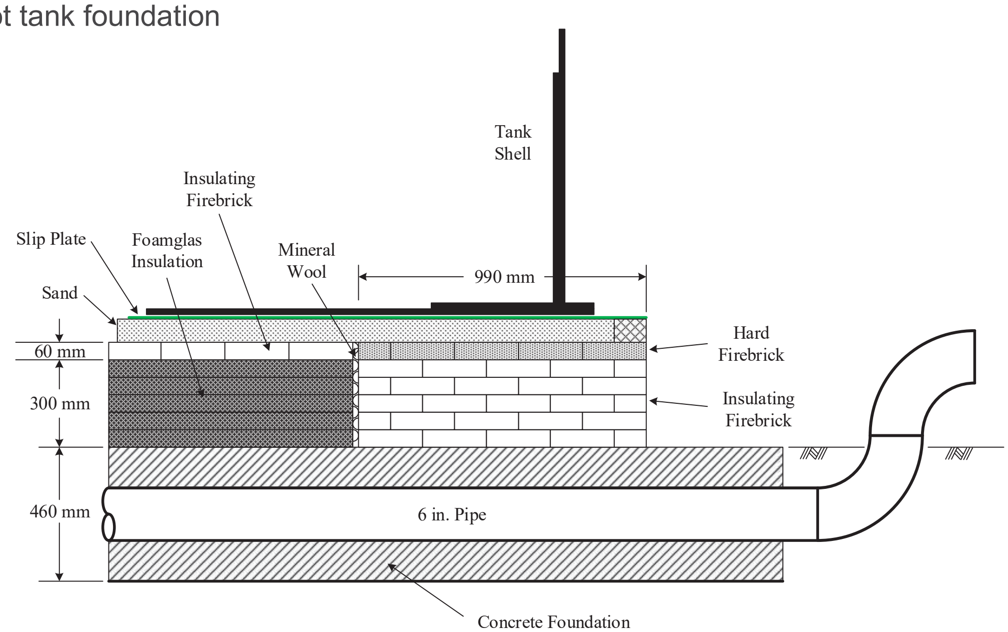
- Tank foundation cooling air passages



Foundation Design Basis - Continued

SolarDynamics

- Hot tank foundation



Parabolic Trough Thermal Storage

SolarDynamics

- Indirect thermal storage
  - Therminol heat transfer fluid in the collector field
  - Nitrate salt thermal storage fluid
  - Oil-to-salt heat exchange during charging; salt-to-oil heat exchanger during discharging
- 300 °C cold tank temperature, and 385 °C hot tank temperature
- All carbon steel construction
- Tank dimension limits
  - 12 m tall based on allowable soil bearing pressures
  - 40 m diameter to avoid ASME Section II requirements for post weld heat treatment of carbon steel with thicknesses greater than 38 mm
- 78 tanks built to date, with only 1 reported leak (perhaps due to a weld defect)

Central Receiver Thermal Storage

SolarDynamics

- Receiver supplies salt directly to the cold tank or to the hot tank based on diversion valve positions
- 295 °C cold tank temperature, and 565 °C hot tank temperature
- Carbon steel cold tank, and Type 347H stainless steel hot tank
- Tank dimensions are similar to parabolic trough projects
- 4 storage systems built to date: Solar Two; Gemasolar; Crescent Dunes; and Noor III
- No cold tank leaks
- 4 hot tank leaks to date: 2 at Gemasolar; and 2 at Crescent Dunes
  - Primarily due to problems with the foundation
  - No evidence of stress relaxation cracking, intergranular stress corrosion cracking, incorrect selection of weld filler materials, or unexpected corrosion processes

Central Receiver Thermal Storage - Continued

SolarDynamics

- Revised hot tank design and operation
  - Tank specification addenda to API Standard 650 regarding friction forces between the foundation and the floor
  - For transient conditions, CFD/FEA analyses of salt flow distributions, metal temperature distributions, and floor and wall stress distributions
  - 30-year low cycle fatigue analyses
  - Foundation materials, particularly at the perimeter of the tank, that limit local settlement due to tank thermal expansion and contraction cycles
  - For a given inventory level and temperature, DCS permissives on inlet flow rate and temperature
- An increase in tank dimensions brought new failure modes, but the problems are generally understood and practical solutions are at hand

Concrete Thermal Energy Storage and Pumped Heat Variant

Bright Energy Storage Technologies
July, 2019

Thermal Energy Storage (TES) Enables New Options for Nuclear Power

- Reduce or delay reactor rebuild costs by running the existing steam turbines /generators with half of the existing reactors
- New, dispatchable capacity without building new reactors or same peak capacity with fewer reactors, with high flexibility
- Make non-GHG emitting nuclear plants a vital part of renewable power integration
- Enable the next generation of flexible nuclear energy to provide zero carbon firming of renewable assets

Bright Energy

2

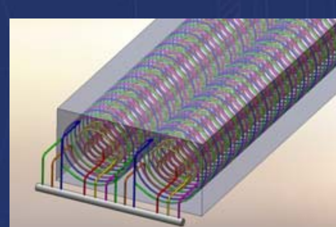
Bright's TES Technology

- Patented high performance concrete and steel tube systems
- Designed to operate at up to 600^0 C
- Low cost, modular, factory built, stacked and configured on site
- Configurable for every thermal generation design
- Two TES designs
    - Thermally charged with steam
    - Thermally charged with CT exhaust / heated air

Bright Energy

TES Module Details

Gas Charged TES block



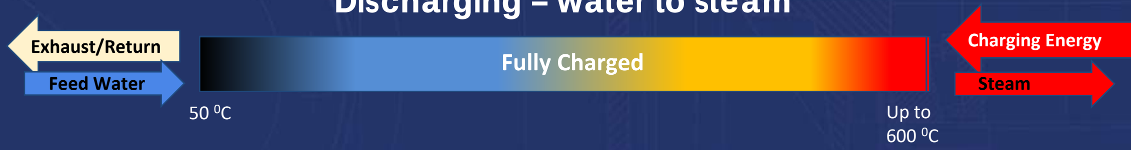
Steam Charged TES block

TES Block Placement

TES Charge and Discharge

- Boiler steam or hot gas, depending on application, flows in one direction through the TES, heating the concrete
- Charging process creates a thermocline, highest temperature at charging inlet
- Water pumped in opposite direction to discharge, resultant steam exits TES at ~hot end temperature, delivering consistent high quality steam

Charging – steam or hot gas
Discharging – water to steam



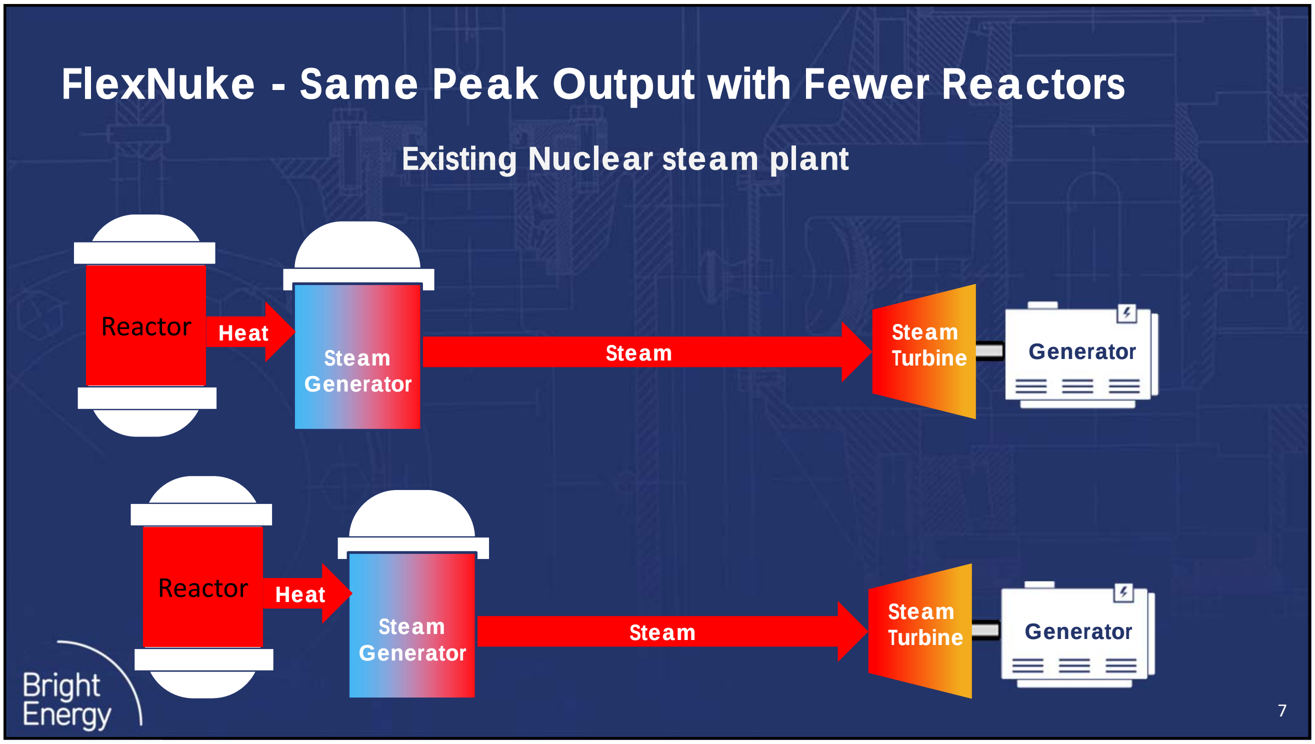
5

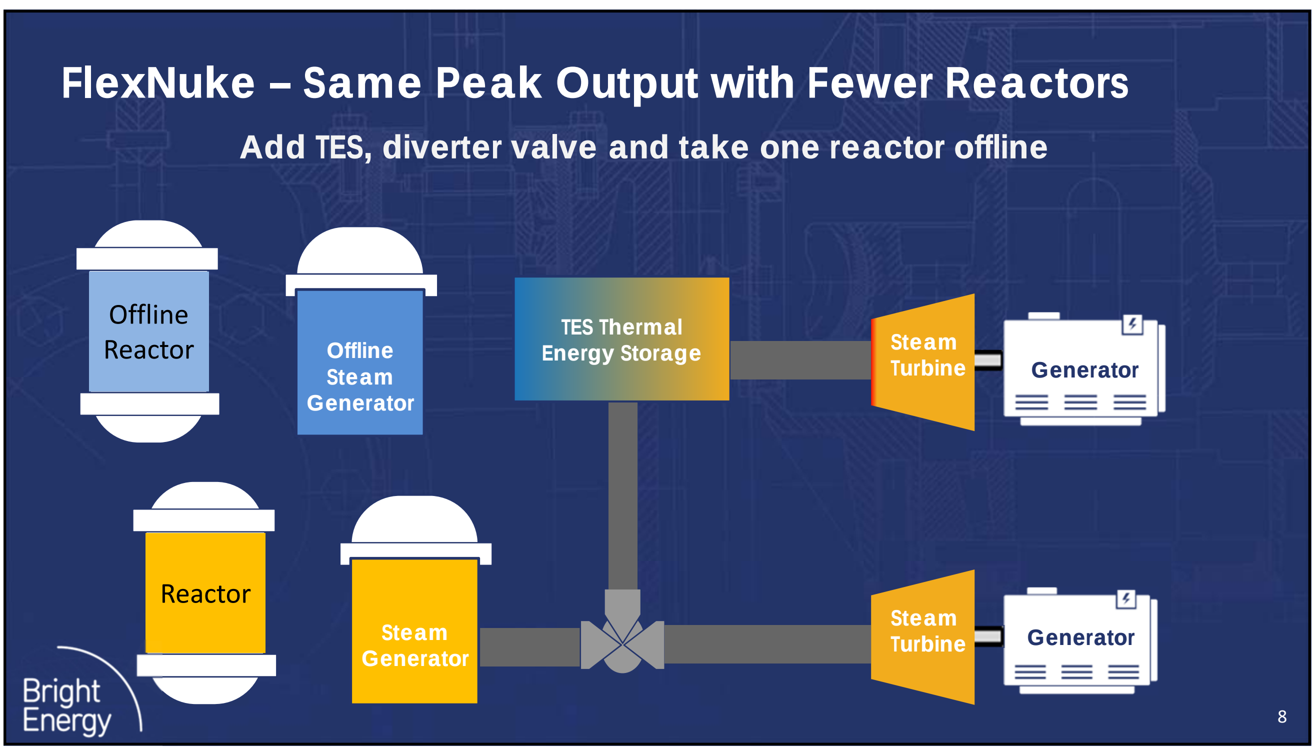
Industry and DOE Funded Bright TES Test Program

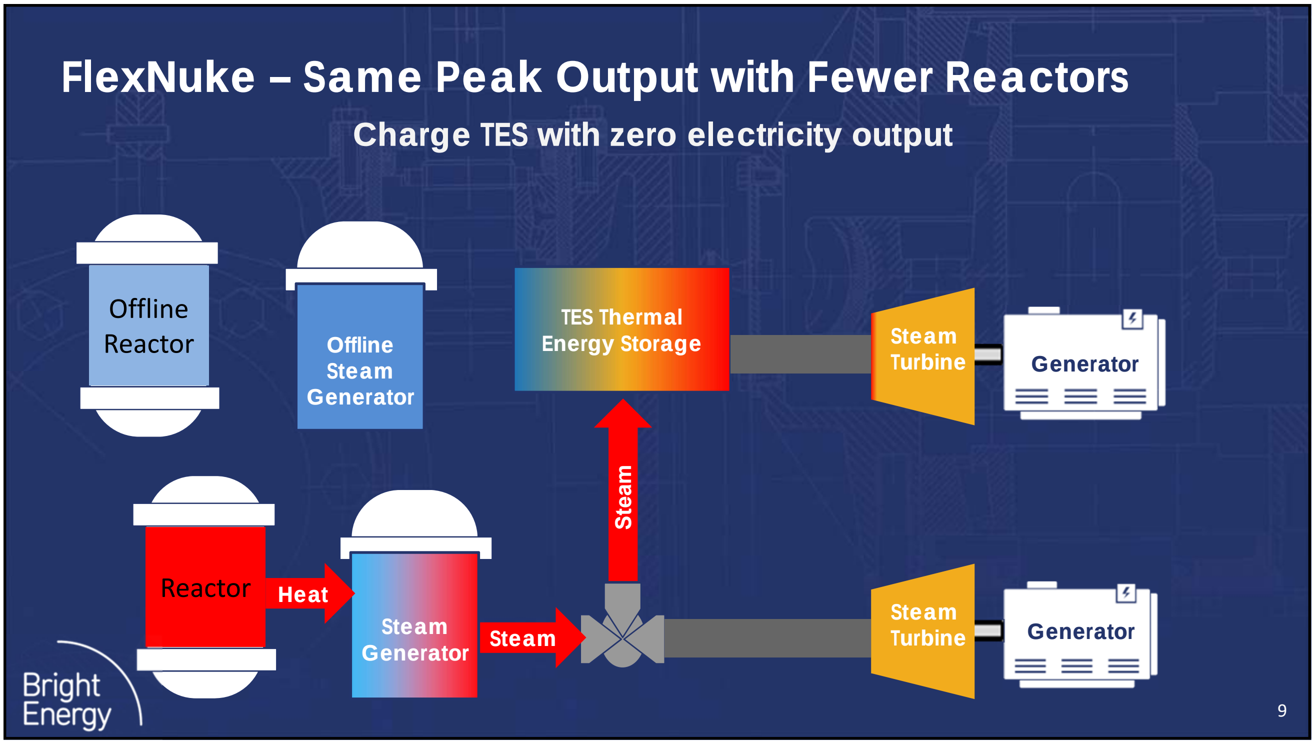
- **Electric Power Research Institute (EPRI)**
  - Currently funding Bright study of TES materials and assembly adequacy to application
  - Industry funders are Southern Company, Tri-State, and Salt River Project
- **$5 million DOE FOA Award June, 2019**
  - Awarded to Bright Energy, EPRI, Southern Company team
  - Grant to build and test 10 MWh_e Pilot at working generation plant
- **Bright seeking an additional pilot/test opportunity**
  - Nuclear, perhaps at INL?
  - Geothermal in CA, perhaps with California Energy Commission funding
  - Other TBD

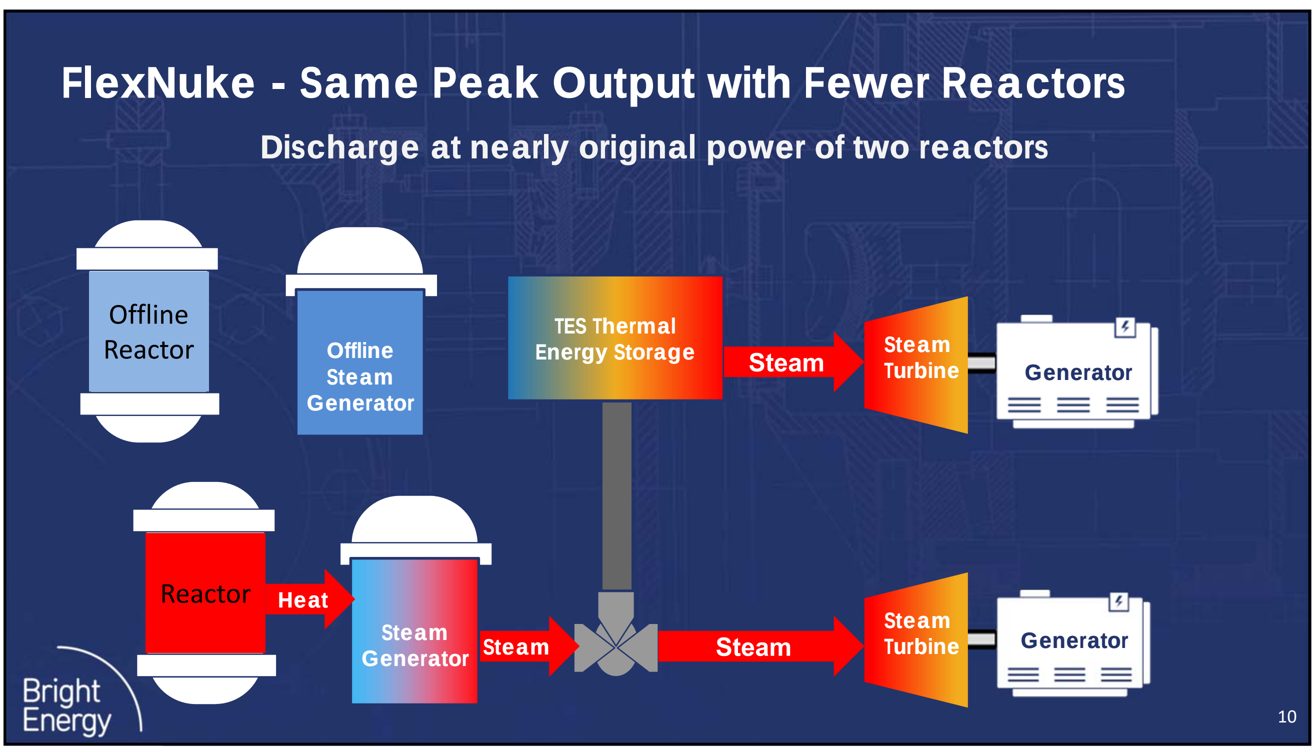
Bright Energy

6

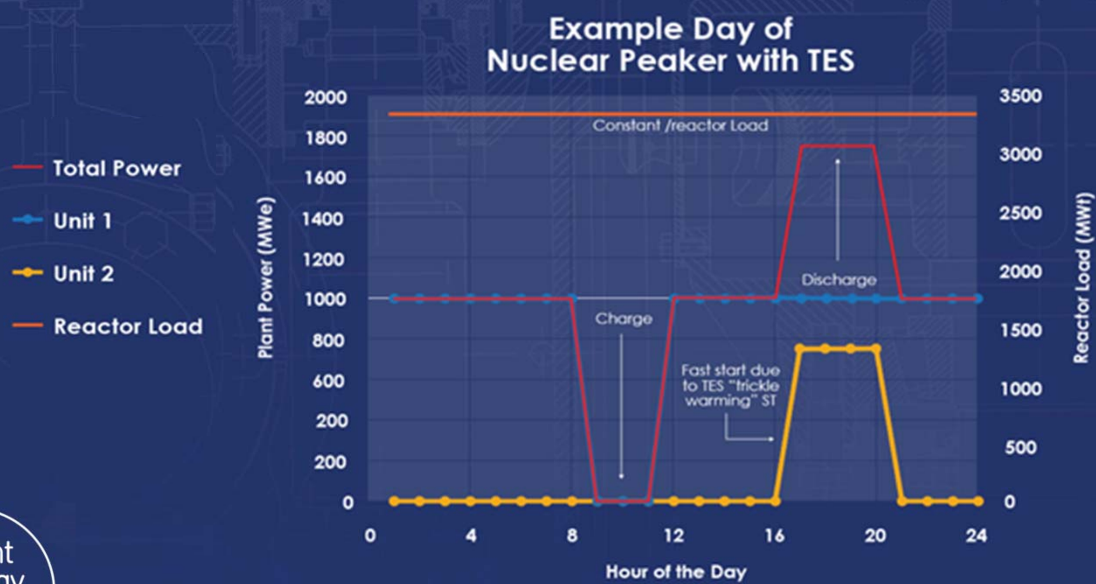

FlexNuke - Same Peak Output with Fewer Reactors
Existing Nuclear steam plant
Reactor
Heat
Steam Generator
Steam
Steam Turbine
Generator
Reactor
Heat
Steam Generator
Steam
Steam Turbine
Generator
Bright Energy
7


FlexNuke – Same Peak Output with Fewer Reactors
Add TES, diverter valve and take one reactor offline
Offline Reactor
Offline Steam Generator
TES Thermal Energy Storage
Steam Turbine
Generator
Reactor
Steam Generator
Steam Turbine
Generator
Bright Energy
8


FlexNuke – Same Peak Output with Fewer Reactors
Charge TES with zero electricity output
Offline Reactor
Offline Steam Generator
TES Thermal Energy Storage
Steam Turbine
Generator
Steam
Reactor
Heat
Steam Generator
Steam
Steam Turbine
Generator
Bright Energy
9

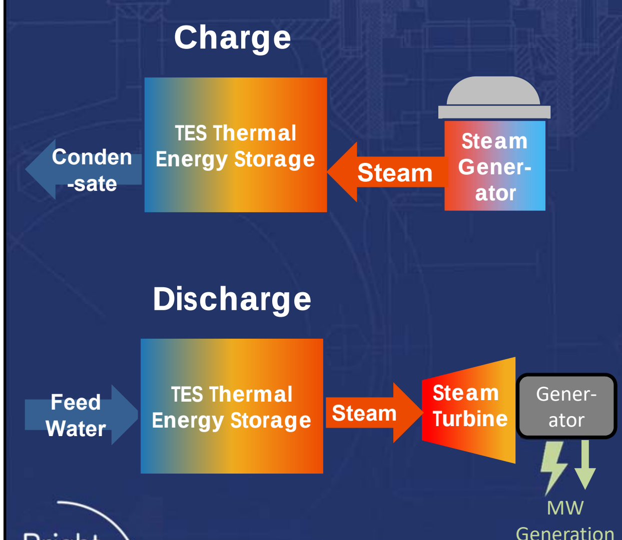

FlexNuke - Same Peak Output with Fewer Reactors
Discharge at nearly original power of two reactors
Offline Reactor
Offline Steam Generator
TES Thermal Energy Storage
Steam
Steam Turbine
Generator
Reactor
Heat
Steam Generator
Steam
Steam
Steam Turbine
Generator
Bright Energy
10

FlexNuke - Convert Baseload to Load Following Peaker



Bright Energy

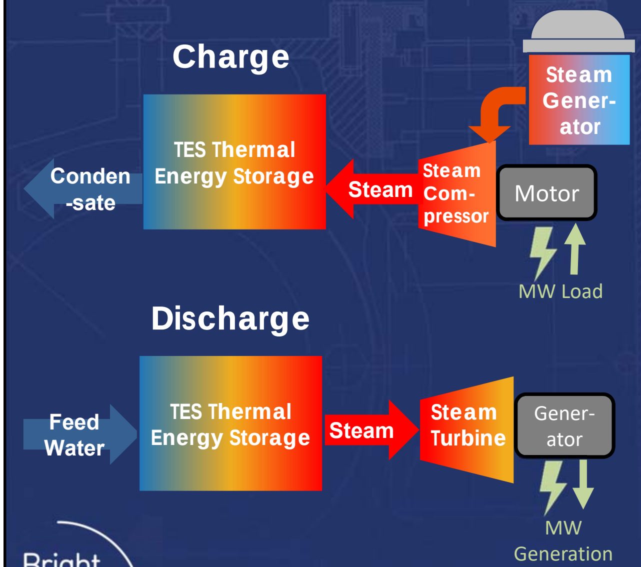
Baseline TES Configuration - $278/kW and $62/kWh



- $278/kW + $62/kWh Total Project Cost
- 71% estimated RTE
- 4 hour discharge
- 2.9 hour charge
  - We can vary this ratio of charge/discharge to just about whatever we want by varying the ST we purchase for discharge.
- 62 bar charge pressure
- 20 bar discharge pressure
- Assumed $200/kW ST designed for 20 bar discharge

Bright Energy

Pumped Steam w/Storage Variant - $375/kW + $62/kWh



- $375/kW + $62/kWh Total Project Cost
- 58% estimated RTE
- 4 hour discharge
- 5.3 hour charge
  - We can change the charge/discharge time/power ratio by changing the discharge ST rating. Going with a higher power ST will require more charge time, but will lower the cost of the compressor in terms of $/kW
- 155 bar charge pressure
- 62 bar discharge pressure
- Assumes $200/kW ST

Bright Energy

13

TES Performance

- **Thermal energy losses**
  - Less than 1% energy loss per day
  - Estimated heat-to-heat efficiency >92%, fuel to electric efficiency depends on steam turbine
- **Ramping and Steam Quality**
  - TES can ramp steam output in less than minute - "hot end" of TES blocks always delivers high quality steam after feedwater fed into cold end
  - "Discharged" defined by when hot end of TES no longer at adequate temperature to deliver requisite steam quality
- **Maintenance - ruptured steam tube embedded in concrete**
  - ID tube(s) during routine maintenance, cut, crimp/weld and abandon in place
  - 75,000 steam tubes, loss of a small number has marginal impact on system performance

14

Bright Energy Background

- **Angel-backed startup based in Arvada, CO, founded in 2010, 15 employees**
- **Several themes common in development concepts**
  - Low capital costs per kW/kWh, high efficiency, low cost heat exchangers and heat storage media, re-use of existing capital equipment
  - Must be competitive against operating costs of incumbent generation equipment, not just better than competing storage systems
- **Sustainable advantages**
  - Lowest cost solutions with 25+ year lifetime
  - Proprietary technology
  - Strategic relationships with the industry, EPCs and Concrete Fabricators

15 15

Contact Information:

Kevin Pykkonen
VP Development
Kevin@BrightES.com
(303) 907 9845

16

Westinghouse Modular Heat Storage: A Flexible Approach to Next Generation Grid Needs

Cory Stansbury

Principal Engineer

Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors, Idaho State University, July 23-24, 2019

WAAP-11446

Westinghouse

1

OUR VISION & VALUES

Westinghouse will remain the first choice for safe, clean and efficient energy solutions.

We enhance our delivery of that vision by living our values:

- Safety & Quality First
- Valuing Ethics, Integrity & Diversity
- Passion for Serving Our Customers Globally
- Dedication to Each Other Through Servant Leadership
- Creating Value for Shareholders, Customers & Employees
- Consistently Delivering Our Commitments

Brief History of Westinghouse Energy Storage Activities

- Energy storage investigations started at an “Innovation Kickoff” meeting held in early 2015; FENOC representatives were on hand and were supportive of energy storage as one topic area → Group voted to pursue this project
- Project focused initially on assisting legacy plants and pure arbitrage
- Inability to cleanly tie into existing plant balance of plant (components did not have enough margin) and lack of customer interest shifted focus
- Project continued, focusing on integration into new-build (especially next generation plants) and in standalone form
- Part of winning submission to ARPA-E “DAYS” project in 2018

Westinghouse

Westinghouse Non-Proprietary Class 3 © 2019 Westinghouse Electric Company LLC. All Rights Reserved.

Brief History of Westinghouse Energy Storage Activities

Technologies Considered

- Compressed air energy storage
- Cryogenic energy storage
- Thermal energy storage
- Batteries
- Hydrogen
- Pumped hydroelectric
- Desalination
- District heating
- Synthetic Fuel

Decision Criteria

Large scale storage market

1. Competitive landscape / technology gaps
2. Overall economics
3. Upfront capital cost scalability
4. Plant Integration (legacy or new build)

Evaluated Characteristics

1. **Geographic independence**
2. Demand responsiveness
3. Footprint
4. Operation and maintenance (O&M) feasibility
5. Environmental impact

Westinghouse

High-Level Goals

Given a goal of competing in the large/very large storage arena (GWh+) and coupling to nuclear plants, product should:

- Utilize common materials which are widely/locally sourceable
- Operate at low pressures and have intrinsic safety characteristics
- Minimize additional piping/heat exchange area contacted by primary working fluid
- Be modular in nature and fast to construct with varying workforce skill levels
- Achieve long life (>20,000 cycles)
- Require minimal maintenance, inspection, and renewal costs
- Meet cost and performance goals relative to a wide selection of markets and stacked services

Embrace Simple / Low Cost Solutions in Creative Ways

Westinghouse

Why Concrete?

A wide variety of thermal storage solutions were investigated:

- Salts
- Reversible chemical reactions
- Phase change materials
- Packed beds
- Hot oils
- Supercritical fluids
- Hybrid combinations

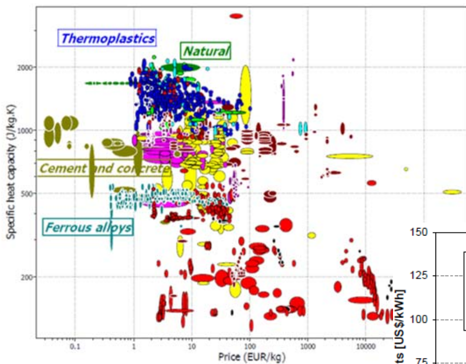
Concrete + Oil Offered a Variety of Desirable Properties

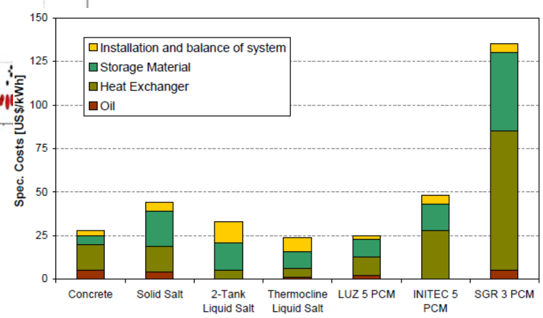
- Locally-available
- Significant understanding of performance at temperature
- "Engineered" and prequalified with material selections
- Extremely low-cost (possibility for Low marginal cost/kWh)
- Low risk of uncontrolled energy release
- Enormous experience in construction at large scale

Concrete was judged to give a good combination of consistency / "designability" and low cost

Westinghouse

Why Concrete?





References

1. A. Inés Fernández et. al, "SELECTION OF MATERIALS WITH POTENTIAL IN THERMAL ENERGY STORAGE," Universitat de Barcelona.
2. U. Herrmann; M. Geyer, "Overview on Thermal Storage Systems," Flabeg Solar International GmbH, Workshop on Thermal Storage for Trough Power Systems, February 2002.

Westinghouse

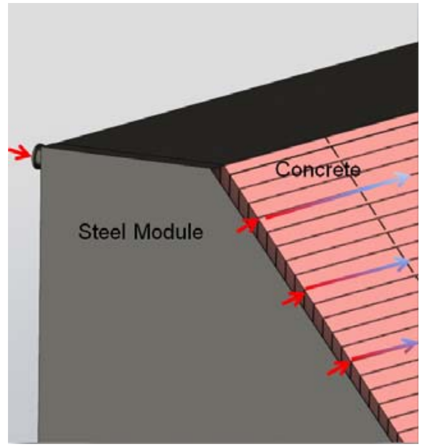
Challenges with Sensible Heat Storage

- Materials with great specific heat tend to have poor thermal conductivity
- At low temperatures and pressures, costs associated with tubes in concrete become more challenging
  - Tube pitch must be tight to evenly heat concrete, increasing volume of oil, tube amount, and fabrication difficulties
  - Tube, header, and oil cost quickly dwarf concrete costs
  - Concrete/tube interface is predisposed to cracking with cycling, making heat transfer more difficult
- Westinghouse wondered if oil and concrete could be made to play nicely together…?

Westinghouse

The Westinghouse Solution

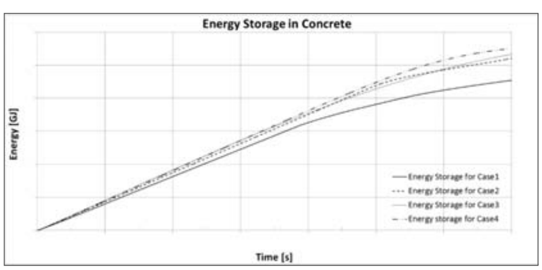
- Westinghouse is looking to flip the traditional method inside-out
- If we can develop a concrete and oil which are compatible, we can eliminate tubing
- Using thin plates with narrow gaps creates huge surface area relative to volume and minimizes oil fraction

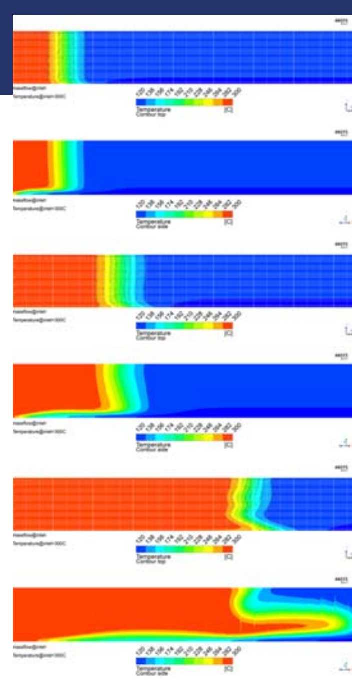


Westinghouse

The Westinghouse Solution

- The large amount of surface area, relative to heat storage, along with the high dT of charge (low velocity), means that a slow, thermal wave is established in the concrete





Westinghouse

Concrete Development and Characteristics

Precast panel considerations and goals:

- Fabrication/erection tolerances
- Cast-in features
- Thermal properties
- Expansion/contraction/cracking caused by
  - Thermal
  - Hydration
  - Creep/shrinkage
- Cost
  - Materials
  - Fabrication
- High density / low porosity
- Eliminate traditional reinforcement (i.e. rebar)
- Concrete mix must not degrade at high temperatures or have adverse interaction with the heat transfer fluid

Westinghouse

Three Applications: One Heat Storage Block

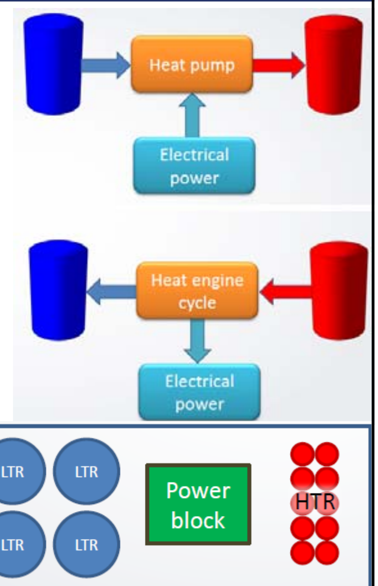
- Stand-alone storage: Pumped heat supercritical CO_2 (sCO_2) concept (ARPA-E)
- Coupled storage with new-build PWR: Provides additional operational flexibility and economic certainty in future markets
- Coupled storage with advanced reactors: lead fast reactor (LFR) + heat storage = unmatched flexibility and economics in generation

Thermal Storage Technology is Flexible

Westinghouse

Applications - Standalone Storage

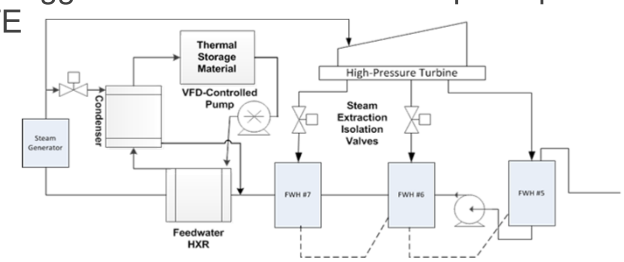
- Under development as part of ARPA-E "DAYS" project
- Pumped Heat Energy Storage (PHES) uses a heat pump and electricity to create a hot and cold reservoir (HTR & LTR)
- This cycle is reversed and the differential is used in a power cycle to generate electricity
- Not a new idea, but sCO_2 allows performance at 300°C / 0°C which would have required much greater temperature extremes prior; thus permitting low cost solutions, like concrete and ice



Westinghouse

Applications - New Build PWR

- When the BoP is designed from the onset to interface with thermal storage, these systems can be integrated
  - Use main steam to heat oil/concrete, thus reducing output
  - Provide additional output by using stored heat to eliminate extraction steam flow needed for feedwater heating, thus keeping it in the turbine (more steam in turbine = more MW)
- Modeling suggests 20-25% additional output is possible w/ ~60% RTE



Westinghouse

"Future-Proof" New Nuclear

Westinghouse Non-Proprietary Class 3

Modeling of Financial Performance

Westinghouse is working to develop our own evaluation tools and understanding

- Financial/technical model of 11 storage technologies + multiple implementations of thermal storage (including sensitivity)
  - Captures capital cost and levelized cost of storage (LCOS)
  - Models across multiple mission sets to capture nuance of how performance metrics impact different energy storage applications
  - Integrated with broader, characteristic-based evaluation tool to help rank technologies on an overall scale
- Hour-by-hour model of coupled "hybrid" plant performance, capital costs, levelized costs, and financial viability against state-of-the-art combined cycle plants in grids with high percentages of non-dispatchable generation
- Initial results are extremely promising to offer a step-change in achievable financial performance

Westinghouse

15

Westinghouse Non-Proprietary Class 3

External Engagement and Modeling

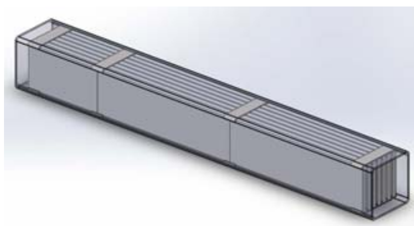
- Engagement of Experts:
  - Steve Brick: Clean Air Task Force
  - Jesse Jenkins: MIT and Harvard
  - Customized Energy Solutions
- What is a reasonable penetration level for non-dispatchable sources?
- How is storage valued in different markets? How is this impacted by penetration?
- What is the impact of technical characteristics?
  - Charge Rate - $/kWh
  - Round Trip - $/kW
- What is an ideal combination of renewables, nuclear, nuclear hybrid, standalone, and nuclear-coupled storage?

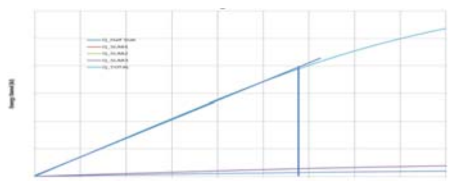
Westinghouse

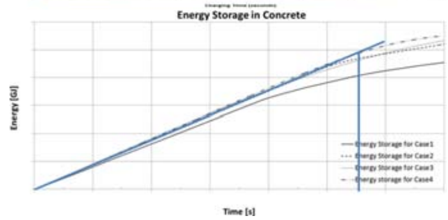
16

Proof of Principle Testing

- Small scale test designed to prove concept
- Test is instrumented to show "thermal wave" and characterize performance
- Results will be compared against CFD to validate computational methods
- Test uses marble plates in a square "tube"
- Similar scaling to full scale, 40-foot "module" (achieves ~81% of the linear charge duration of full scale)

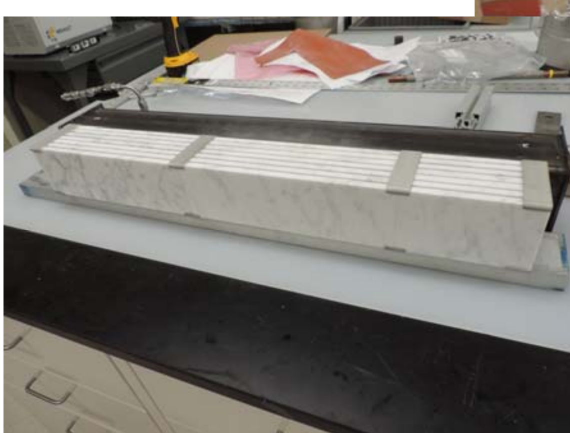






Westinghouse

Proof of Principle Testing



Westinghouse

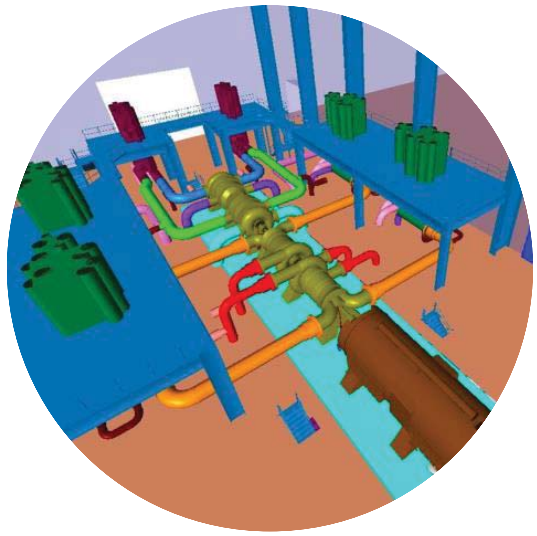
Questions?

Westinghouse

DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

COLD STORAGE SYSTEM FOR SODIUM FAST REACTOR FLEXIBILITY



Gédéon Mauger & Nicolas Tauveron | CEA
Heat Storage Workshop | Idaho Falls | July 23-24, 2019

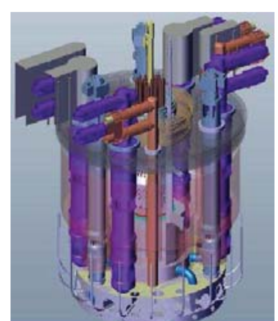
CONTENTS

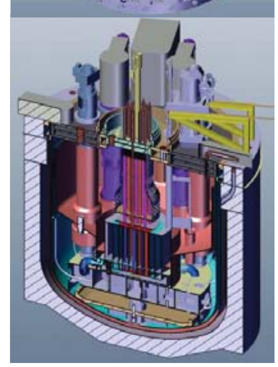
CONTEXT

ASTRID PROJECT

Advanced Sodium Technological Reactor for Industrial Demonstration

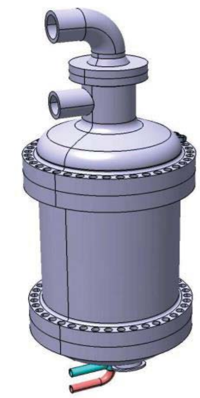
- Pool type 1500 MW – 600 MWe sodium-cooled fast reactor
- Main layout choices
  - Conical inner vessel
  - 3 primary pumps
  - 4 intermediate heat exchangers
  - 4 secondary sodium circuits set in motion by electromagnetic pumps
- Innovative options are investigated
  - A low void effect core (CFV)
  - An in-vessel core catcher for corium
  - **A Gas Power Conversion System (PCS)**





ASTRID POWER CONVERSION SYSTEM (1/2)

Two PCS are investigated for ASTRID [1]



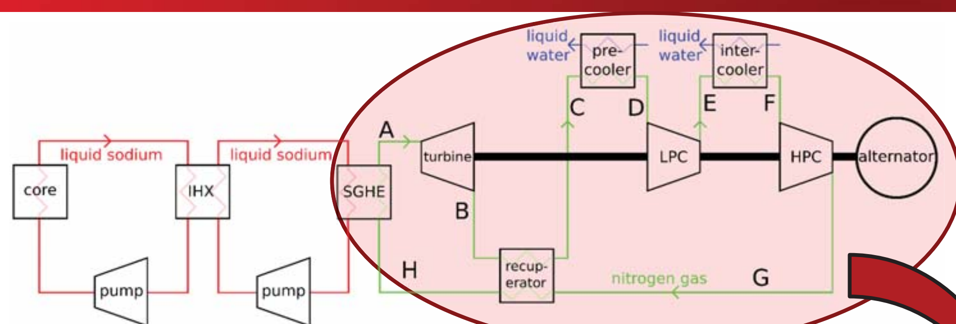
Sodium Gas Heat Exchanger (CEA/DTN)

- Steam PCS (Rankine cycle) versus **Gas PCS (Brayton cycle):**
  - Safety: Sodium Water Reaction (SWR & SWAR), decay heat removal [2]
  - Technology maturity : turbomachinery, exchangers (SGHE), operability
  - Technical-economics: plant efficiency, investment cost

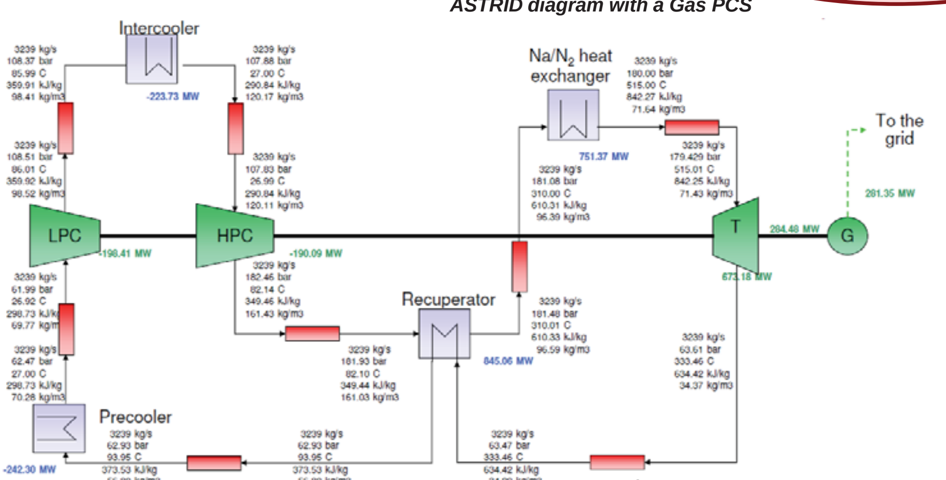
Arabelle™ steam turbine (General Electric, from 700 to 1900 MWe)

GT26 gas turbine (General Electric, 345 MWe)

ASTRID POWER CONVERSION SYSTEM (2/2)



ASTRID diagram with a Gas PCS



Gas PCS heat balance diagram

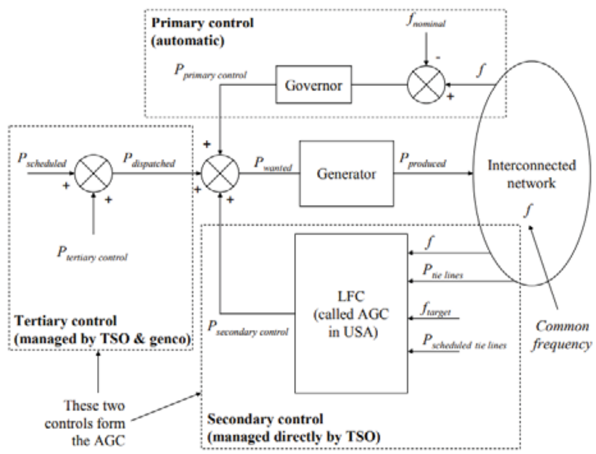
C-92

RESERVE SERVICES FOR FREQUENCY CONTROL

- To maintain the security and the quality of the supply of electricity, the frequency of an electrical grid must be controlled:
  - Primary control: local automatic control which delivers reserve power in opposition to any frequency change;
  - Secondary control: centralized automatic control which delivers reserve power in order to bring back the frequency to its target value;
  - Tertiary control: manual change in the dispatching and unit commitment in order to restore the secondary control reserve and to manage eventual congestions.

- For each control level some dedicated power is kept in reserve to be able to re-establish the balance between load and generation at any time. In addition, the requirements of each reserve are different, especially in terms of power quantity and timing. For example, we considered for ASTRID:
  - Primary reserve: 2.5% of nominal power available in 30 seconds (half of which in 15 seconds);
  - Secondary reserve: 4.5% of nominal power available in 133 seconds.

- In this study we considered as a sizing transient (in terms of storage and dynamics) a step of 7% of nominal power available in 133 seconds.



COLD STORAGE SYSTEM AND CATHARE MODEL

COLD STORAGE SYSTEM (1/2)

- In nuclear reactors, frequency control is performed either with boron dilution (PWR) or with the use of control rods (ASTRID):
  - They must operate at 93.5% of nominal electrical power to ensure a reserve of +7%;
  - For ASTRID this means an operating point at 98% of nominal core power (because of efficiency degradation);
  - It creates thermomechanical loads at the core and hot collector structures.

- The initial idea is that lowering the cold temperature increases the efficiency of the Brayton cycle with recovery:

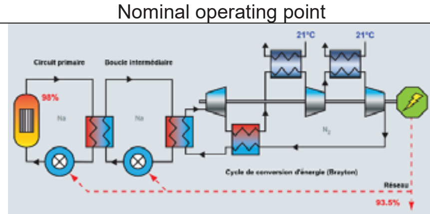
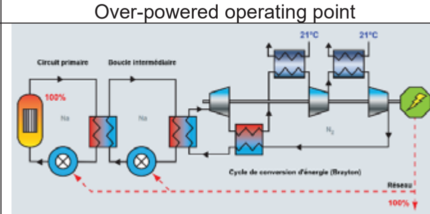
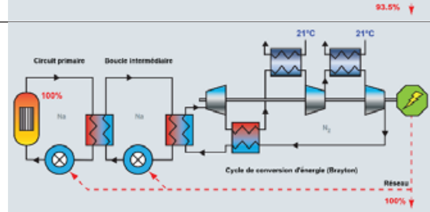
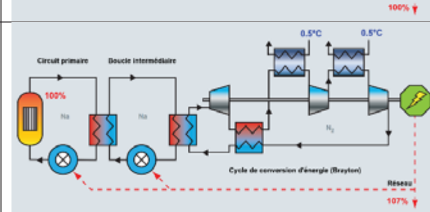
$$\eta_{th} = 1 - \frac{\left(P^+/P^-\right)^{\frac{\gamma-1}{\gamma}}}{T^+/T^-}$$

- A cold water storage (0.5°C in this study) is used to carry out the frequency control (Patent FR3060190 - 2018-06-15 - BOPI 2018-24) [3,4,5]. The use of water with glycol or salt or ice-based storage can be considered to achieve even lower temperatures.

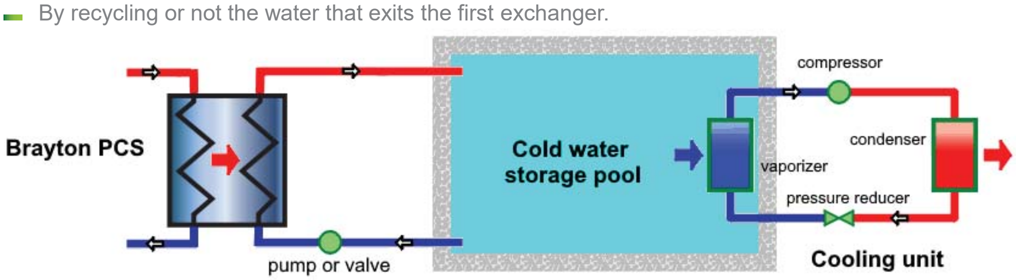
- There are already high-capacity cold storage systems in the fields of air conditioning (shopping centers, offices), refrigeration (ice rinks), etc.

240 MW.h ice storage for air conditioning (Enertherm, Paris)

COLD STORAGE SYSTEM (2/2)

	Nominal operating point	Over-powered operating point
Without cold storage system		
With cold storage system		

- Several design for the interface between the Brayton cycle and the cold storage have been studied:
  - By using existing cycle coolers or **dedicated coolers**;
  - By recycling or not the water that exits the first exchanger.

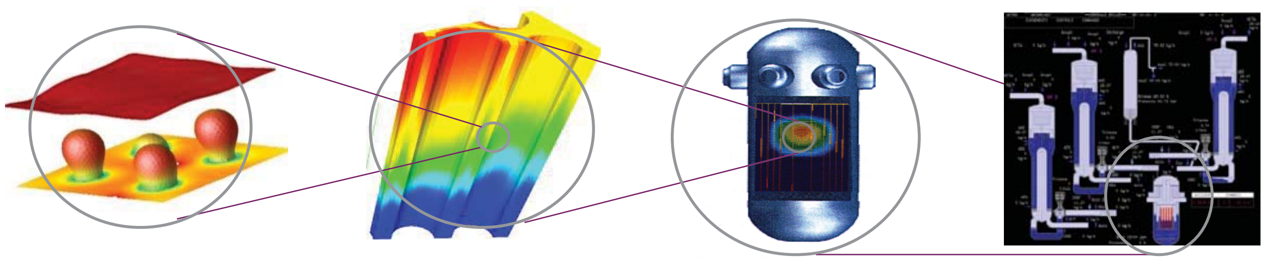


THE CATHARE SYSTEM CODE (1/2)

CATHARE : **C**ode for **A**nalysis of **TH**ermalhydraulics during **A**ccident and for **R**eactor safety **E**valuation

The CATHARE code is a thermo-hydraulic safety code developed since 1979 by joint effort of FRAMATOME, EDF, IRSN and CEA [6].

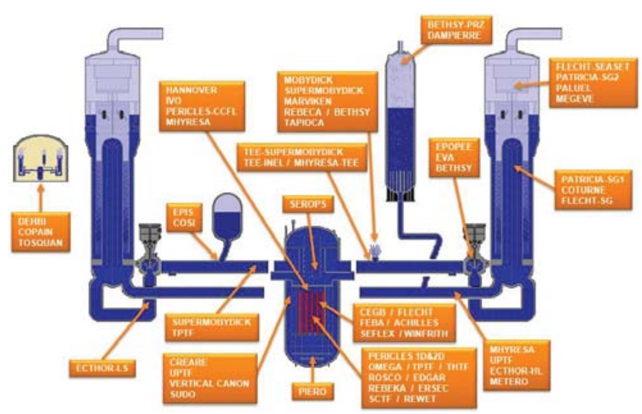
Used to calculate at a system scale the thermo-hydraulic of a reactor in various operating states for various incidental or accidental sequences



Instant local scale $\sim 1\mu m$ | Local scale $\sim 1mm$ | Component scale $\sim 1cm$ | System scale $\sim 10cm$

THE CATHARE SYSTEM CODE (2/2)

- Modelling of large type of experiments and reactors [7] based on:
  - A modular topological and technical description of the facility;
  - A generic set of equations based on the 6 equations 2 phase flow model (allowing thermal and momentum non equilibrium between the 2 phases);
  - A dedicated fluid description including equation of state and closure laws for mass, momentum and energy equations.
- Main uses:
  - Safety Analysis;
  - Design purposes (plant or component);
  - Quantify the conservative analysis margins;
  - Define and verify emergency procedures;
  - Reference code for real plant simulator.
- Some applications:
  - Standard light water reactors;
  - New Gen III concepts;
  - Gen IV concepts: SFR [8,9] and GCR [10,11,12,13];
  - Power conversion systems [14];
  - Experimental reactors;
  - Naval propulsion;
  - Other reactors : BWR, RBMK, LFR, SCLR;
  - Cryogenic rocket engines (ARIANE GROUP).

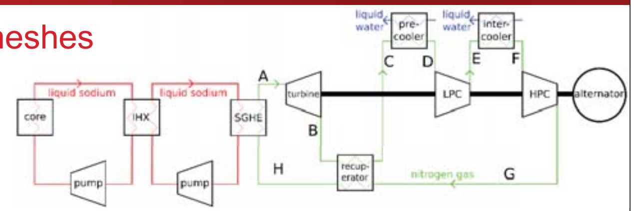


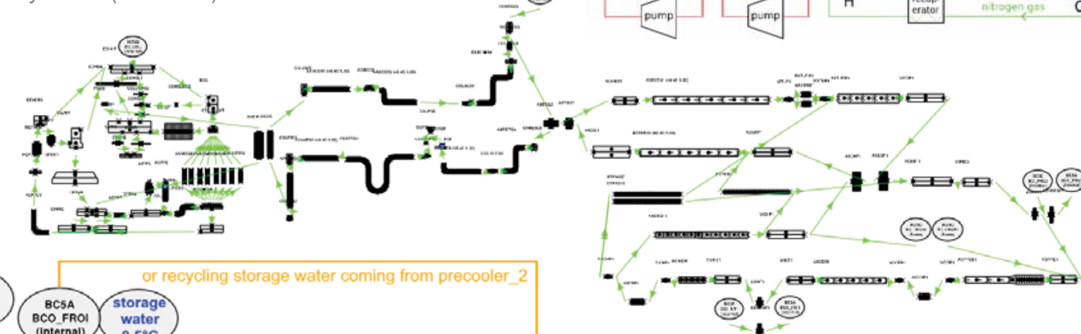
CATHARE validation tests for PWR application

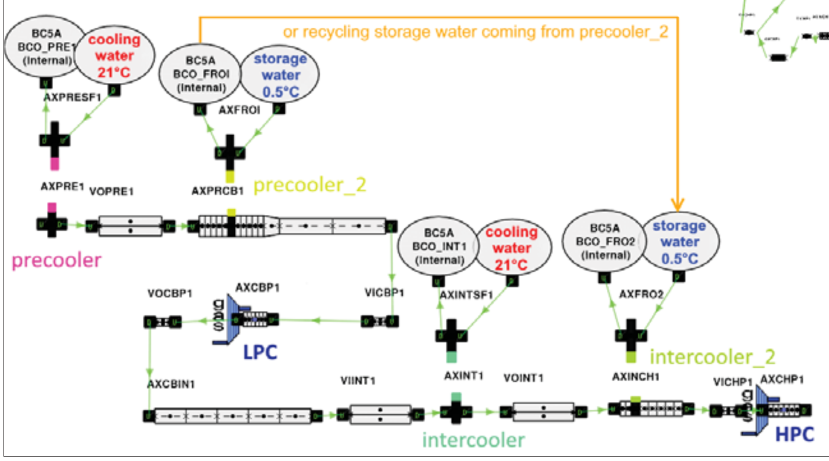
CATHARE MODELLING OF THE COLD STORAGE SYSTEM

Whole Reactor : 3335 CATHARE meshes

- Primary circuit : 1375 meshes
- Secondary circuit : 940 meshes
- Tertiary circuit (Gas PCS) : 1020 meshes







Dedicated exchangers precooler_2 and intercooler_2 are modelled

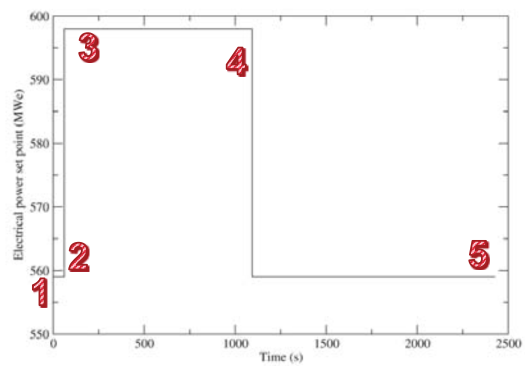
COLD STORAGE SIZING AND SYSTEM DYNAMICS

TRANSIENT SCENARIO

- During the transient, two PID controllers are used:
  - control of electrical power by the water flow rate coming from the cold storage (0.5°C). Actuators are not modelled but could be either valves (gravity system) or pumps with a total opening/closing time of 2 minutes.
  - control of pressure of the Brayton cycle by adding/removing nitrogen. If not activated, the pressure decreases by about 1 bar (due to overcooling), which slightly reduces the system efficiency.

- Reactor's primary and secondary circuits evolve naturally without any controller (only reactivity feedbacks are considered)

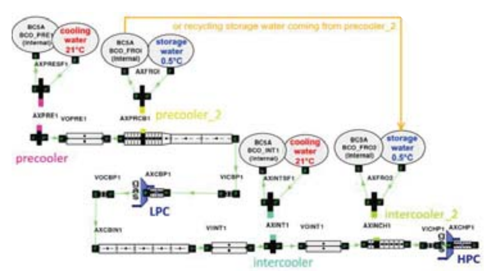
- Transient carried out with the CATHARE code:
  - **1** t_1=0s : beginning of the calculation, reactor at nominal power;
  - **2** $t_2=t_1$+60s: the electrical power set point is subject to a step from 559 MWe to 598 MWe (+7%);
  - **3** $t_3=t_2$+133=193s : electrical power is expected to have reached the new set point (598 MWe);
  - **4** $t_4=t_3$+15*60=1093s : after 15 minutes of over-power, the set point returns to its nominal value (559 MWe);
  - **5** $t_5=t_4$+133+20*60=2426s : after 20 minutes at nominal power the calculation is stopped.

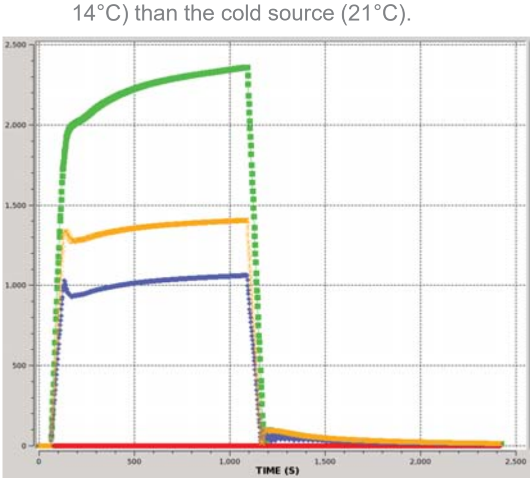


- During the calculation we are interested in:
  - the amount of cold water from the storage required to complete the transient;
  - the dynamics of the electrical power increase;
  - the impact on the primary circuit.

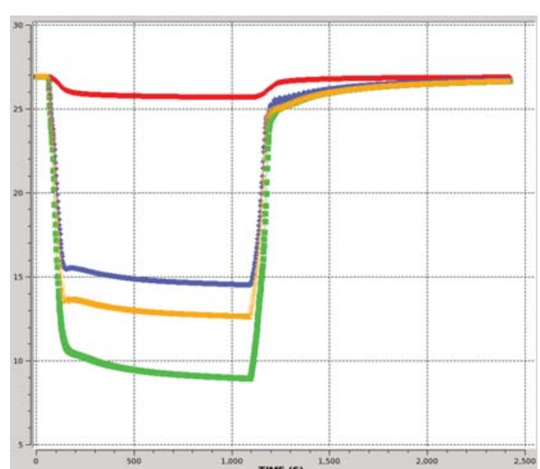
RESULTS (1/4)

- Four interfaces between the Brayton cycle and the cold storage are compared:
  - Green curves : only precooler_2 is used with water from the storage;
  - Red curves : only intercooler_2 is used with water from the storage;
  - Blue curves : both precooler_2 and intercooler_2 are used with water from the storage;
  - Orange curves : precooler_2 is used with water from the storage and intercooler_2 with water that exits precooler_2 as it is colder (about 14°C) than the cold source (21°C).





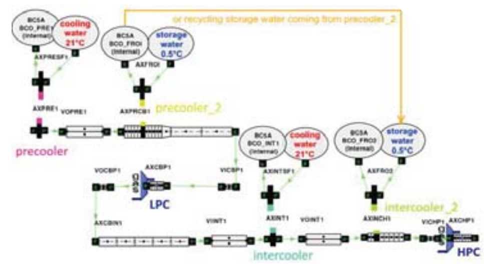
Cold water flowrate in precooler_2

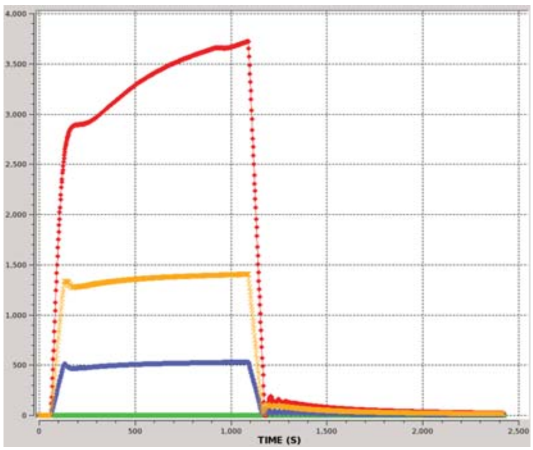


Nitrogen temperature at LPC inlet

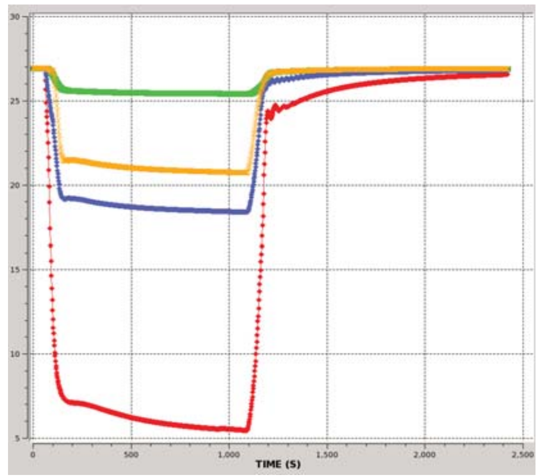
RESULTS (2/4)

- Four interfaces between the Brayton cycle and the cold storage are compared:
  - Green curves : only precooler_2 is used with water from the storage;
  - Red curves : only intercooler_2 is used with water from the storage;
  - Blue curves : both precooler_2 and intercooler_2 are used with water from the storage;
  - Orange curves : precooler_2 is used with water from the storage and intercooler_2 with water that exits precooler_2 as it is colder (about 14°C) than the cold source (21°C).





Cold water flowrate in intercooler_2



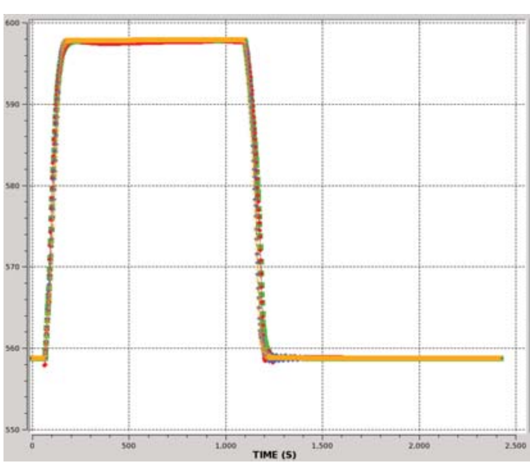
Nitrogen temperature at HPC inlet

RESULTS (3/4)

- In all cases, the electrical power step respects the criteria of the secondary reserve:
  - +7% of electrical power reached in 133 seconds;
  - maintaining overpower for 15 minutes.

- About 1500 m³ of cold water at 0.5°C are needed in the storage to achieve this transient. The use of water with glycol or salt or ice-based storage could be considered to reduce the storage size which is already reasonable.

- The efficiency of the system calculated by CATHARE is about 3: 120 MW of cold are needed to increase the electrical power by 40 MWe



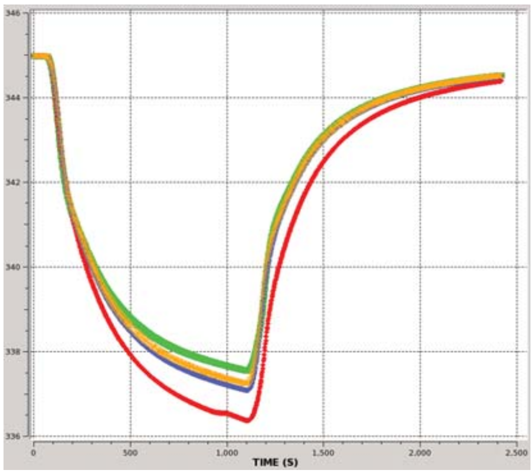
Electrical power delivered by the alternator

Cycle/storage interface	Total amount of cold water (in m³)
Only precooler_2	2403
Only intercooler_2	3557
Precooler_2 + Intercooler_2	1656
Precooler_2 + Intercooler_2 (with recycled water)	1462

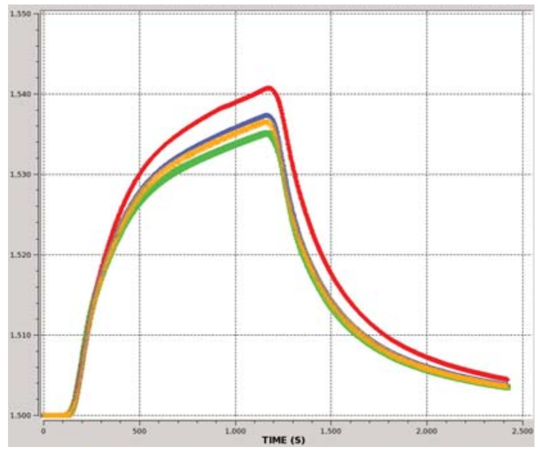
Olympic-size swimming pool contains about 3000 m³ of water

RESULTS (4/4)

- The impact on primary circuit (which evolves in a natural way) is limited to variations of the order of %
- The decrease in the nitrogen temperatures induces a slight decrease in sodium temperatures in the primary and secondary circuits, which causes an increase in core power (reactivity feedback effect)
- It would be interesting to repeat these calculations with the controllers of the primary and secondary circuits to assess the impact on the dynamics and on the cold water requirement



Sodium temperature at SGHE outlet



Core power (MW)

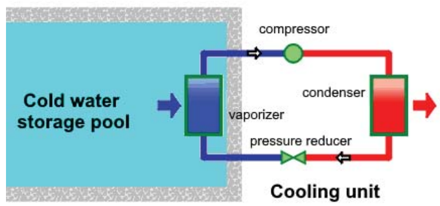
ENERGY BALANCE
AND
RECHARGING STRATEGIES

SCENARIO

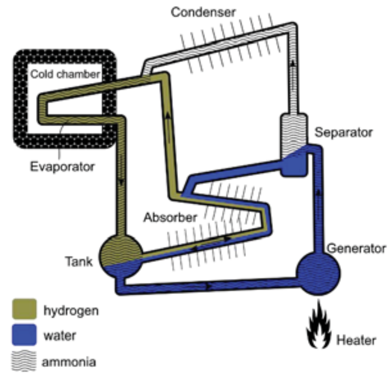
- The cold storage can be restored in two ways:
  - Intermittently during base load operation (implies operating in load-following mode) → - storage size + efficiency
  - Continuously during nominal load operation → + storage size - efficiency

- Energy balance of the cooling system over 1 hour is made:
  - Cold thermal energy used for frequency control (system efficiency is taken to 4 → 4 MW to produce 1 MWe);
  - Cold thermal energy produced by the cooling unit (efficiency is taken to 2.5 → 1 MWe to produce 2.5 MW);
  - Heat losses are estimated at 30% of the cold thermal energy used.

- Note that an absorption refrigerator could use the waste heat from the coolers (466 MW at 90°C) to provide the energy needed to drive the cooling process.



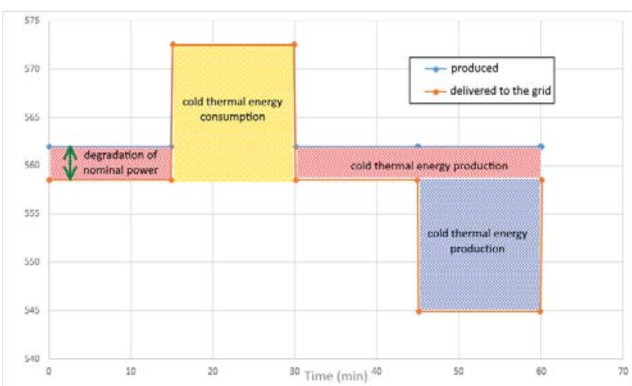
Principle of vapor-compression refrigeration



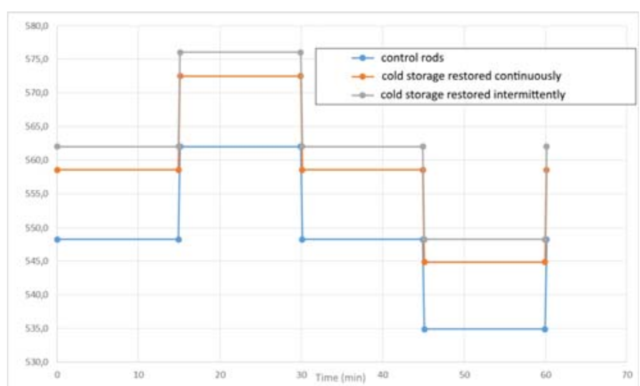
Principle of the absorption refrigerator

- During this hour of study we considered:
  - For primary control a +2.5% call and a -2.5% call for electrical power of 15 min each once an hour;
  - For secondary control a +4.5% call (in addition to a primary call) and a -4.5% call of 15 min each once a week i.e. 5.4 sec per hour.

RESULTS (1/2): CONSIDERING ONLY THE PRIMARY RESERVE



1-hour plan of the electrical powers produced by the alternator and delivered to the grid with continuous recharging option

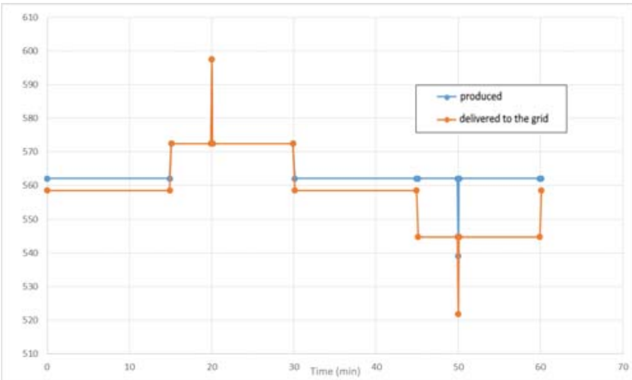


1-hour plan of the electrical powers delivered to the grid: comparison of the 3 options

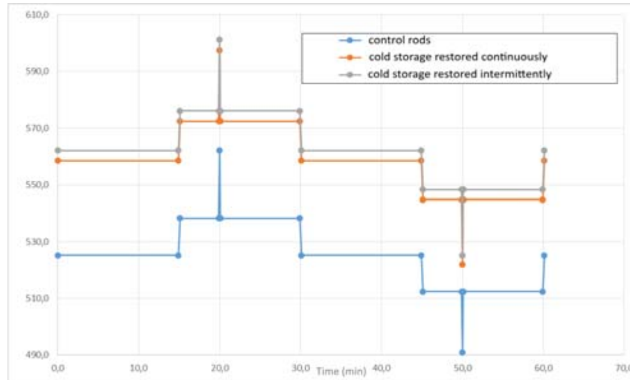
Option for frequency control	Nominal electrical power delivered to the grid (MWe)	Nominal gross reactor efficiency (%)
Control rods	548.3	36.55
Cold storage restored continuously	558.5	37.23
Cold storage restored intermittently	562	37.47

RESULTS (2/2): CONSIDERING ALSO THE SECONDARY RESERVE

- Insignificant for the cold storage solution because the amount of cold energy used by the secondary reserve is very low compared to the primary reserve due to the low occurrence of secondary power demands. However, this severely degrades the nominal power control rods solution for frequency control



1-hour plan of the electrical powers produced by the alternator and delivered to the grid with continuous recharging option



1-hour plan of the electrical powers delivered to the grid: comparison of the 3 options

Option for frequency control	Nominal electrical power delivered to the grid (MWe)	Nominal gross reactor efficiency (%)
Control rods	525.2 (548.3)	35.01 (36.55)
Cold storage restored continuously	558.4 (558.5)	37.23 (idem)
Cold storage restored intermittently	562 (idem)	37.47 (idem)

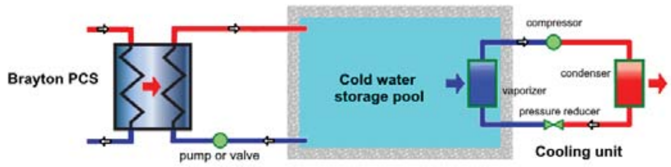
Considering a capacity factor of 80%, the same 600 MWe reactor produces 233 GWe.h more per year

CONCLUSION

CONCLUSION

- This quantitative study follows a more qualitative study on the processes that can be used for frequency control (nitrogen inventory, bypass, thermal or mechanical storages). Cold storage seemed to be the most promising option from an energy, technological maturity and size point of view.

- The architecture with dedicated coolers added in the Brayton cycle and recycled water is promising:
  - half of an olympic-size swimming pool (1500 m^3) of cold water (0.5 °C) is enough to perform a step from 559 MWe to 598 MWe (+7%) during 15 minutes (secondary reserve);
  - the regulatory dynamics of primary and secondary control are respected;
  - even with continuous recharging of the cold storage, the nominal electricity production is slightly degraded.



- Some items will require further studies:
  - the design, the cost and the pressure drop of the dedicated coolers;
  - the fast start and the consumption of the pump for cold water supply;
  - a two-part storage: cold at the top and “hot” at the bottom allowing a gravitational circulation of the water;
  - the feasibility of using Brayton coolers as an heat source for an absorption refrigerator cycle;
  - the impact of the primary and secondary circuits controllers on the system dynamics and efficiency;
  - the use of water with glycol or salt or ice-based storage to achieve lower temperatures;
  - A detailed economic analysis.

REFERENCES

1. *G. Laffont et al., “ASTRID power conversion system based on steam and gas options,” Proceedings of 2013 International Congress on Advances in Nuclear Power Plants (ICAPP-13), Jeju Island, Korea, April 14–18, 2013.*
2. *F. Bertrand, G. Mauger, M. Bensalah, P. Gauthé, Transient behavior of ASTRID with a gas power conversion system, Nuclear Engineering and Design, Volume 308, 20-29, 2016.*
3. *G. Mauger & N. Tauveron, « CONVERTISSEUR, CENTRALE NUCLEAIRE ET PROCEDE ASSOCIES », Demande de brevet français n°16 62263, V/REF : BD 17376, N/REF : S60688 FR HA-P, 2016.*
4. *G. Mauger, « Etude d’un système de froid pour le réglage de fréquence d’ASTRID équipé d’un SCE à gaz », CEA Technical Memo DEN/DANS/DM2S/STMF/LMES/NT/17-019/A, 2017.*
5. *INPI, Bulletin officiel de la propriété industrielle, Brevets d’invention, n°18/24, June 15, 2018.*
6. P. Emonot & al., “CATHARE-3: a new system code for thermal-hydraulics in the context of the NEPTUNE project,” Proceedings of the 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-13), Kanazawa City, Japan, September 27–October 2 (2009).
7. *G. Geffraye & al., “CATHARE 2 V2.5_2 : a Single Version for Various Applications,” Proceedings of the 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-13), Kanazawa City, Japan, September 27–October 2 (2009).*
8. *D. Tenchine & al, “Status of CATHARE code for sodium cooled fast reactors,” Nuclear Engineering and Design, 245, pp. 140-152 (2012).*
9. *D. Tenchine, D. Pialla, Paul Gauthé, A. Vasile, “Natural convection test in Phenix reactor and associated CATHARE calculation,” Nuclear Engineering and Design, 253, pp. 23-31 (2012).*
10. *F. Bentivoglio & al., “Validation of the CATHARE 2 code against experimental from Brayton cycle plants,” Nuclear Engineering and Design, 238, pp. 3145-3159 (2008).*
11. *F. Bentivoglio & N. Tauveron, “Validation of the CATHARE 2 code against Oberhausen II data,” Nuclear Technology, Vol.164, October (2008).*
12. *O. Widlund & al., “Comparison of the thermal-fluid analysis codes CATHARE and FLOWNEX with experimental data from pebble bed micro model,” 4th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Cairo, Egypt (2005)*
13. *M. Polidori & al., “HE-FUS3 benchmark result,” FP7 GoFastR DEL D1.5-6 (2012).*
14. *G. Mauger, N. Tauveron, F. Bentivoglio, A. Ruby, “On the dynamic modeling of Brayton cycle power conversion systems with the CATHARE-3 code,” Energy, 168, pp 1002-1016, (2019).*

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Saclay | 91191 Gif-sur-Yvette Cedex
T. +33 (0)1 69 08 88 01

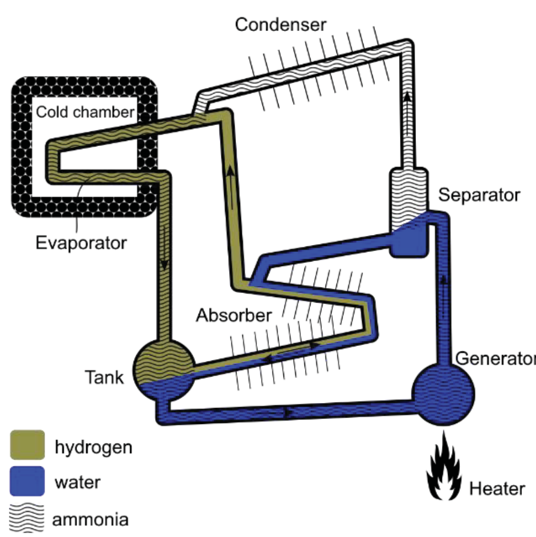
Etablissement public à caractère industriel et commercial

RCS Paris B 775 685 019

Direction de l'Energie Nucléaire
Direction déléguée aux Activités Nucléaires de Saclay
Département de Modélisation des Systèmes et Structures
Service de Thermo-hydraulique et de Mécanique des Fluides
Laboratoire de Modélisation et de simulation à l'Echelle Système

ABSORPTION REFRIGERATOR

- Principle:
  - The absorption phenomenon creates the low pressure of the cycle
  - The heater creates the high pressure of the cycle
- Cycle description:
  - Ammonia evaporates in the cold chamber, thus extracting heat from its surroundings, at low temperature thanks to a low partial pressure environment (due to hydrogen)
  - Gaseous ammonia is absorbed by the ammonia at low concentration, forming a concentrated ammonia solution
  - This solution is heated in a boiler: the ammonia evaporates, its pressure and temperature increase
  - The water solution is depleted and regenerates the ammonia at low concentration in the separator
  - Gaseous ammonia passes through the condenser, transferring its heat outside the system and condenses



Principle of the absorption refrigerator

High-Temperature Particle-Based CSP with Thermal Storage

Exceptional service in the national interest

Sandia National Laboratories

Clifford K. Ho
Concentrating Solar Technologies
Sandia National Laboratories
Albuquerque, New Mexico

SAND2019-8509 PE

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy | U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Overview

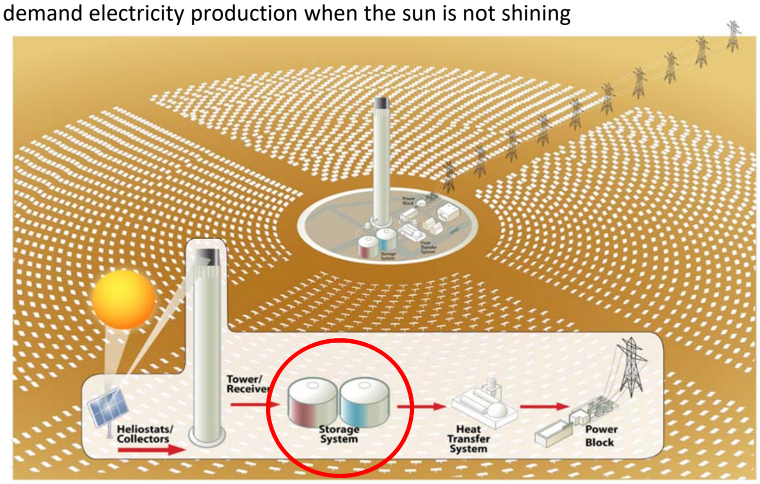
Sandia National Laboratories

- Introduction
- Particle-Based CSP
- High Temperature Particle Storage
- Conclusions

2

CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



3

DOE Gen 3 CSP Program

- Higher operating temperatures
  - Higher efficiency electricity production
    - Supercritical CO_2 Brayton Cycles (>700 ˚C)
    - Air Brayton Combined Cycles (>1000 ˚C)
  - Thermochemical storage & solar fuel production (>1000 ˚C)

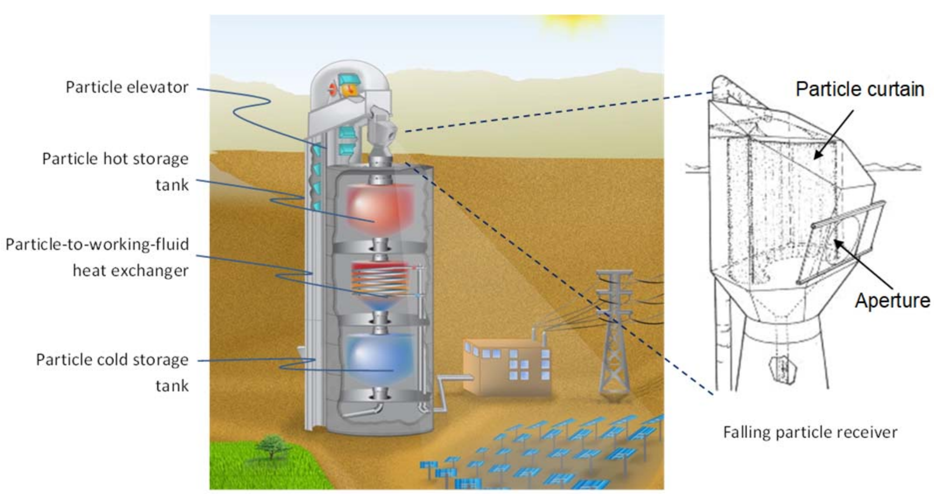
➡ Particle-based CSP systems with high-temperature storage

4

Overview

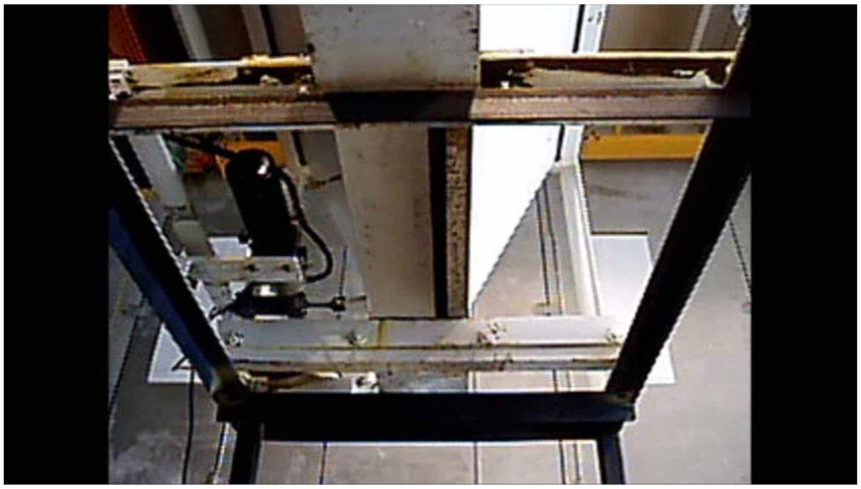
- Introduction
- Particle-Based CSP
- High Temperature Particle Storage
- Conclusions

High Temperature Falling Particle Receiver



Goal: Achieve higher temperatures, higher efficiencies, and lower costs

Particle Receiver Designs – Free Falling



7

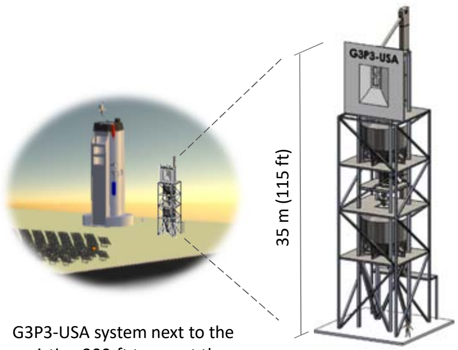
Value Proposition

- Proposed particle receiver system has significant advantages over current state-of-the-art CSP systems
  - Sub-zero to over ~1000 °C operating temperatures
  - No freezing and need for expensive trace heating
  - Use of inert, non-corrosive, inexpensive materials
  - Direct storage (no need for additional heat exchanger)
  - Direct heating of particles (no flux limitations on tubes; immediate temperature response)

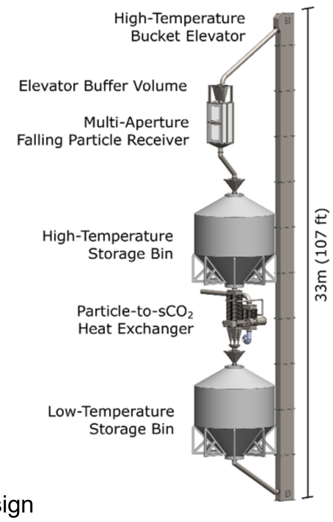
8

Gen 3 Particle Pilot Plant (G3P3)

Integrated System



G3P3-USA system next to the existing 200-ft tower at the National Solar Thermal Test Facility Sandia National Laboratories, Albuquerque, NM



Baseline Design

9

Overview

- Introduction
- Particle-Based CSP
- High Temperature Particle Storage
- Conclusions

10

Particle Storage Considerations

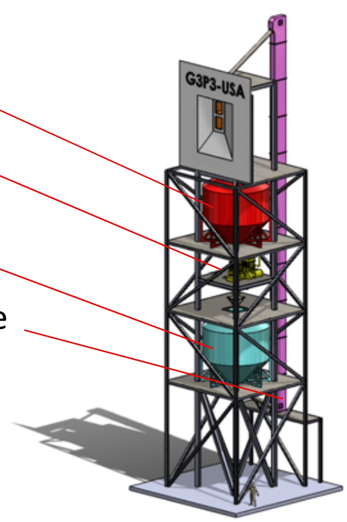
- Configuration
  - Two-tank vs. Single-tank thermocline
- Sizing and shape
  - Energy storage capacity
  - Shape: heat loss vs. stress
- Particle Materials
  - Engineered vs. natural materials
- Cost
  - Levelized cost of storage options

11

Configuration | Sizing and Shape | Particle materials | Cost

Two-Tank Particle Storage

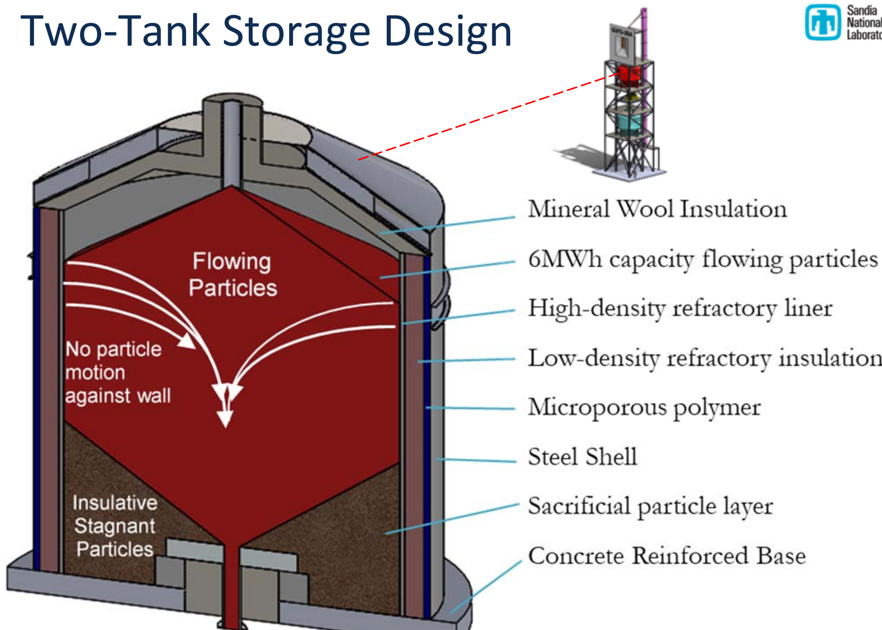
- Hot Particle Storage
- Particle Heat Exchanger
- Cold Particle Storage
- Particle Lift and Conveyance



12

Configuration | Sizing and Shape | Particle materials | Cost

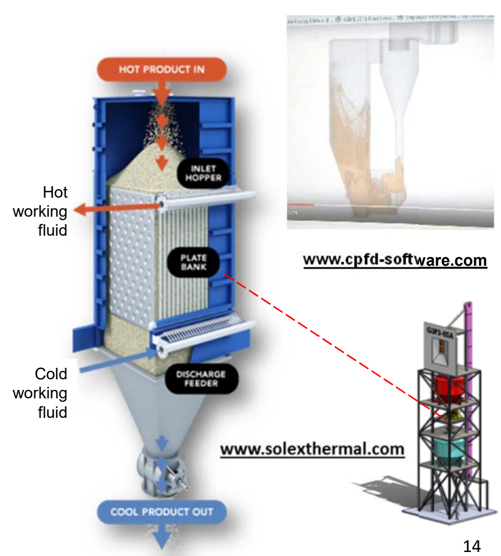
Two-Tank Storage Design



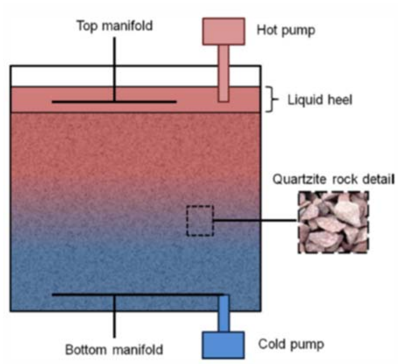
Particle Heat Exchanger

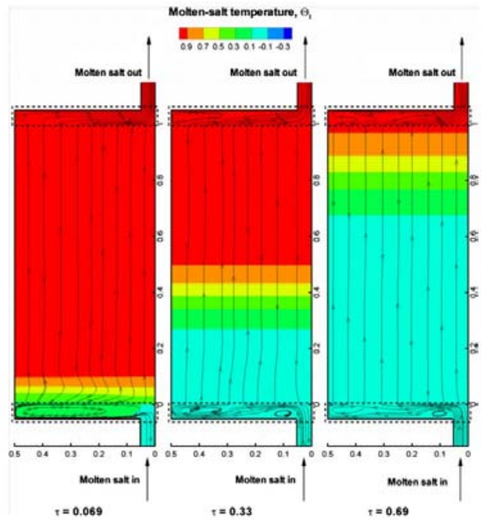
(for Two-Tank storage)

Type	Pros	Cons
Fluidized Bed	High heat-transfer coefficients	Energy and mass loss from fluidization
Moving packed bed	Gravity-fed particle flow; low erosion	Low particle-side heat transfer



Single-Tank Thermocline Storage





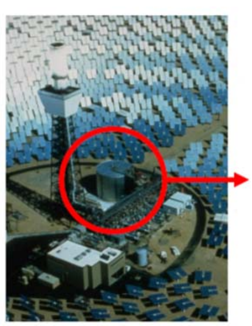
Fluekiger et al. (2013, 2014)

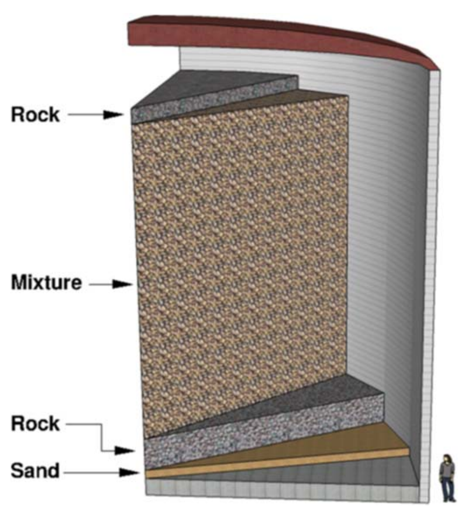
Issues:
- Thermal gradients
- Thermal ratcheting

Solar One Thermocline Test (1982-1986)

Faas et al., SAND86-8212

- 300 °C, 182 MWh_t, oil HTF, sand/gravel, 13 m tall, H/D=0.66

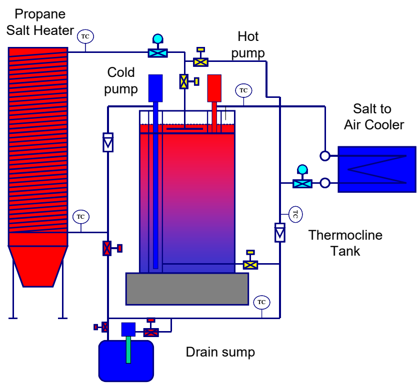




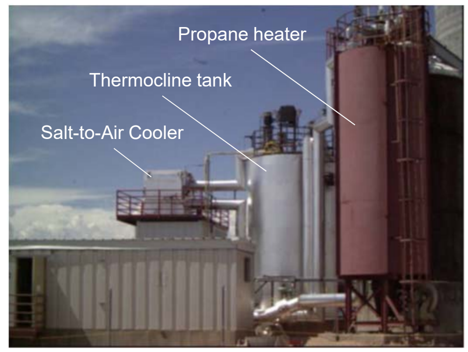
Fluekiger et al. (2012)

Sandia Thermocline Test (2001)

- 400 °C, 2.3 MWh_t, salt HTF, sand/gravel, 6.1 m tall, H/D = 2.0



Pacheco et al., JSEE, 2002



Brosseau et al., SAND2004-3207

Configuration Findings

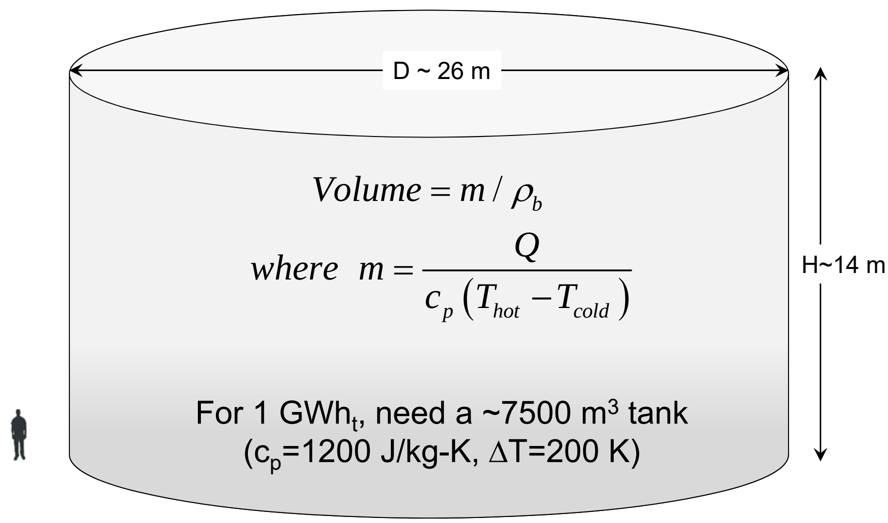
Thermocline Storage

- Heat-transfer fluid flows across a bed of particles for charging and discharging
- Single tank may reduce materials and cost by 30%
- Thermal ratcheting may cause tank damage
- Diffuse temperature profile reduces performance
- Quartzite rock and silica sand worked well with molten salt

Two-Tank Storage

- Particles are heated first and then stored in hot tank
- Requires particle conveyance to tanks and heat exchanger(s)
- Requires particle-to-working fluid heat exchanger
  - Gravity-driven moving packed bed
  - Fluidized bed

Tank Sizing



$$Volume = m / \rho_b$$

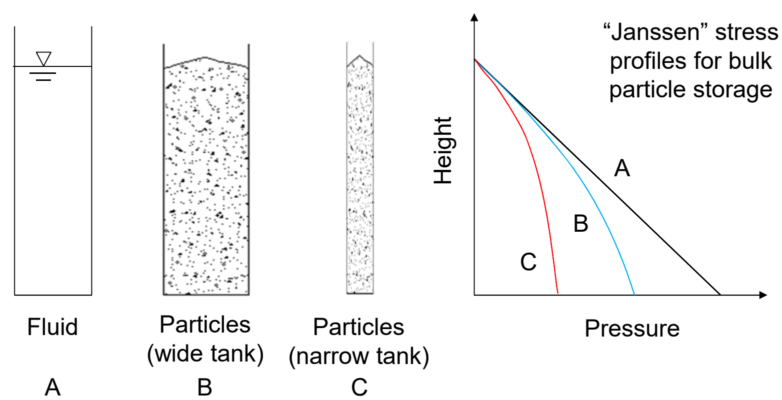
$$where \quad m = \frac{Q}{c_p \left(T_{hot} - T_{cold}\right)}$$

For 1 GWh_t, need a ~7500 m^3 tank
(c_p=1200 J/kg-K, ΔT=200 K)

19

Tank Shape

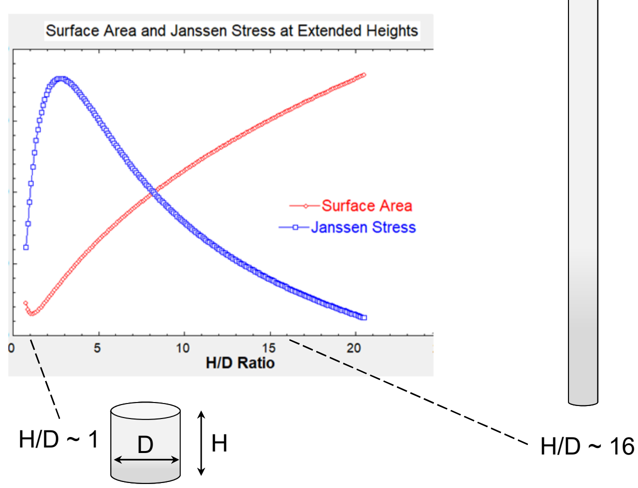
- Consideration of heat loss and wall stresses



20

Tank Shape

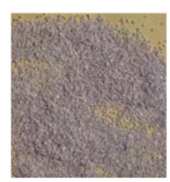
- Consideration of heat loss and wall stresses



Particle Materials

- Thermocline storage
  - High heat capacity
  - Low void fraction
  - Low cost
  - Brosseau et al. (SAND2004-3207)

Quartzite rock



Silica Sand

Siegel, Wiley, (2012)

Storage Medium	Specific Heat (kJ/kg-K)	Latent or Reaction Heat (kJ/kg)	Density (kg/m^3)	Temperature Range (°C) Cold	Hot	Gravimetric Storage Density (kJ/kg)	Volumetry Storage Density (MJ/m^3)	References
Sensible Energy Storage—Solids								
Concrete	0.9	–	2200	200	400	315	693	23
Sintered bauxite particles	1.1	–	2000	400	1000	385	770	24
NaCl	0.9	–	2160	200	500	315	680	23
Cast iron	0.6	–	7200	200	400	210	1512	25
Cast steel	0.6	–	7800	200	700	210	1638	23
Silica fire bricks	1	–	1820	200	700	350	637	23
Magnesia fire bricks	1.2	–	3000	200	1200	420	1260	25
Graphite	1.9	–	1700	500	850	665	1131	26
Aluminum oxide	1.3	–	4000	200	700	455	1820	27
Slag	0.84	–	2700	200	700	294	794	28

Particle Materials

Cost of particle materials (delivered)

Pacheco et al., JSEE, Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants (2002)

Table 1 Cost of crushed rock, sand, and taconite delivered to Albuquerque, NM

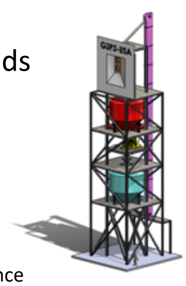
Rock	Cost Material, \$/tonne	Transport -ation, \$/tonne	Supplier
Limestone, ¾ inch crushed	41	7	Rocky Mountain Stone, Albuquerque, NM
Limestone, 1 inch crushed	15	6	LaFarge, Albuquerque, NM
Limestone, ½ inch crushed	17	6	LaFarge, Albuquerque, NM
Marble, ¾ inch crushed	120	7	Rocky Mountain Stone, Albuquerque, NM
Taconite, 1.2 cm pellets	66	44	Dale Paulson Geneva Steel, Provo, Utah
Quartzite, ¾ inch crushed	43	7	Rocky Mountain Stone, Albuquerque, NM
Silica Sand, 8 mesh	14	3	J.P.R Decorative Gravel, Albuquerque, NM
Filter Sand, 8x12	89	34	Colorado Silica Sand, Colorado Springs, CO
Filter Sand, 6x9	168	34	Colorado Silica Sand, Colorado Springs, CO
Filter Sand, 6x12	153	34	Colorado Silica Sand, Colorado Springs, CO

23

Configuration | Sizing and Shape | **Particle materials** | Cost

Particle Materials – Two-Tank CSP

- CARBO Ceramic Beads
  - Cost
    - \$1 - \$2/kg
  - Durability
    - Low wear/attrition
  - Optical properties
    - High solar absorptance
  - Good flowability
    - Spherical and round
  - Low inhalation hazard



24

Configuration | Sizing and Shape | **Particle materials** | Cost

Comparison of Energy Storage Options

Ho, Applied Thermal Engineering, 109 (2016)

	Energy Storage Technology					
	Solid Particles	Molten Nitrate Salt	Batteries	Pumped Hydro	Compressed Air	Flywheels
Levelized Cost[1] ($/MWh$_e$)	10 – 13	11 – 17	100 – 1,000	150 - 220	120 – 210	350 - 400
Round-trip efficiency[2]	>98% thermal storage ~40% thermal-to-electric	>98% thermal storage ~40% thermal-to-electric	60 – 90%	65 – 80%	40 – 70%	80 – 90%
Cycle life[3]	>10,000	>10,000	1000 – 5000	>10,000	>10,000	>10,000
Toxicity/ environmental impacts	N/A	Reactive with piping materials	Heavy metals pose environmental and health concerns	Water evaporation/ consumption	Requires large underground caverns	N/A
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	< 600 °C (decomposes above ~600 °C)	Very expensive for utility-scale storage	Large amounts of water required	Unique geography required	Only provides seconds to minutes of storage

25

Overview

- Introduction
- Particle-Based CSP
- High Temperature Particle Storage
- Conclusions

26

Conclusions

- CSP investigating high-temperature particle storage
  - Ambient to ~1000 °C (no freezing)
  - Single-tank thermocline storage
    - Reduced material, potentially lower cost (30%), thermal ratcheting
  - Two-tank particle storage
    - Requires particle conveyance and heat exchanger
- Particle materials
  - Quartzite rock, silica sand for thermoclines
  - Sintered bauxite (ceramic particles) for CSP G3P3
- Hot particle storage
  - Economical long-duration storage option

27

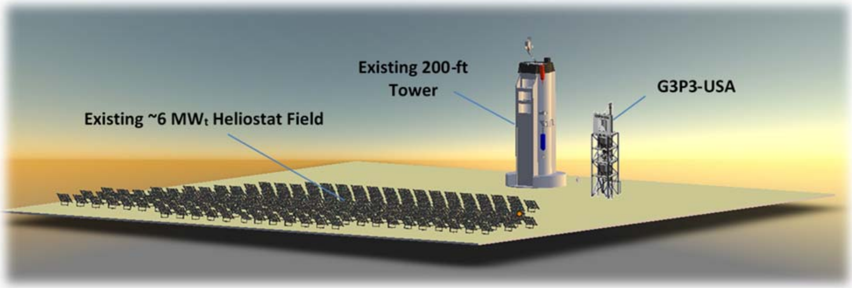
Acknowledgments

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

- This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211

28

Questions?



Cliff Ho, (505) 844-2384, ckho@sandia.gov

BACKUP SLIDES

Thermal Energy Storage Goals

- Capable of achieving high temperatures (> 700 C)
- High energy and exergetic efficiency (>95%)
- Large energy density (MJ/m^3)
- Low cost (<$15/$kWh_t$; <$0.06/kWh_e for entire CSP system)
- Durable (30 year lifetime)
- Ease of heat exchange with working fluid (h > 100 W/m^2-K)

Sintering Potential of Particles

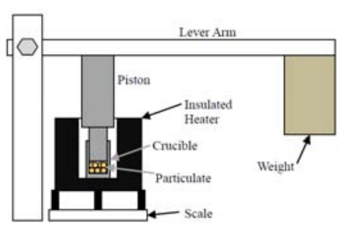


Figure 2. Diagram of Experimental Setup

Figure 3. Image of Experimental Setup

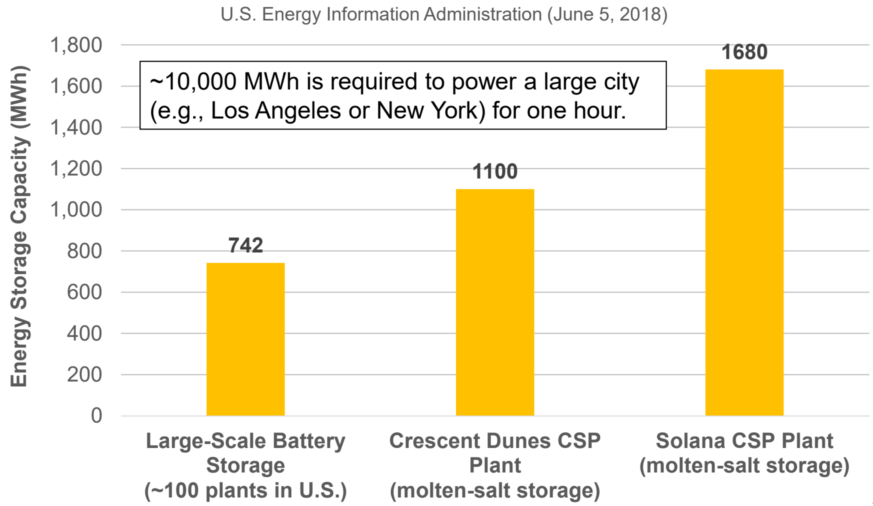
Table 1. Candidate Particulates

Particulate Name	Mineral	Melting Temperature (°C)
Green Diamond (70 x 140)	Olivine	1400 [5]
CARBO*ACCUCAST* ID50-K	Alumina	2000 [6]
Riyadh, Saudi Arabia White Sand	Silica Sand	1600 [7]
Preferred Sands of Arizona Fracking Sand	Silica Sand	1600 [7]
Atlanta Sand & Supply Co. Industrial Sand	Silica Sand	1600 [7]

Figure 4. Image of Experiment at 1000°C

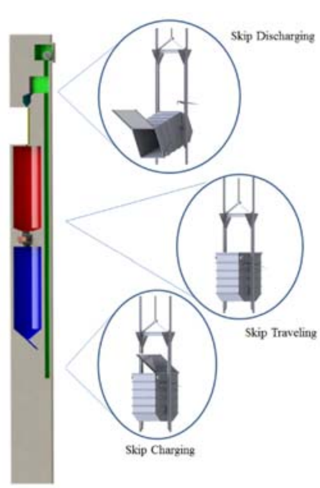
Al-Ansary et al., "Characterization and Sintering Potential of Solid Particles for Use in High Temperature Thermal Energy Storage System," SolarPACES 2013

Comparison of Large-Scale Battery and Thermal Energy Storage Capacity in the U.S.

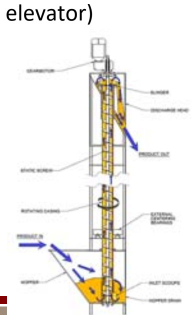


33

Particle Elevators



- Evaluate commercial particle lift designs
  - Requirements
    - ~10 – 30 kg/s per meter of particle curtain width
    - High operating temperature ~ 550 °C
  - Different lift strategies evaluated
    - Screw-type (Olds elevator)
    - Bucket
    - Mine hoist

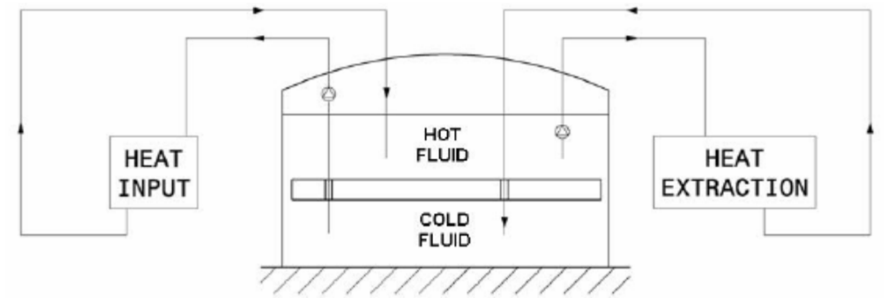


Repole, K.D. and S.M. Jeter, 2016, *Design and Analysis of a High Temperature Particulate Hoist for Proposed Particle Heating Concentrator Solar Power Systems*, in *ASME 2016 10th International Conference on Energy Sustainability, ES2016-59619*, Charlotte, NC, June 26 - 30, 2016.

34

Alternative Thermocline Design

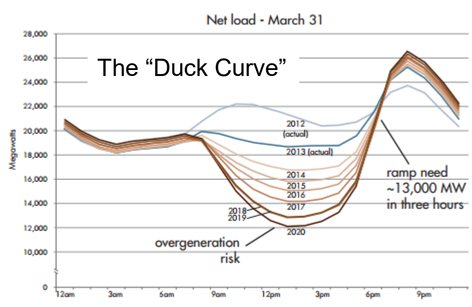
- Single-tank thermocline storage with no filler
  - Uses baffle to separate hot and cold fluids and prevent mixing



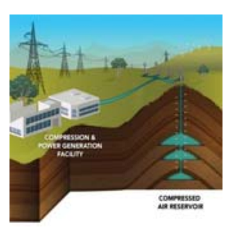
Lata and Blanco, SolarPACES 2010

Problem Statement

- Current renewable energy sources are intermittent
  - Causes curtailment or negative pricing during mid-day
  - Cannot meet peak demand, even at high penetration
- Available energy storage options for solar PV & wind
  - Large-scale battery storage is expensive
    - $0.20/kWh_e - $1.00/kWh_e
  - Compressed air and pumped hydro – geography and/or resource limited



Source: California Independent System Operator



Need

- Renewable energy technology with reliable, efficient, and inexpensive energy storage

→ Concentrating solar power (CSP) with thermal energy storage

37

Integrated Energy Systems (IES) at TerraPower

Heat Storage for Gen IV Reactors

July 23rd, 2019

Integrated Energy System (IES) – Synergies between thermal energy storage and TerraPower reactor technologies increase nuclear versatility

Storage allows 'de-coupling' of the reactor from power conversion applications and allows TerraPower to massively re-think how nuclear power is delivered

Approach:

Leverage decoupling by mating a reduced output (capital cost), simplified heat only reactor to a thermal storage system.

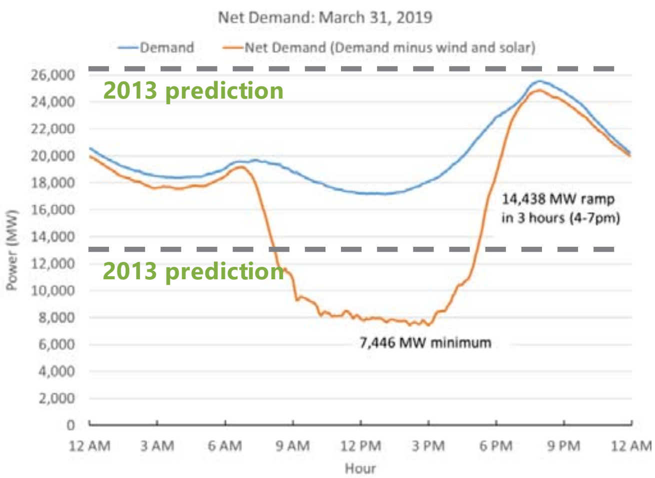
Storage system *load follows* electricity and industrial heat use applications, off-site.

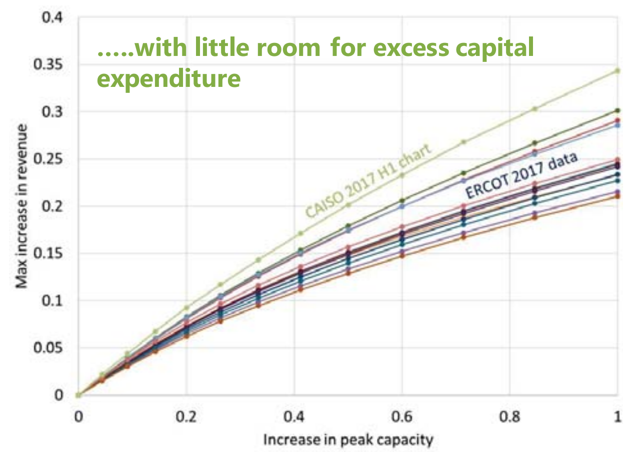
IES allows for a simplified Nuclear Plant suitable for diverse applications

With our Integrated Energy System architecture:

- Reduces reactor and total system costs
- Enables flexible electric demand (load) following and "profit following"
- Provides very high temperature industrial process heat at gas competitive costs, not possible with LWRs
- TerraPower Reactor safety enables coupled nuclear-industrial systems
- Improves effective efficiency and stability of renewables

Nuclear power will need to be more dynamic in highly renewable markets…





California can be considered a prototype of the future grid; currently has 22% of total generation from intermittent renewable energy; expected to reach 35% of total generation by 2030

TerraPower

Storge output (MW) and capacity (MWh) costs guide whether value is achievable in markets with a spread in energy pricing

- Salt storage returns from electricity arbitration are primarily driven by the capacity of storage (MWh) and arbitrage spread ($/MWh)
- Given the current cost curve and 7% WACC, attractive arbitration opportunities arise from
  - 5h spread exploitation at $50/MWh spread
  - 3h spread exploitation at $75/MWh spread
- This example does not take into account the additional capacity revenues which improve the economics

Geography	Future Capacity payment $ / MW / day
Japan	98
UK	55
USA (PJM)	98
Canada (Ontario)	98

IRR % impact of Energy Storage Wholesale Arbitrage[1]

Turbine and heat storage sizing (i.e. power to capacity ratio)

Turbine size / Tank size	Average spread of all arbitrage hours ($/MWh) $25/MWh	$50/MWh	$75/MWh	$100/MWh
1MW / 3 MWh	-%	4%	8%	11%
1MW / 4 MWh	0%	6%	10%	14%
1MW / 5 MWh	2%	7%	12%	17%
1MW / 6 MWh	3%	9%	14%	19%
1MW / 7 MWh	3%	10%	16%	21%
1MW / 8 MWh	4%	11%	17%	23%
1MW / 9 MWh	5%	12%	19%	25%
1MW / 10 MWh	5%	13%	20%	27%

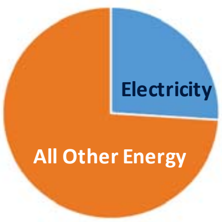
Note 1: When a WACC of 7% is considered then the area to the right and bottom of the red line is profitable architectures

TerraPower

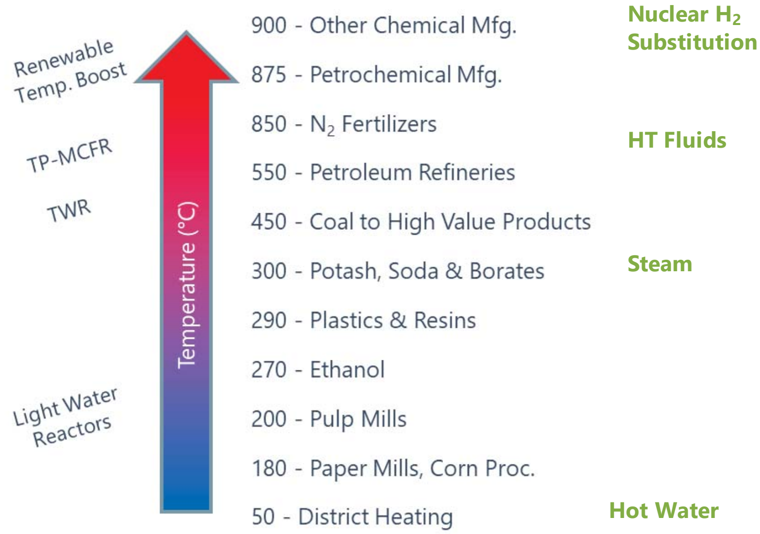
In order to reduce CO_2 emissions outside of electricity generation, nuclear needs to flexibly supply heat

World CO_2 Emissions
36,000,000,000 tons/yr

Can nuclear help reduce emission outside the electricity sector?



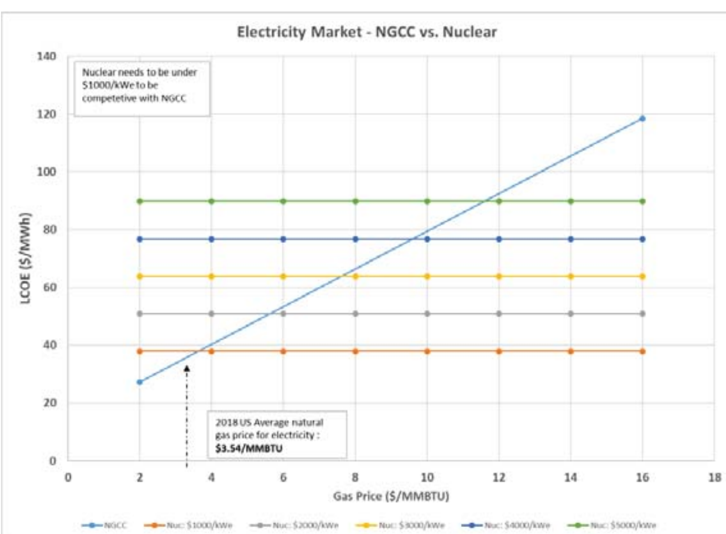
Non-electrical uses of energy are the World's largest source of CO_2

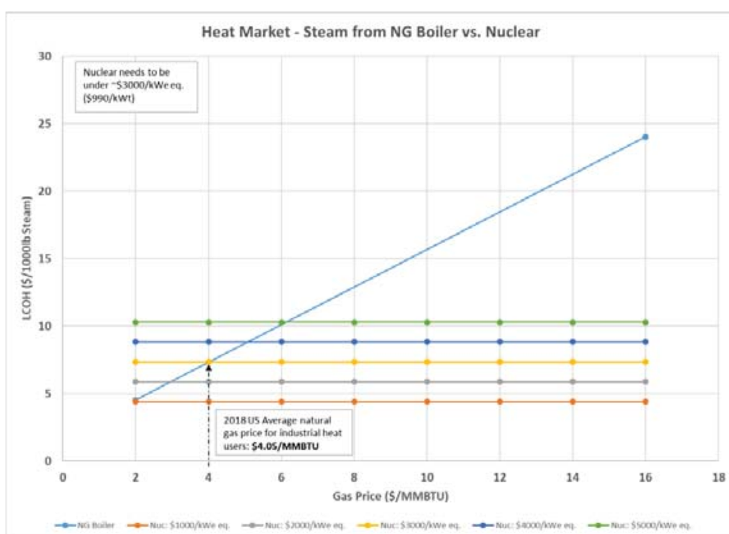


Source: Joint Institute For Strategic Energy Analysis, *Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions* (2016).

TerraPower

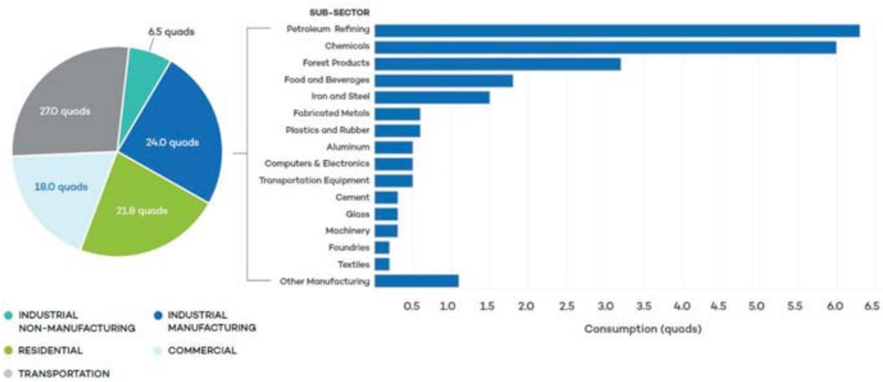
Nuclear is economically attractive as a heat supply





TerraPower

HT reactors can serve multiple heat markets and make a measured impact on CO_2 reduction



Industrial manufacturing consumes a considerate amount of energy, much of which is driven by petroleum refining chemicals, and forest products sub-sectors.

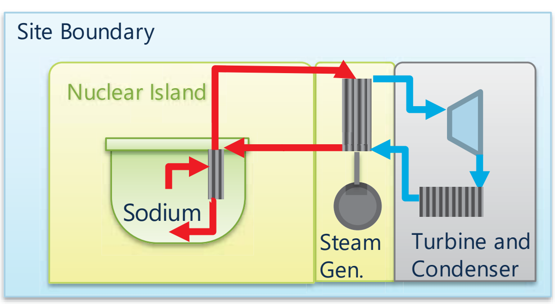
Source: Energy Futures Initiative (EFI), 2017; compiled using data from U.S. Department of Energy, 2015

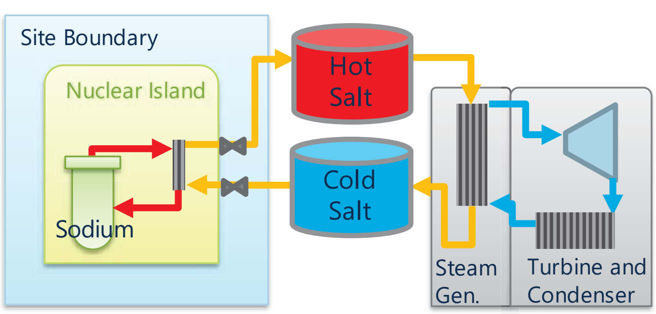
Market/Sector	Energy Needed/Consumed	Total US CO_2 Reduction Potential (10^6 tons/yr)	Process Temps
Electrical Power Peaking	US Total: 165TWh/yr	~100	NA
Pulp/Paper Mills	200MWt per plant	65	Up to 280°C
Plastics Production/Resins	300MWt per facility	15	300°C
Oil Refining	100-1000MWt per refinery	120	Up to 550°C
Ethylene Cracking	250-500MWt per cracking unit	16	750-850°C
Steam Methane Reforming	25-100 million scft/day	60	800-900°C
Hydrogen Production (from H_2O) Refining Ammonia Steel Making	Total: 45GWt 15GWt 35GWt	 17 18 20	300-850°C

LCOH dictated by NG costs

Market	LCOH estimate ($/MWh) Low Grade	High Grade
South Korea	61.17	69.81
France	56.06	65.95
Japan	52.48	62.37
Czech Republic	43.56	52.20
US Northeast	40.36	49.62
Brazil	38.60	47.24
United Kingdom	38.44	48.34
Poland	38.19	46.83
India	34.34	42.98
US West	33.23	42.50
South Africa	31.51	40.15
US Midwest	29.69	38.96
Australia	29.43	38.70
US South	23.00	32.27
Canada	15.32	24.59

TWR-IES offers advantages that can massively effect cost and regulatory scenarios





Traditional SFR
- Intermediate loop needed to avoid water/primary sodium interface
- Baseload power generation
- Pool is a more compact primary system with some safety and operability advantages

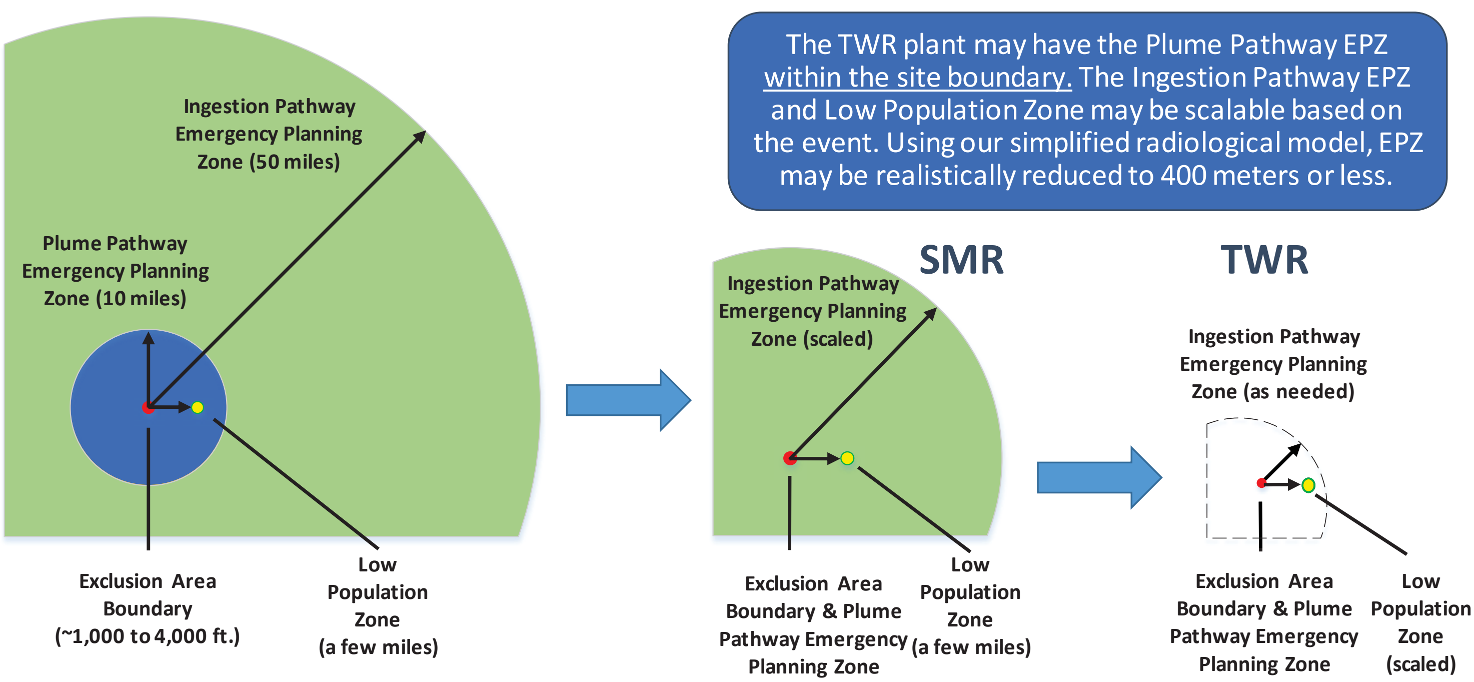
TWR-IES
- Minimizes nuclear island equipment and costs
- Avoids Na/Water interaction
- Applies recent developments in thermal energy storage to complement intermittent generation
- Loop type reactor prevents salt activation and retains safety advantages

Question: "Why has the nuclear-to-thermal storage architecture, with all of its attributes, never before been pursued?"

1. New motivations for nuclear have flexible generation capability (due to increased penetration of intermittent renewable energy)
2. Increased value in modern times to decarbonize beyond electricity generation
3. Commercially-ready, GWh-scale thermal storage has only come about in the last ~10 years
4. TerraPower reactor safety enables the "decoupled" architecture where thermal storage and BoP systems are located outside the nuclear site boundary
   - Low pressure, substantial primary coolant substantially sub-cooled, passive long-term decay heat removal
   - "At-the-fence" EPZ allows flexible siting and co-location of industrial end users
5. Architecture is a direct response to the recent cost trends and cost drivers for nuclear power

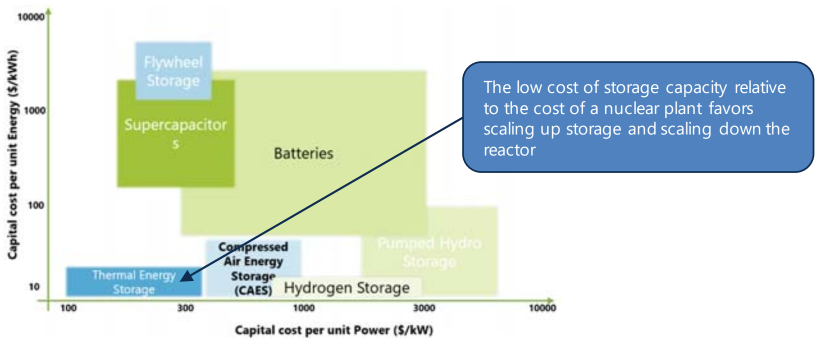
Scaling the TWR EPZ

Current LWR



GWh-scale thermal energy storage has been developed and is commercially ready

- Molten salt TES developed for solar power industry
- GWh-scale systems commercially demonstrated in the last ~10 years
- Relatively inexpensive compared to other forms of energy storage; order of magnitude (more) less expensive than today's battery technology
- Currently used "solar salt" is eutectic mixture of 60% $NaNO_3$ - 40% KNO_3 and allows heat to be stored in temperature range of ~250 to ~615 °C
- Very compatible with SFR temperatures (360-545 °C)



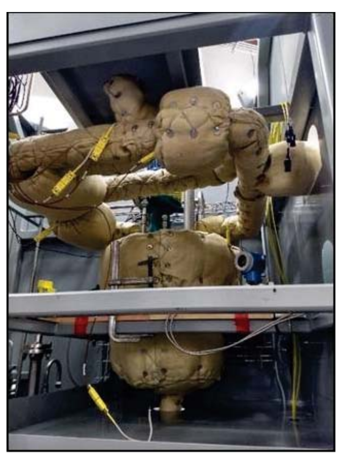

Solana Generating Station (2013, U.S., ~4200 MWht)


Cerro Dominador Project (*under construction*, Chile, ~4800 MWht)

TerraPower

Thermal Energy Storage overlaps heavily with TerraPower's technology development program

- The TWR program is developing liquid metal technologies applicable to TES heat transport and heat exchange
- The MCFR program will inherently develop molten salt technologies applicable to TES
  – NaKMg eutectic needed for intermediate loop also applicable to storage


600°C Salt Test Loop at TerraPower

"Energy storage allows the generator to control a plant's output, matching supply with demand and dispatching when electricity is most valuable" - SolarReserve


Crescent Dunes 566°C / 2.7 GWht

TerraPower

Conclusions

- IES provides the versatility nuclear power needs to integrate with intermittent renewables and be able to compete in a future, dynamic energy infrastructure
- Opportunity exists for nuclear to impact CO_2 emission from non-conventional customers (go beyond electricity)
- IES Architecture reduces the reactor to its simplest form; opens up new possibilities for cost and risk reduction
- A TWR-IES demonstration can be supported with today's reactor and storage technologies
- We will be "breaking the mold" for deployment of advanced nuclear reactors. While breaking that mold, currently formed around conventional LWRs, we have an opportunity to reshape the system architecture in a way that makes sense in today's energy landscape and that of the future.

TerraPower

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Molten Chloride Salts for Thermal Energy Storage

Heat Storage for Gen IV Reactors for Variable Electrify from Base-Load Reactors
Idaho Falls, ID
July 23-24, 2019

Craig Turchi, PhD
Thermal Sciences Group
National Renewable Energy Laboratory
craig.turchi@nrel.gov


Crescent Dunes Solar Energy Facility, USA

CSP Gen3 Molten Salts

- Higher thermal stability
- Lower cost


SolarReserve Crescent Dunes Molten-salt HTF plant (USA)

CSP Recent Salt History

- Halotechnics (2009): Combinatorial screening of chloride salts
- 2012 MURI "High Operating Temperature Fluids" (5 years, $5M)
  - UCLA (metals): Selected Lead-Bismuth eutectic
  - University of Arizona (salts): Selected NaCl-KCl-$ZnCl_2$ eutectic
- Gen3 Roadmap (NREL/TP-5500-67464, 2017) Conclusions:

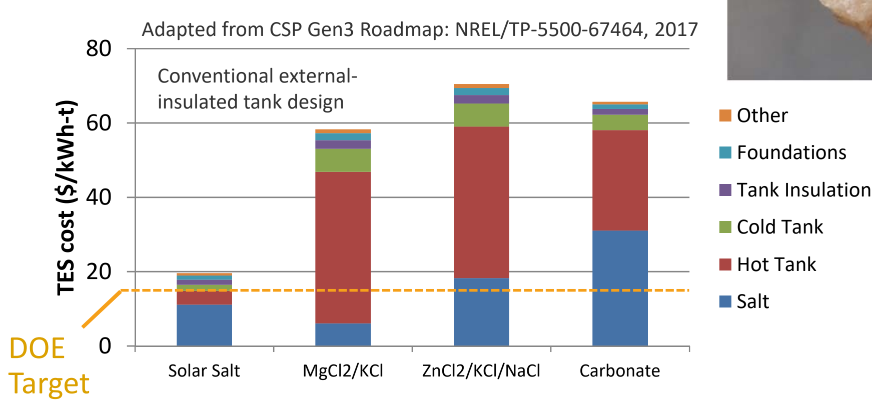
Salt	Composition by wt.	Melting Point (°C)	Heat Capacity (J/g-K)	Density (kg/L)	FOB Cost ($/kg)	Cost* ($/kWh$_t$)
$NaNO_3/KNO_3$ (SolarSalt)	0.60/0.40	220	1.5	1.7	0.8	10
$ZnCl_2$/NaCl/KCl	0.686/0.075/0.239	204	0.81	2.4	0.8	18
$MgCl_2$/KCl	0.375/0.625	426	1.15	1.66	0.4	5
$Na_2CO_3/K_2CO_3/Li_2CO_3$	0.334/0.345/0.321	398	1.61	2.0	2.5	28

* DOE cost goal is < $15/kWh$_t$

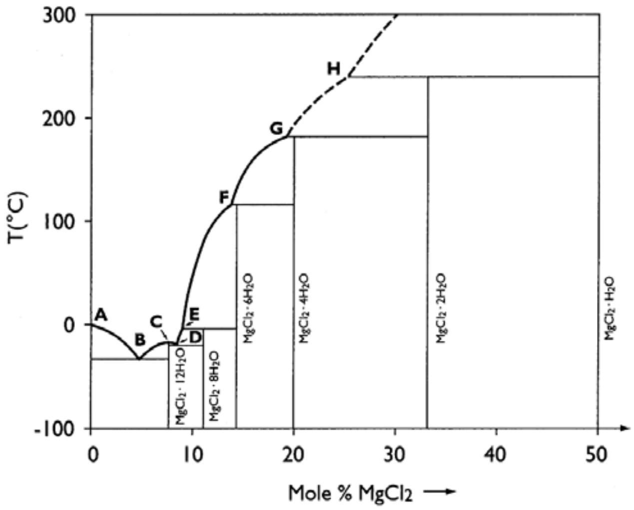
Gen3 CSP with Molten Chloride Salts

Primary Challenges

1) Corrosion control
2) Containment cost



Purification Protocol for $MgCl_2$ Salt Hydrates



G. Kipouros and D. Sadoway (2001)

Thermal purification

- Step-wise dehydration at 117°C, 180°C, 240°C, and 400°C
- Hydrolysis of $MgCl_2$ releases H_2O to form MgOHCl and HCl(g)

Chemical purification

- Reduction of MgOHCl and impurity cations by elemental Mg

Reactions during Purification

- Dehydration and hydrolysis at 117°–400°C

$$MgCl_2 \cdot xH_2O \rightarrow MgOHCl + HCl(g)$$

- Thermal decomposition of MgOHCl above ~550°C

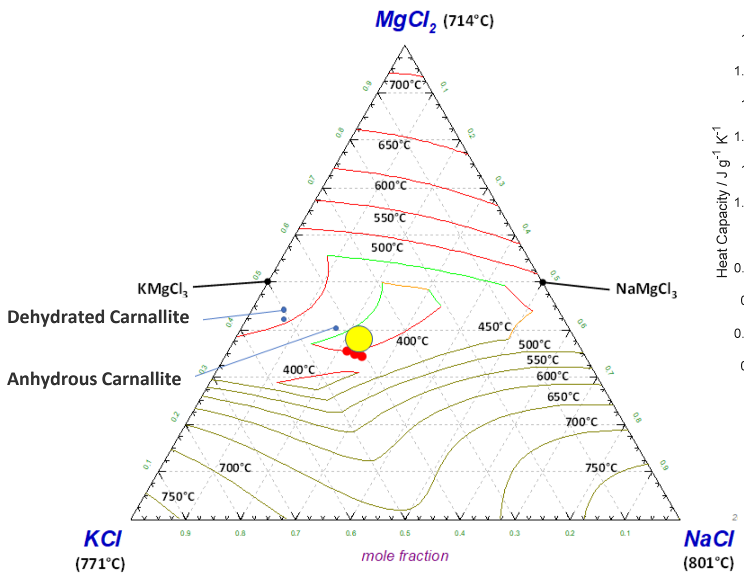
$$MgOHCl = MgO + HCl(g)$$

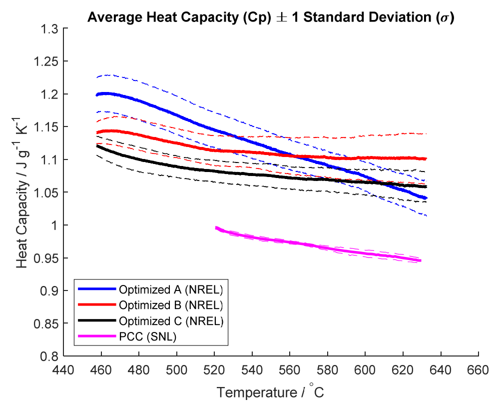
- Recovery of $MgCl_2$ during chemical purification at ~650°–800°C

$$MgOHCl + \frac{1}{2}Mg = MgO + \frac{1}{2}MgCl_2 + \frac{1}{2}H_2\text{(g)}$$

- MgOHCl is the major undesired species
  - Its formation by hydrolysis produces HCl(g): corrosion problem
  - Its thermal decomposition produces HCl(g): corrosion problem
  - Its thermal decomposition produces MgO (largely insoluble/non-recoverable): erosion problem

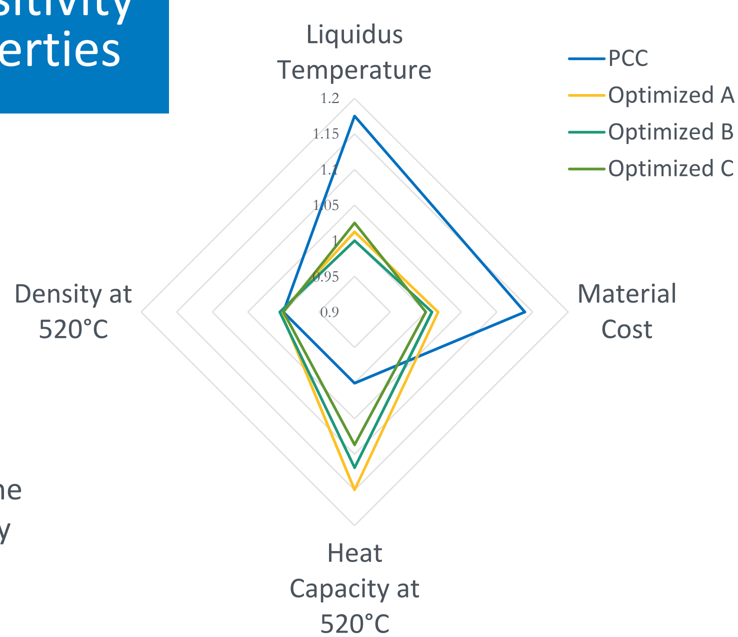
Optimizing Chloride-Salt Formulation





Phase diagram of Na/K/Mg–Chloride modeled with FactSage [Mohan et al., Energy Conversion and Management 167 (2018).

Performance Sensitivity to Different Properties



All values are normalized to the ***lowest*** value of each category

Industrial Experience: Salt Handling

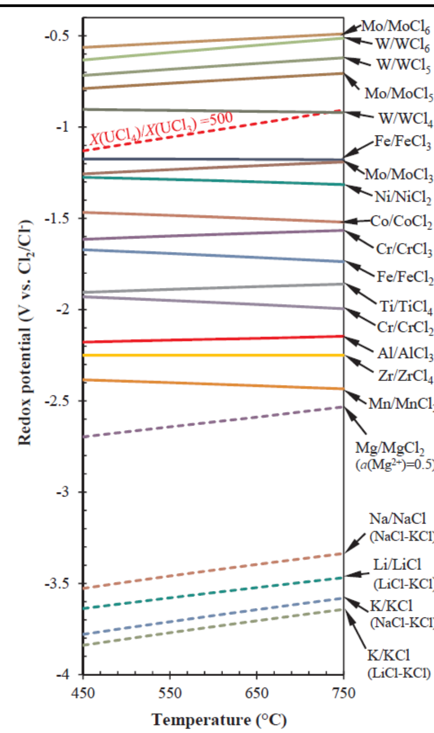
ICL DSM Dead Sea Magnesium Ltd

ICL/DSM Handling Molten Chlorides for Magnesium Production:

- 260,000 tons per year of carnallite ($MgCl_2$/KCl) is dehydrated, melted, and mixed with NaCl as feedstock for Mg production
- This molten salt, and the melting/ purification technology, is being applied for the Gen3 project
- The salt melter and electrolytic vats are lined with refractories, to protect the carbon steel vessels; carbon steel tank shells have been in use for over 20 years

Corrosion Protection

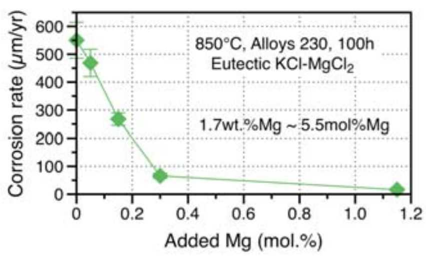
Mg^0 is used to protect other metals (e.g., Fe, Cr, Ni) within containment alloys against oxidation and extraction as mobile chlorides.



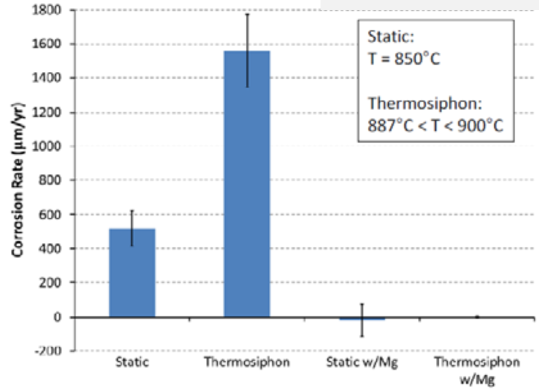
Redox potentials of various redox couples as a function of temperature in chloride salts.
Solid line: metal dissolution at aMn+ of 10−6
Dotted line: reduction of oxidants.
Guo et al., Progress in Materials Science, **97** (2018).

Corrosion Protection

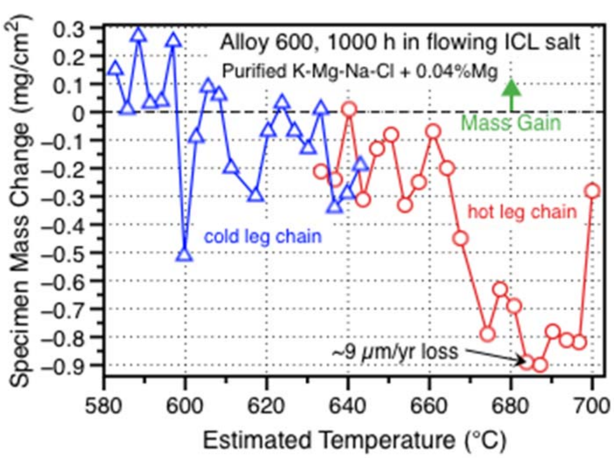
- Above 650 °C Mg metal in the melt acts as an oxygen getter and redox control to protect against corrosion
- Testing at Savannah River and Oak Ridge National Labs



Corrosion of Haynes 230 in chloride melt SRNL-STI-2019-00017



1000 h flowing salt experiment showed low attack (2018)



- 2.4 cm/s flow rate
  - Calculated from hot spot test
- Low mass changes observed
  - 1000 h operation
  - 20 specimens in hot and cold legs
- Near classic behavior apparent
  - Mass loss in hot leg = dissolution
    - Higher solubility
  - Mass gain in cold leg = precipitation
    - Lower solubility

Highest mass loss < 9 µm/year metal loss (goal is < 15 µm/year)

Pint et al. "Reestablishing the paradigm for evaluating halide salt compatibility to study commercial chloride salts at 600°-800°C," Materials and Corrosion, (2019).

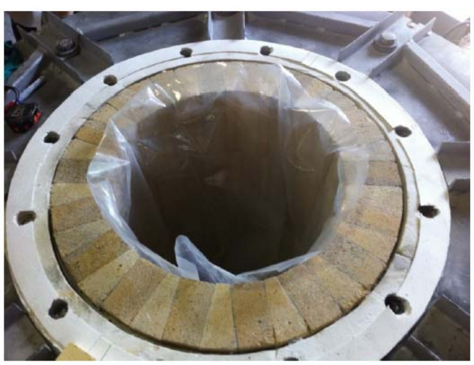
Chemical Sensors

Argonne National Lab's Multifunction Voltammetry Sensor

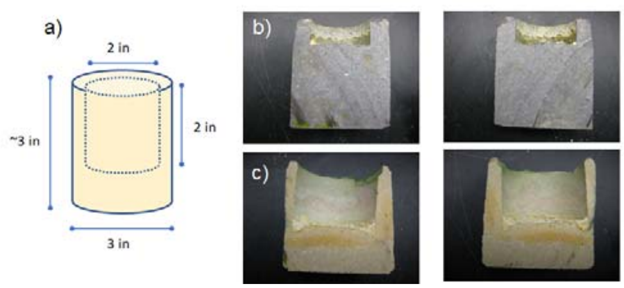
Measure concentration of:

- impurity species, e.g., MgOHCl,
- corrosion products, e.g., Cr^{2+} , Fe^{2+}, etc.,
- soluble Mg,
- as well as Salt Redox Potential
  - Measurements of salt potential indicate salt health and the propensity for corrosion of structural metals to occur

Tank Design Requires Internal Insulation



Refractory-lined, stainless-steel tank tested for use with chloride salts (Jonemann 2013).



Salt Tank Modeling

Equipment Geometry: Floor

Hydrogen Content: 0%

Equipment Hot Face Temperature = 1328 °F

Layer Number	Material	Index Number	Material Maximum Temp (°F)	Layer Thickness (in)	Thermal Conductivity (BTU-in/hr-ft²-F)	Hot Face Temperature (°F)	Mean Layer Temperature (°F)
1	Durrath HD 45	1818	2948	9	13.28	1328	1291.99
2	K-23	425	2400	6	1.37	1255.98	1015.45
3	WDS Flexipor	1802	2012	1	0.17	774.92	471.18

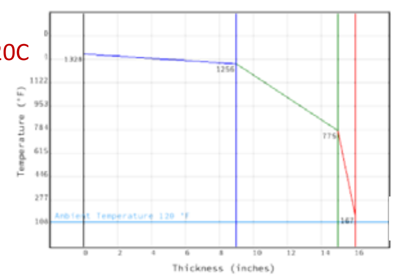
Equipment Cold Face Temperature = 167.43 °F

Equipment cold face emissivity: **0.85**
Cold face wind velocity: **0 mph**
Cold Face Convection Condition: **Natural**

Total Thickness: **16 inches**
Heat Flux (q): **102.52 BTU/hr-ft²**
Ambient Temperature: **120 °F**

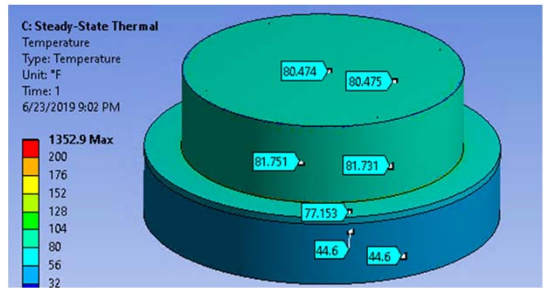
Temperature Profile

Hot salt at 720C



Steel tank wall at ~60C

16” thick, 3-layer refractory barrier required to insulate tank shell

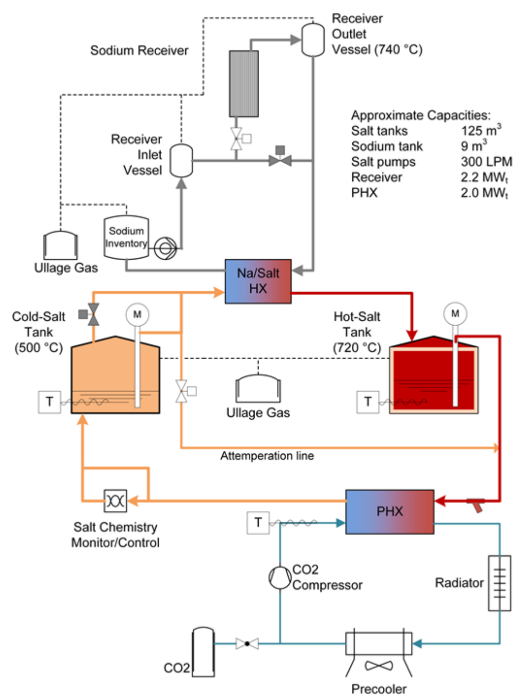


Tank wall and foundation modeling

The Case for Sodium

CSP considering the use of liquid sodium for the solar receiver:

- >100x higher thermal conductivity
- T_{mp} = 98 °C vs. 420 °C for salt
- Lower corrosivity



Integrated 2-MW_t System Test if Phase 3 funded

Phase 3 testing planned for Sandia's National Solar Thermal Test Facility

Key Risks to be Addressed:

1. Demonstrate effective salt chemistry and corrosion control
2. Fabricate cost-effective thermal storage tanks
3. Operate liquid-HTF receiver at 720°C
   - Confirm temperature and heat transfer rates
   - Demo startup, shutdown, and power ramping
   - Define guidelines for receiver operations
4. Validate pumps, valves, and piping
5. Validate primary HX performance
6. Perform component and system modeling and simulate full-scale performance

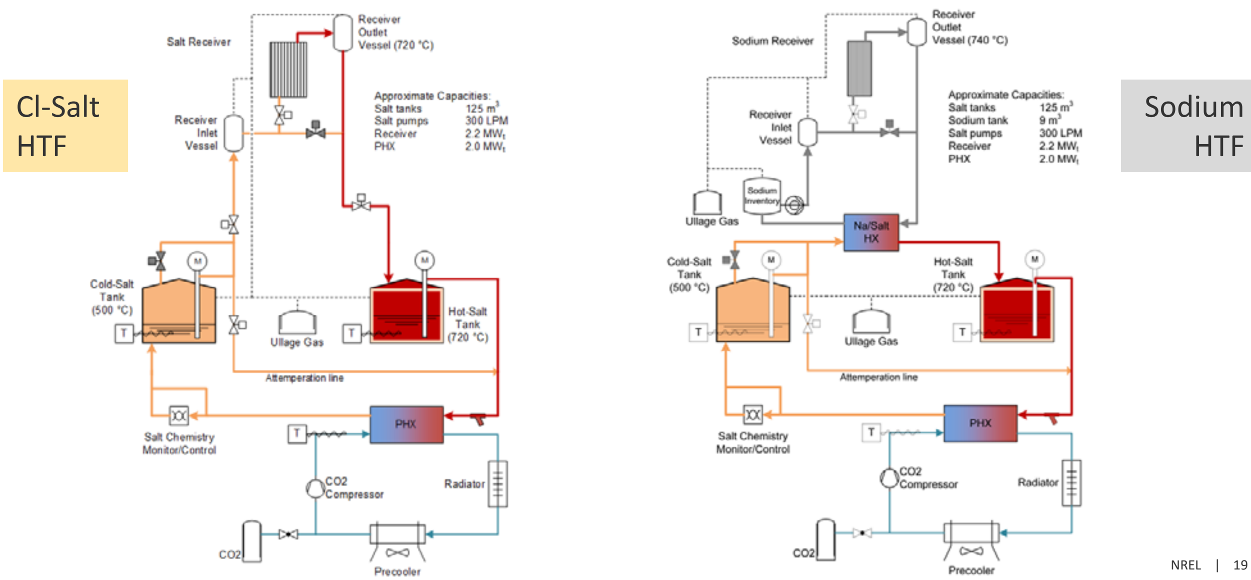
Thank you

www.nrel.gov

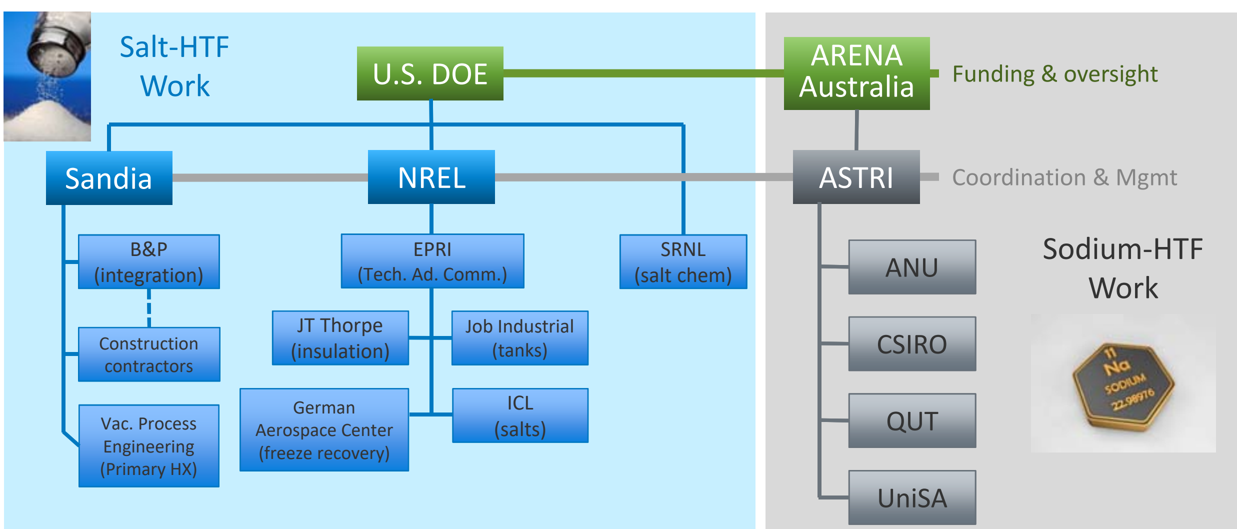
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Liquid-HTF Pilot System Alternatives

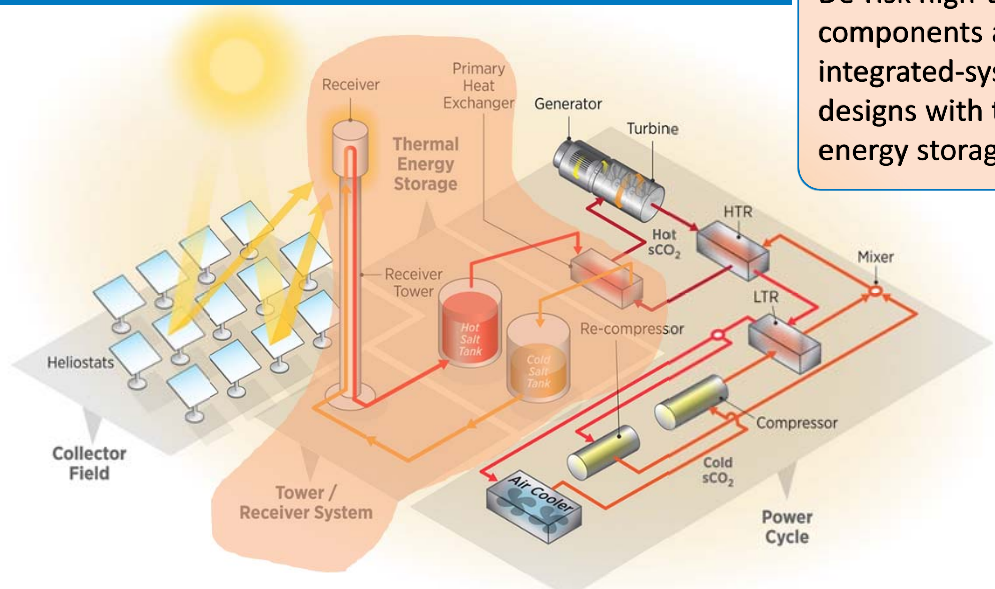


Liquid-Pathway Team



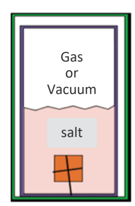
Gen3 Liquid Pathway Thermal Transfer System

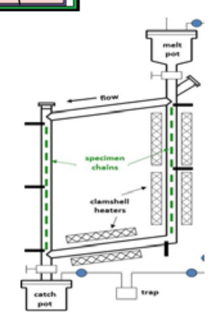
Goal:
De-risk high-temperature components and develop integrated-system designs with thermal energy storage at >700 °C



Assessing Compatibility -- ORNL

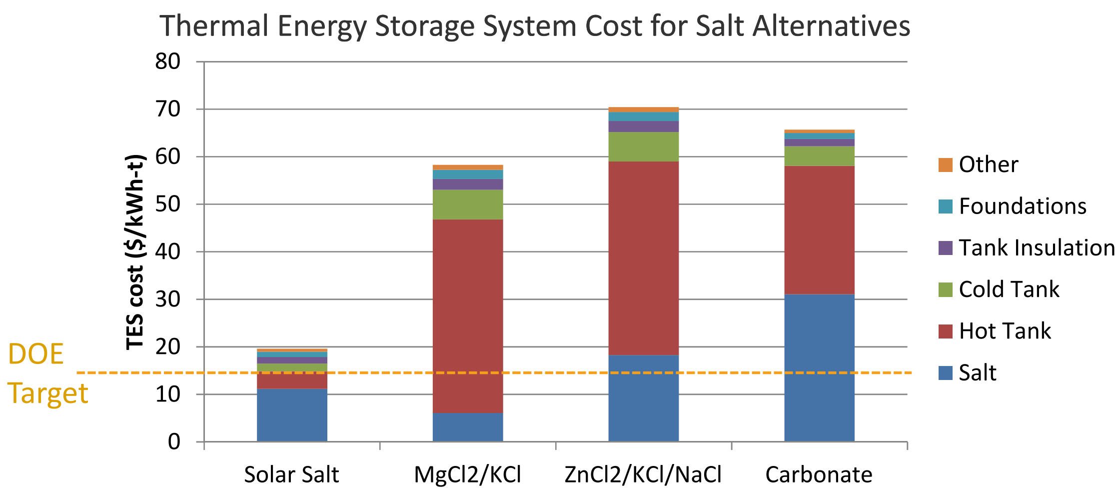
- Thermodynamics
  - First screening tool but data are not always available
- Capsule
  - Isothermal test, first experimental step
  - Prefer inert material and welded capsule to prevent impurity ingress
  - Dissolution rate changes with time: key ratio of liquid/metal surface
- Thermal convection loop (TCL)
  - Flowing liquid metal by heating one side of "harp" with specimen chain in "legs"
  - Relatively slow flow and ~100°C temperature variation (design dependent)
  - Captures solubility change in liquid: dissolution (hot) and precipitation (cold)
    - Dissimilar material interactions between specimens and loop material
- Pumped loop
  - Most realistic conditions for flow
  - Historically, similar qualitative results as TCL at 10x cost





Source: Pawel JNM 2017

Containment is the Primary Cost Issue



Adapted from CSP Gen3 Roadmap: NREL/TP-5500-67464, 2017

BraytonEnergy SRNL

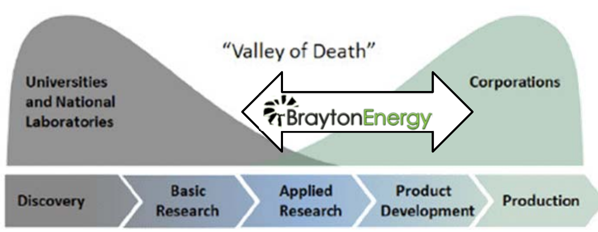
Thermochemical Energy Storage for CSP and Nuclear Power Management

Jamison Couture, Presenting
Shaun Sullivan, Principal Investigator

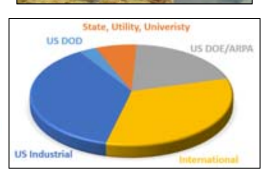
BraytonEnergy

"… to design and build hardware solutions for sustainable, efficient energy systems through applied research, revolutionary innovation, sound engineering, and dedicated partnerships with our clients."

- A private Advanced Energy R&D firm
- Located in Hampton, NH
  - About 50 miles north of Boston

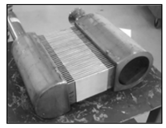


SRI International



BraytonEnergy

- Turbomachinery solutions
  - Power systems
  - Biomass
  - UAVs
  - Transportation
- CSP components
- High-temperature compact heat exchangers
- Energy storage solutions
- Advanced system modeling and analysis



3

Energy Storage Applications

Apollo is a concentrated solar power project

- Advanced Low Cost, Scalable Energy Storage Solution
  - Metal Hydrides
  - Wide range of applications

Transform Base Load Nuclear Reactor Plants into Load Following

4

CSP Energy Storage Focus

		Sensible			Phase Change	Thermo-Chemical		Electro-Chemical
PROJECT	**-**	**GEN3 T1 Brayton Energy**		**GEN3 T1 NREL**	**GEN3 T2 BE**	**APOLLO**	**SRI/ Echogen**	**SOA (2018)**
Description	-	Baseline	Alt	Chloride Salt	PCM	Metal Hydrides	Direct Contact	**Batteries**
Media	-	SiO_2 Particles	MgO Brick	KCl/MgCl	$MgCl_2$	$CaSi_2$/TiFe	$MgCO_3$	**Li-ion**
Energy Density	kJ/kg	116	96	116	353	343	329	**657**
Bulk Density	*kg/m³*	1,643	3,581	1,540	2,050	2,450	3,580	
Energy Capacity	kJ/m³	190,588	343,776	177,870	723,240	840,000	1,176,030	**1,324,042**
Specific Cost	$/kg	0.06	0.11	0.32	17.15	5.50	0.40	**73.00**
Capacity Cost	$\$/kWh_t$	**2**	**4**	**10**	**175**	**58**	**4**	*160*
	$\$/kWh_e$	*5*	*10*	*25*	*438*	*144*	*11*	**400**
DT of Storage	-	*per 100 °C*	*per 100 °C*	*per 100 °C*	*"isothermal"*	*"isothermal"*	*"isothermal"*	
Difficulty		Particle Trans.		Very Corrosive	cost incl. HEX	H_2 Permeation		

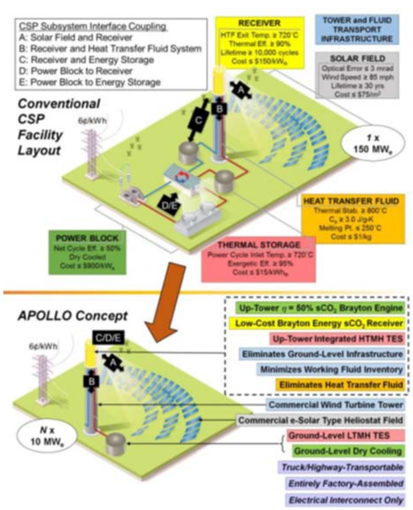
Thermochemical storage offers a viable alternative to electrochemical energy storage.

* Most research focused on sCO2 cycle & temps 740 to 780 ℃

5

Apollo Program – Objective

- Meet DOE's $0.06/kW-hr CSP Energy target by 2020.
  - Couple solar absorber, thermal energy storage, commercial wind turbine tower technology, and a high-efficiency sCO2 Brayton cycle into a single system.
  - Departure from the state-of-the-art in CSP plant layout.
  - Critical to the success of this program is a thermochemical Thermal Energy Storage (TES) system which consists of a coupled high temperature metal hydride (HTMH) and a low temperature metal hydride (LTMH).



6

Apollo Program – Metal Hydrides

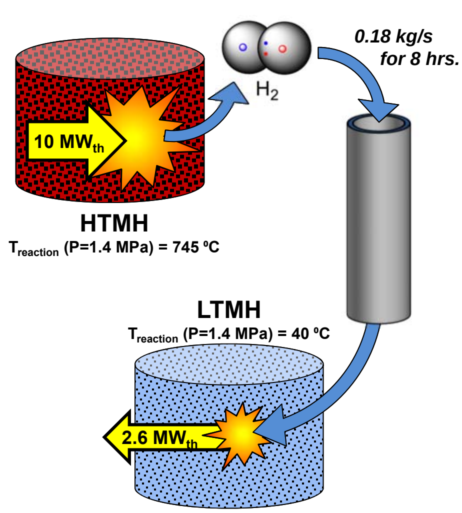
Why metal hydrides?

- Metal hydrides (MH): Brayton seeking a thermal storage system light enough to be placed on top of tower, thereby reducing piping and field installation costs.

- SRNL's unique MH formulation +
  Brayton integral heat exchanger ➔
  high exergetic efficiency, low cost, light weight

7

Metal Hydride TES Charging

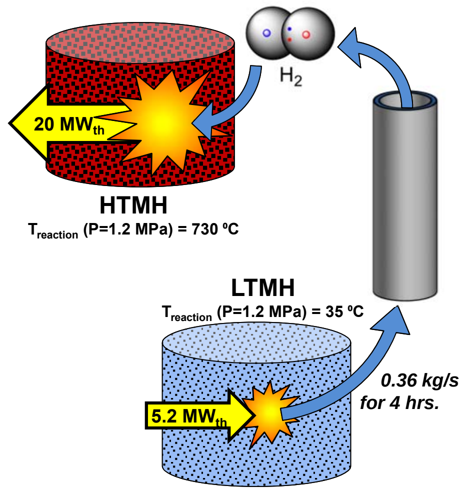


- Thermal (concentrated solar) energy is added to the HTMH, which *endothermically* releases hydrogen at its high reaction temperature
- The hydrogen flows into the LTMH, where it is *exothermically* absorbed at a lower reaction temperature
  - The released energy is absorbed by a flowing glycol loop, which then rejects it to ambient via an air cooled heat exchanger
- The energy is stored at low temperature in chemical bonds within the LTMH

8

Metal Hydride TES Discharging

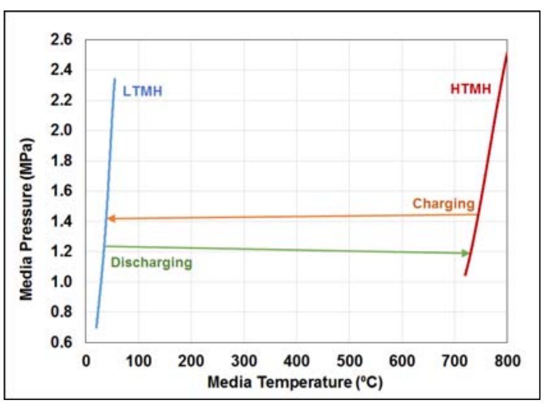
- Waste heat from the sCO_2 power cycle is absorbed into the same flowing glycol loop and transferred into the LTMH
  - This thermal energy is absorbed by the LTMH, which *endothermically* releases the stored hydrogen at its low reaction temperature
- The hydrogen flows back into the HTMH, where it is *exothermically* absorbed at a high reaction temperature
  - The released energy is transferred into the sCO_2 power cycle working fluid, heating it to the cycle turbine inlet temperature



9

Metal Hydride Pairing

- A well-chosen pairing of metal hydrides will enable the free flow of hydrogen between the two media at the desired temperatures
- Connecting pipes must be sized for the appropriate pressure drop to maintain intended operating temperatures



10

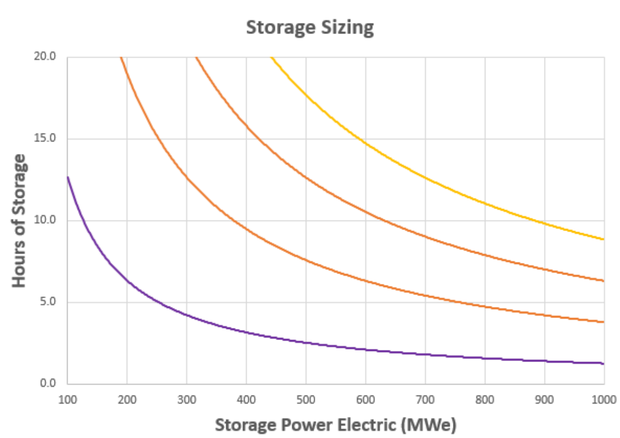
Apollo Metal Hydride Selections

	HTMH	LTMH
Compound	$CaSi_2$	TiFe
ΔH (kJ/molH_2)	110	28
ΔS (kJ/molH_2-K)	130	114
Bulk Density (kg/m^3)	1400	3129
Thermal Conductivity* (W/m-K)	3.5	7
Weight Capacity (kg_{H2}/kg_{MH})	0.023	0.0153
Specific Heat (J/kg-K)	950	500
Raw Material Cost ($/kg)	-	5.2

*Enhanced with 10wt% of Expanded Natural Graphite

11

Scalability of MH



MH Volume: HT / LT (m^3)
2 / 1.3
6 / 4.0
10 / 6.7
14 / 9.4

*40% electrical conversion efficiency assumed

12

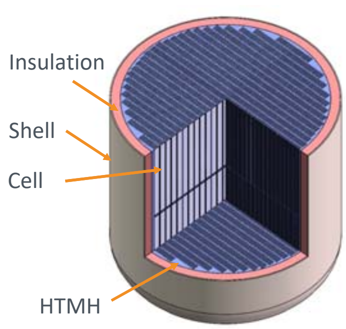
High Temperature MH Storage

- Hydrogen gas reformers use internal insulation on their hydrogen lines to avoid elevated metal temperatures at pressure boundary.
  - Low cost vessel alloys can be specified.
  - A similar internal insulation is proposed for the HTMH storage tanks
- Model assumed a single 200 mm layer of GREENTHERM 23 LI with a conductivity of 0.26 W/m·K for the liner.

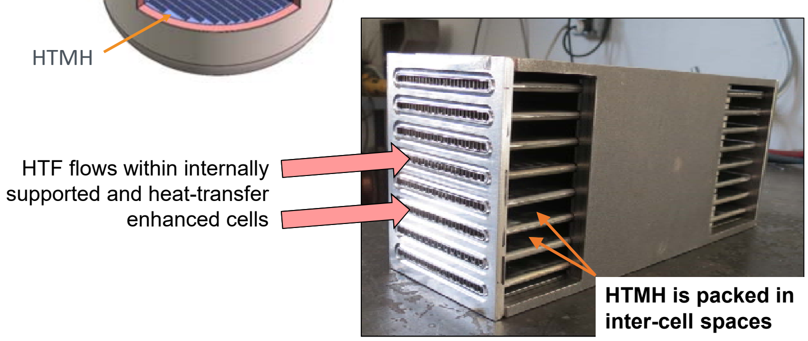
Source: JT Thorpe. “Reformers”.

13

High Temperature MH Storage



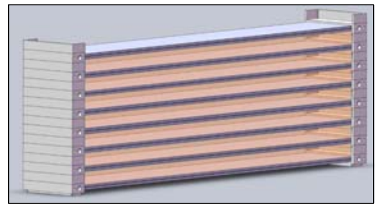
- Majority of cost is in cells
  - Large surface area is required to transfer large amount of heat
- Size PV according ASME BPVC Division VIII Section 1
  - Material used for shell is P91 which has excellent strength and is readily available

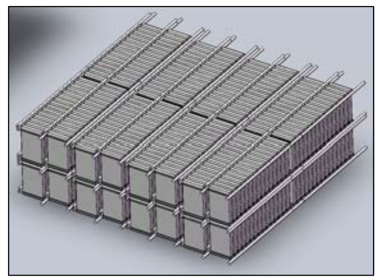


14

Low Temperature MH Storage

- A series of Shell-Tube heat exchangers represents a low-cost solution
  - Glycol in Tubes, LTMH in shell
  - Shell-side H_2 connections required
  - Challenging to make full use of LTMH
    - May require excess LTMH
    - Optimization required



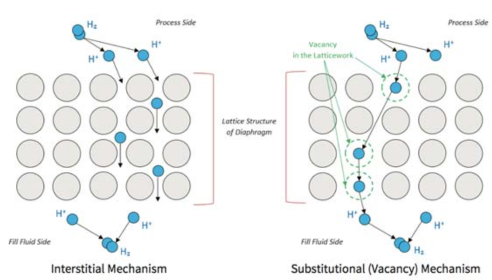


- Alternative design utilizes unit cell plate-fin configuration (as described in HTMH section)
  - High utilization of LTMH media
    - Little to no excess media required
  - Excessive glycol flow area
  - Self-supporting enclosure eliminates the need for thick vessel walls to react the 1.5 MPa shell-side LTMH pressure

15

Difficulties – Hydrogen Permeation

- The diffusion of hydrogen ions through thin metal walls
- Loss of inventory and embrittlement of metals.
  - Diffusion rate dependent on temperature, H_2 concentration and materials.
  - Possible damage to other machinery if diffused into working fluid.

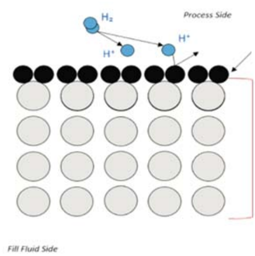


Source: "Hydrogen Permeation". Yokogawa.

16

Difficulties – Hydrogen Permeation

- How to Slow Hydrogen Permeation
  - Material Selection: resistance to oxidizing (Hastelloy)
  - Insulation: Internally Insulate to reduce outer shell wall temperature
  - Plating: Coat process side with tighter lattice work, more oxidization resistant material (Chromate, Gold)

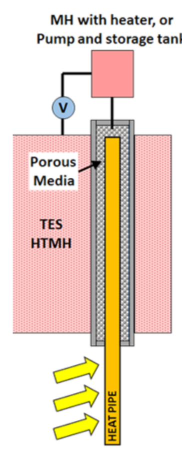


Source: "Hydrogen Permeation". Yokogawa.

17

Active H_2 Capture and Recovery

- Hydrogen permeation from the HTMH into hot metals *will* occur in HTMH storage vessel
- Permeated hydrogen may be captured from the circulating HTF loop and returned to the system. In this system:
  - A passive MH formulation that can absorb freed H_2 from the HTF loop
    - The MH is periodically isolated from the loop and connected to dehydrogenated HTMH or LTMH (via valving), and then heated to release the captured hydrogen and return it back into the TES



18

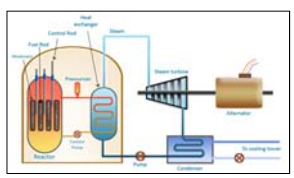
Metal Hydrides Energy Storage

- Competitive, low cost, high capacity storage.
- Low temperature process with low heat loss potential.
- Scalable, allowing for range of utilities.
- Range of MH formulations to tailor reaction temperature to system characteristics.
- Methods can be developed to minimize and/or capture escaped hydrogen.

19

NUCLEAR ENERGY APPLICATION

Base Load Nuclear Power Plant

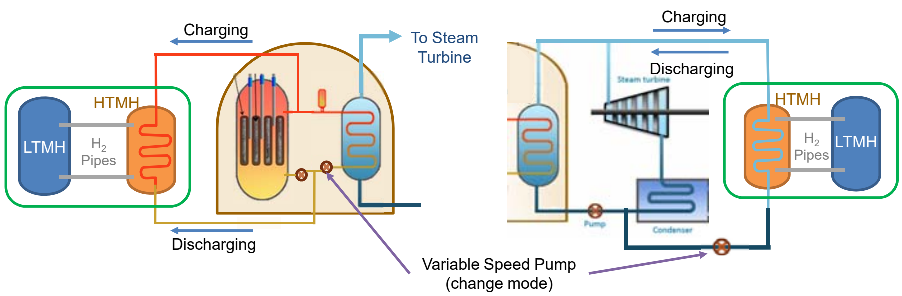


Source: Kiran Daware. "Basic Layout And Working of a Nuclear Power Plant".

Load Following Nuclear Power Plant

Option A

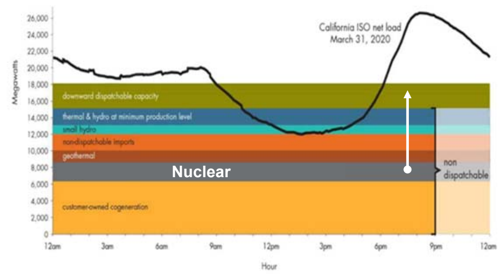
Option B



20

NUCLEAR ENERGY APPLICATION

- Isothermal storage enables the reactor to operate within narrow temp range
  - Select MHs for appropriate reaction temperatures, 600°- 800°C
  - Viable heat source for steam turbines, sCO2, or small recuperated gas turbines
- Load Following Storage



Source: Energy Storage and the California "Duck Curve", Stanford

21

BraytonEnergy SRNL

Thank You!

Questions?

22

Brayton Power Cycles with Peaking Capability and Storage

Bahman Zohuri, PhD
Pat McDaniel, PhD
University of New Mexico
July 24, 2019

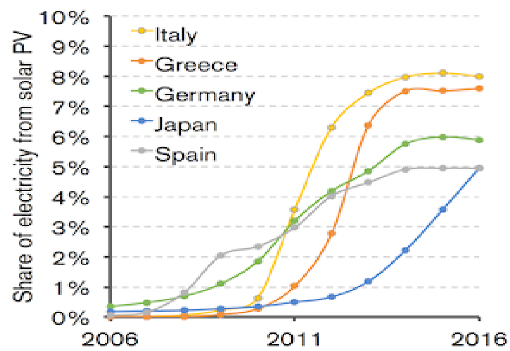
1

Outline

- The Problem
- A Proposed Solution
- Implementing the Solution

2

The Duck Curve and Saturation



As more Renewables come on line, the price of Electricity drops when they are available, but remains High when they are not available.

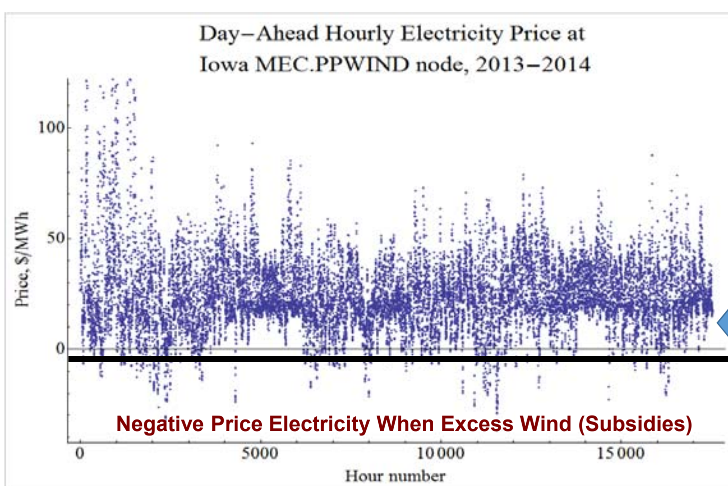
Due to the drop in price with high penetration, the market becomes saturated,

(n.b. Both figures stolen from Charles Forsberg presentation May 2018)

The Problem

Iowa Wholesale Electricity Prices: Two Years

Large Incentive to Sell Peak Electricity and Avoid Sales at Other Times



High Wind Crashes Electrical Prices

Energy Storage is the Obvious Solution

- There are two types of storage available at an arbitrary site.
- Electrical Storage (Obvious choice, typically batteries)
  - Currently approximately $280-$400 /kWh(e) at Terrawatt Scale
  - Essentially doubles the price of electricity
  - DOE is pursuing electrical storage research – Goal is $150/kWh(e)
- Heat Storage (Phase Change Material, Firebrick, Hydrogen Electrolysis)
  - DOE Heat Storage – Goal $15/kWh(t)
  - Can be used by Solar Thermal Plants but not PV
  - Even with conversion losses heat storage can be recovered at less cost

Increased Renewables Parallel increased Cost

- Introduction of increased renewables in Europe (primarily Germany) have driven the cost of electricity in Europe over 20% since 2008.
- In the US during this same period the cost of electricity has dropped by 50% due to the expansion of natural gas systems
- The heavy introduction of renewables into the California energy market has paralleled the European experience while the rest of US has experienced the 50% drop in cost of electricity.

Heat In A Bottle, An Innovative Storage System

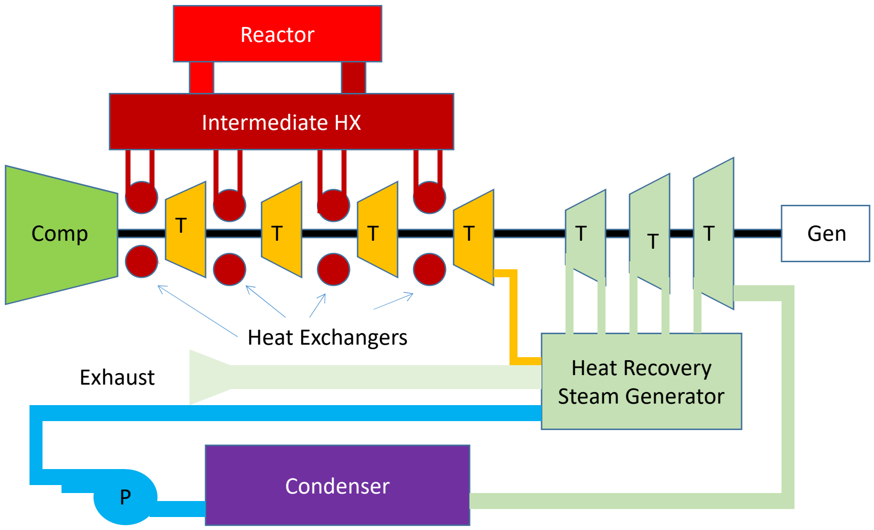
The variability of solar and wind power is causing headaches for utilities. Adding heat storage to light-water reactors could help promote a reliable low-carbon power industry as Implementing the Solution

Nuclear Air Brayton Systems

- It is difficult, but not impossible, for LWR systems to take advantage of lower cost heat storage
- For advanced reactors, particularly Small Modular Reactors, Nuclear Air-Brayton systems may be effective.
- Nuclear Air-Brayton Combined Cycle (NACC) Systems can be built that operate similar to Gas Turbine Combined Cycle Systems
- Nuclear Air-Brayton Recuperated Cycle (NARC) Systems can be built based on the Same Technology
- The only innovation will be a liquid metal/molten salt-to-air heat exchanger. These have been demonstrated in the past on the 1960s ANP program and as heat dumps for the FFTF and are currently proposed for the VTR.

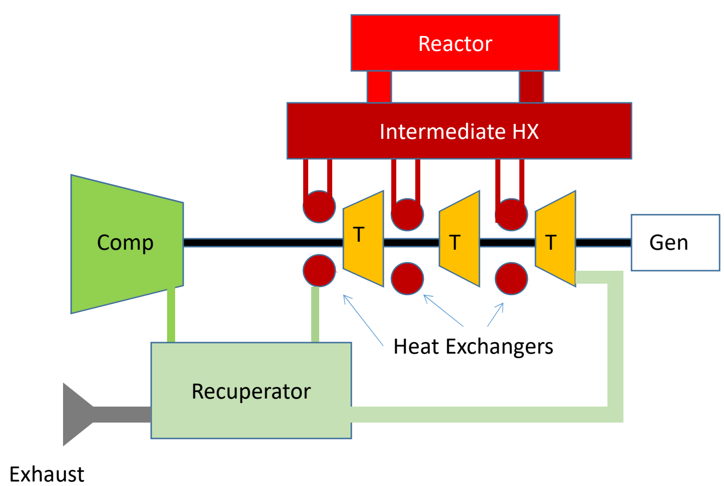
A Possible Solution

Typical NACC System Layout (4T)



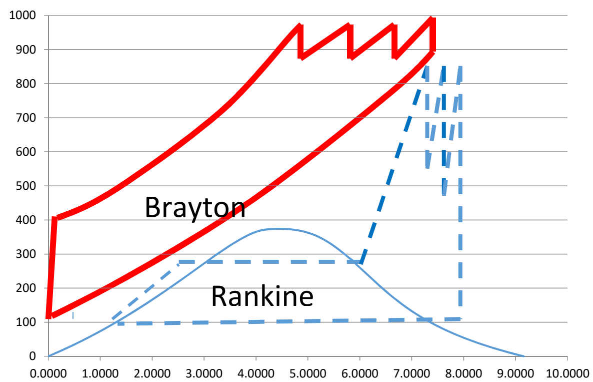
9

Typical NARC System Layout(3T)

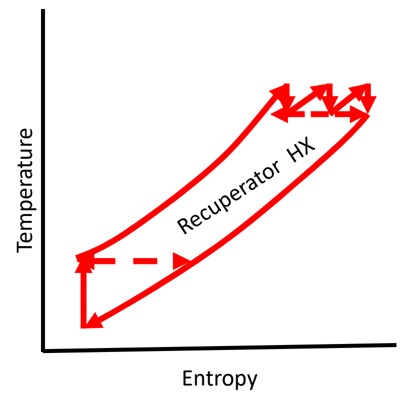


10

Thermodynamic Cycle Diagrams



NACC System

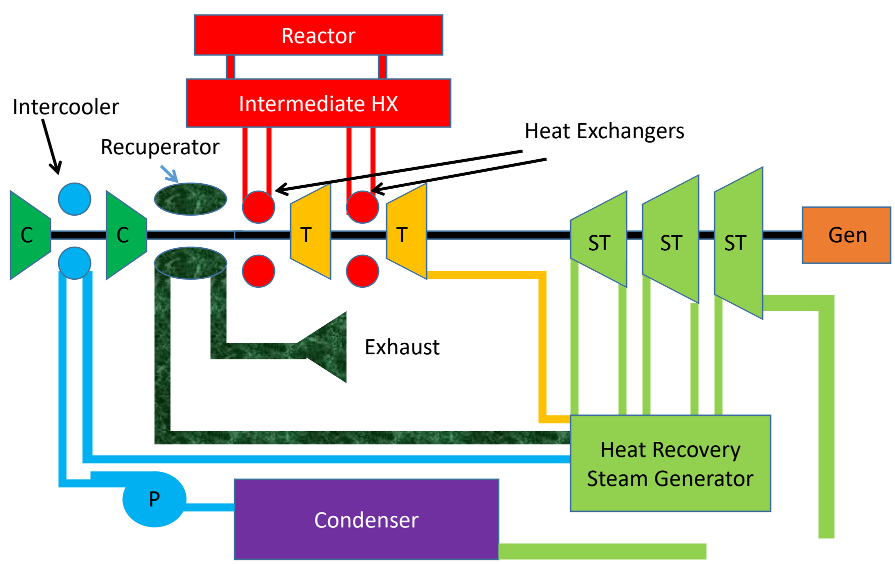


NARC System

A Possible Solution

11

NACC w/Recuperator and Intercooler



12

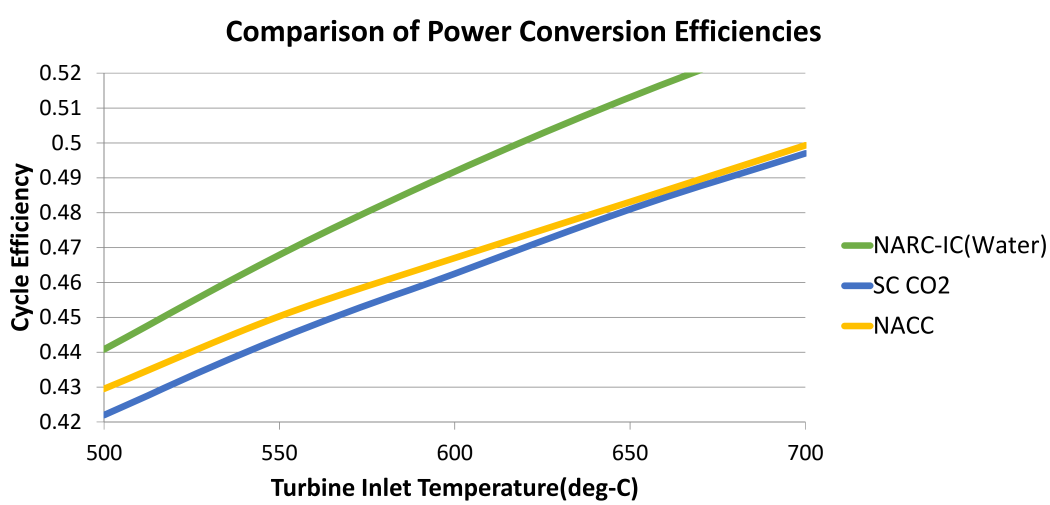
Possible Reactor Heat Sources

Generation IV Systems

- Sodium Cooled Fast Reactor
- Lead Cooled Fast Reactor
- Molten Salt Cooled Reactor
- Gas Cooled Fast Reactor
- Very High Temperature Reactor
- Super-Critical Water-Cooled Reactor

All But the Super-Critical Water-Cooled Reactor should be easily adaptable to an Air-Brayton System.

Baseline Efficiencies vs. Turbine Inlet Temperature



Advantages of NACC and NARC Systems

- NACC Systems Require Significantly Less Cooling Water

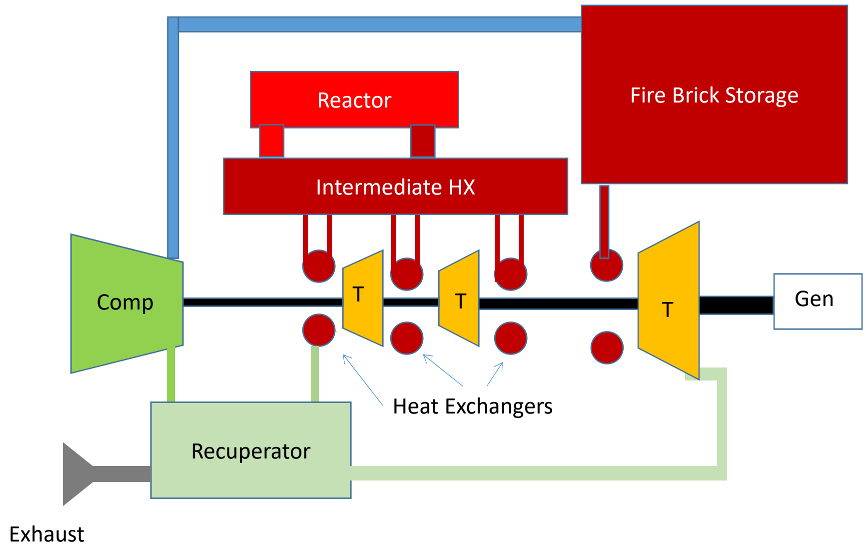
LWR at 35% Efficiency	92.9 MW(t)
NuScale at 31% Efficiency	111.3 MW(t)
Near Term LM NACC at 40.0% Efficiency	40.3 MW(t)
Advanced MS NACC at 44.5% Efficiency	25.5 MW(t)
Near Term LM IC NACC at 42.0% Efficiency	39.8 MW(t)
Advanced MS IC NACC at 45.6% Efficiency	38.4 MW(t)
Near Term LM IC NARC at 46.1% Efficiency	23.6 MW(t)
Advanced MS IC NARC at 51.1% Efficiency	18.6 MW(t)
Near Term/Advanced NARC	0.0 MW(t)

- Gas Turbine Industrial Base is Huge, Dwarfing Steam Turbine Industrial Base
- Liquid Metal/Molten Salt Heat Exchangers Operate at a few atmospheres, vs ~10 Megapascals
- Gas Turbine Maintenance Appears More Cost Competitive

Coupling to Storage Systems - Firebrick

- The most efficient system is probably the Firebrick system
- Firebrick is heated electrically to ~ 2000 K
- This can be accomplished with nuclear system electricity or excess solar electricity
- The stored heat is then recovered by passing compressed air over the Firebrick
- The heated air is mixed with the nuclear heated air and exhausted over the last air turbine
- A variable throat nozzle is required before the last turbine
- The exhaust passes to either the Heat Recovery Steam Generator or Recuperator

NARC System W/Firebrick Storage



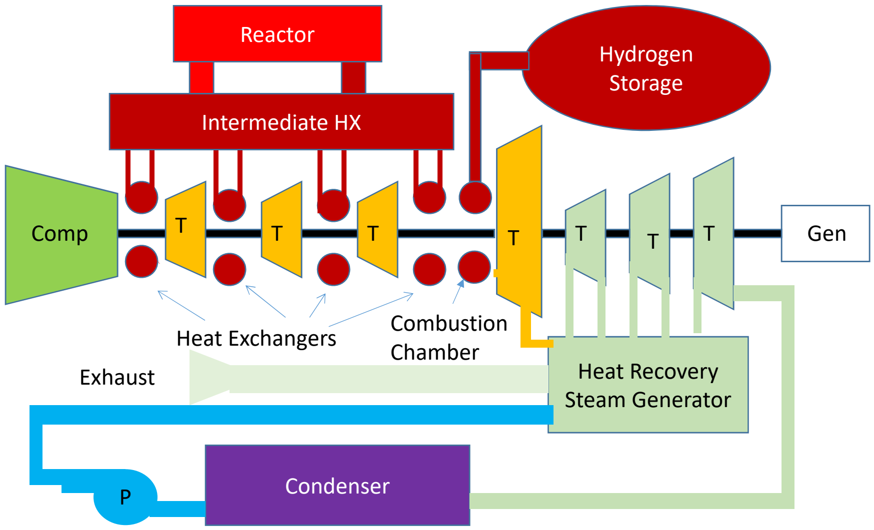
17

Coupling to Storage Systems - Hydrogen

- Produce hydrogen by high temperature electrolysis – 60-80% efficient
- Use nuclear, excess solar, or excess wind electrical power
- Hydrogen Storage is a developed technology
  - Store hydrogen under pressure ~3000-5000 psi
  - Store at ambient temperature
- For power peaking burn hydrogen in a combustion chamber after last sodium/molten salt heat exchanger, prior to last turbine
- If we run out of hydrogen, natural gas or other suitable fuel can be substituted.

18

NACC System with Hydrogen Combustion



Storage Systems Pro/Con

- Firebrick Storage Systems are More Efficient, ~95-98% vs 60%-80% for Hydrogen Electrolysis.
- Producing the heat from electricity on a Multi-Megawatt Hour scale for Firebrick Systems is probably a simpler process than Hydrogen Electrolysis on that scale.
- Storage Systems are sized for the maximum time they will be needed.
  - Firebrick Storage represents a fixed installation.
  - Hydrogen storage can be added to or subtracted from fairly easily (tanks).
- Firebrick Heat Storage must be maintained at high pressure and temperature.
- Hydrogen Storage must be maintained at higher pressure, but ambient temperature is okay.
- The State of the Art for Hydrogen Combustion is probably better understood than manipulating a Firebrick Store for this application.
- Production of Hydrogen has many other applications.

NACC Performance w/Storage

- Consider two levels of final turbine inlet temperature with hot gas injection or hydrogen burn - 1100 K (uncooled), 1700 K (cooled)
- Evaluate a Three Gas Turbine system

Turb 1&2 Nom Exit Temp	Turb 3 Nom Exit Temp	Turb 3 Aug Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Overall Gain
Sodium Near Term System (Normal Inlet Temperatures - 773 K)							
680.5 K	640.5 K	1100 K	32.8%	71.1%	48.4%	1.464	2.522
680.5 K	640.5 K	1700 K	32.8%	74.2%	60.4%	2.347	5.744
Molten Salt Advanced System (Normal inlet Temperature – 973 K)							
792.5 K	722.5 K	1100 K	45.5%	74.5%	51.1%	1.168	1.403
792.5 K	722.5 K	1700 K	45.5%	75.0%	61.6%	1.834	3.070

Implementing the Solution

21

NARC Performance w/Storage

- For NARC Systems the peak augmented last turbine temperatures are driven by the output temperature of the Recuperator to the first heat exchanger. When the Recuperator delivers air at the outlet temperature of the first heat exchanger the burn temperature can go no higher. The reactor must also be throttled back as it is no longer providing heat to the first heat exchanger.
- Evaluate a Three Gas Turbine system

Turb 1&2 Nom Exit Temp	Turb 3 Nom Exit Temp	Turb 3 Aug Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Fractional RX Power
Sodium Near Term System (Normal Inlet Temperatures - 783 K)							
765.5 K	655.5 K	958.7 K	40.9%	78.8%	47.2%	1.390	0.220
Sodium Near Term System (Normal Inlet Temperatures - 783 K, intercooled)							
748.0 k	618.0 K	1011.6 K	43.7%	83.4%	51.1%	1.447	0.285
Molten Salt Advanced System (Normal inlet Temperature – 973 K)							
922.5 K	762.5 K	1204.2 K	48.5%	81.1%	54.8%	1.409	0.203
Molten Salt Advanced System (Normal inlet Temperature – 973 K, Intercooled)							
902.5 K	722.5 K	1268.7 K	51.5%	84.7%	58.4%	1.448	0.276

Implementing the Solution

22

Summary Conclusions

- Air-Brayton Power Conversion Systems appear feasible for Advanced Nuclear Systems.
- Air-Brayton Power Conversion Systems will require significantly less water as a heat dump, allowing more flexibility in siting.
- Air-Brayton Power Conversion Systems will allow Advanced Nuclear Systems to achieve economic performance on a grid with a high penetration of Renewable Power Sources.
- In fact Nuclear Air-Brayton Systems will be the future plants of choice for burning combustible fuels to satisfy increased demand.

23

References

[1] B. Zohuri and P. McDaniel, *Combined Cycle Driven Efficiency for Next Generation Nuclear Power Plants: An Innovative Design Approach, 2nd ed*., Springer, 2018, https://www.springer.com/gp/book/9783319705507

[2] B. Zohuri and P. McDaniel and C. R R. De OLIVERIA, "Advanced Nuclear Open Air-Brayton Cycles for Highly Efficient Power Conversion", *Nuclear Technology*, **192** (1), 48-60, 2015, http://dx.doi.org/10.13182/NT14-42

[3] B. Zohuri and P. McDaniel, *Advanced Smaller Modular Reactors: An Innovative Approach to Nuclear Power* 1st Edition, Springer 2019, https://www.springer.com/us/book/9783030236816

[4] B. Zohuri, *Hybrid Energy Systems: Driving Reliable Renewable Sources of Energy Storage*, 1st Edition, Springer 2018, https://www.springer.com/us/book/9783319707204

[5] B. Zohuri, *Hydrogen Energy*, 1st Edition, Springer 2018, https://www.springer.com/us/book/9783319934600

[6] B. Zohuri, *Nuclear Energy for Hydrogen Generation through Intermediate Heat Exchangers: A Renewable Source of Energy*, 1st Edition, Springer 2016, https://www.springer.com/us/book/9783319298375

[7] B. Zohuri, Application of Compact Heat Exchangers For Combined Cycle Driven Efficiency In Next Generation Nuclear Power Plants, 1st Edition, Springer 2016, https://www.springer.com/us/book/9783319235363

23

Hydrogen Integration:
The Other Storable Product

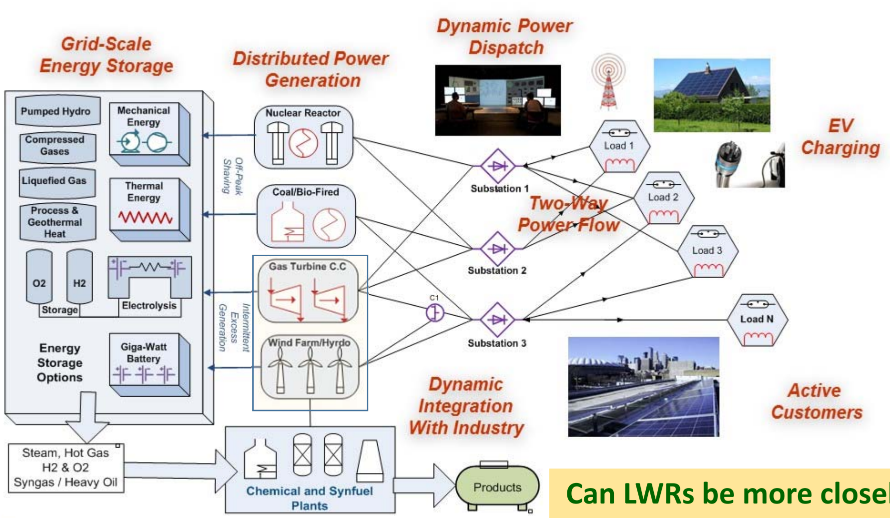
Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors

Idaho Falls, ID; July 23-24, 2019

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Tyler Westover
Richard Boardman

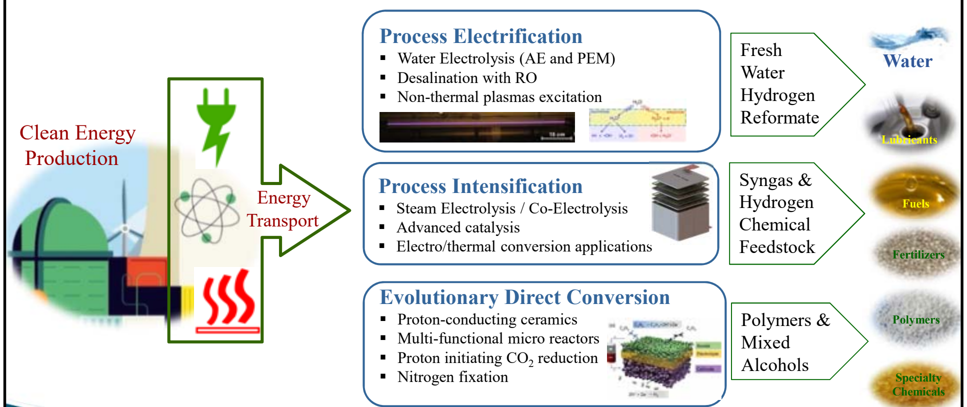
How the grid is evolving…



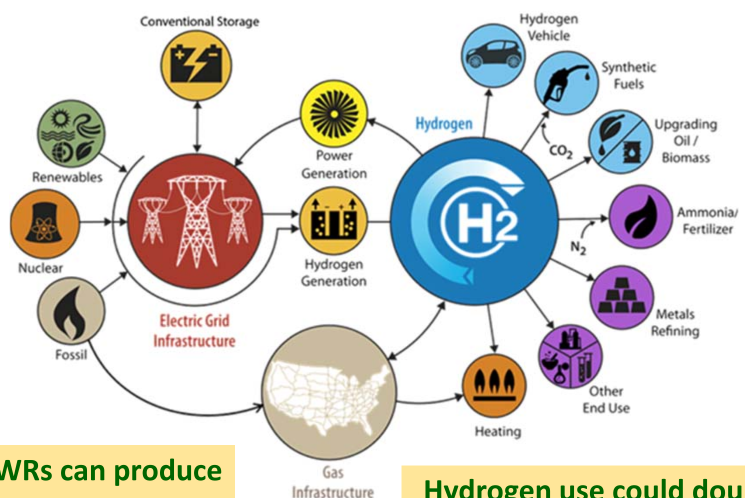
Can LWRs be more closely integrated with industry?

Opportunities for Hybrid Nuclear Plants

- Direct tie to plant substation for electricity dispatch
- Tie in independent steam loop for thermal duties
- Produce energy carriers such as hydrogen and other chemical feedstock



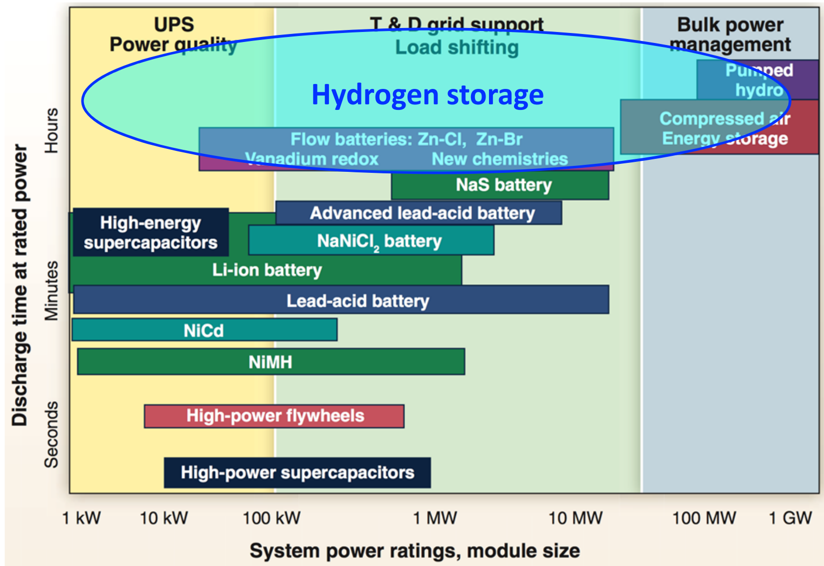
DOE H2@Scale Initiative



50 LWRs can produce ~10 MMT H_2

Hydrogen use could double in the next 10 years; 10 → 20 MMT/yr; then even more … → 30 … → 50 MMT/yr

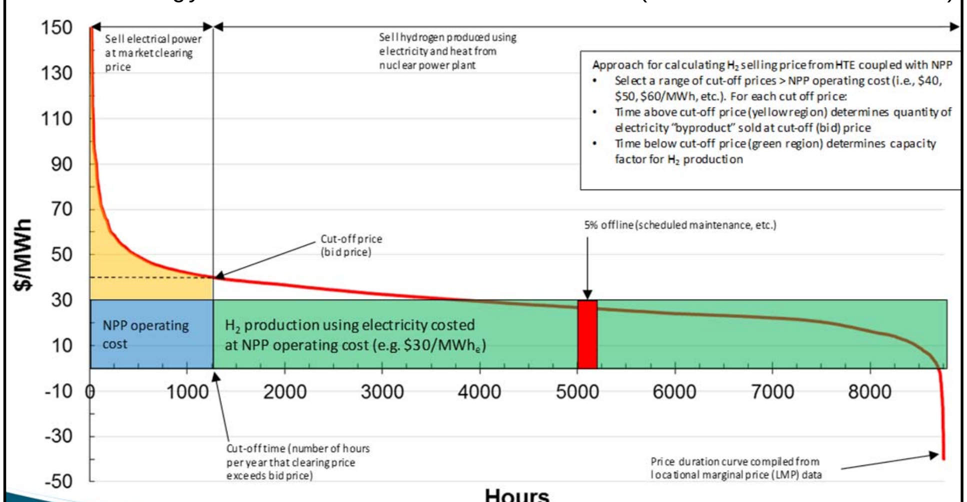
Comparison of discharge time and power ratings



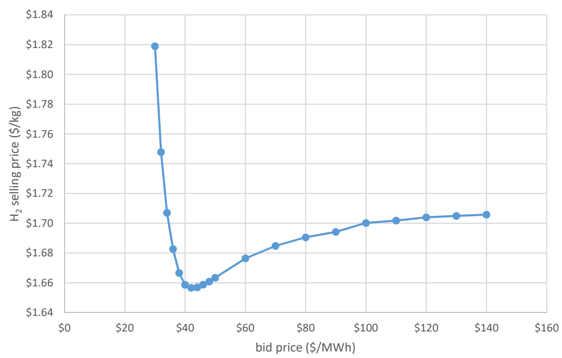
Dunn, Kamath, Tarascon (2011) Science, 334, 928-935

Nuclear Hybrid Plant with High Temperature Steam Electrolysis (HTSE)

Xcel Energy Scenario 2 Price Duration Curve (Minnesota - MINN HUB)



Xcel Energy Scenario 2 Price Duration Curve: Minnesota - MINN HUB



HTSE plant specifications:

- 665 TPD H_2 production capacity
- 972 MWe electrical power input (35.1 kWh/kg H_2)
- 222 MWth thermal input (8 kWh/kg H_2)

System unit costs (based on DC power input):

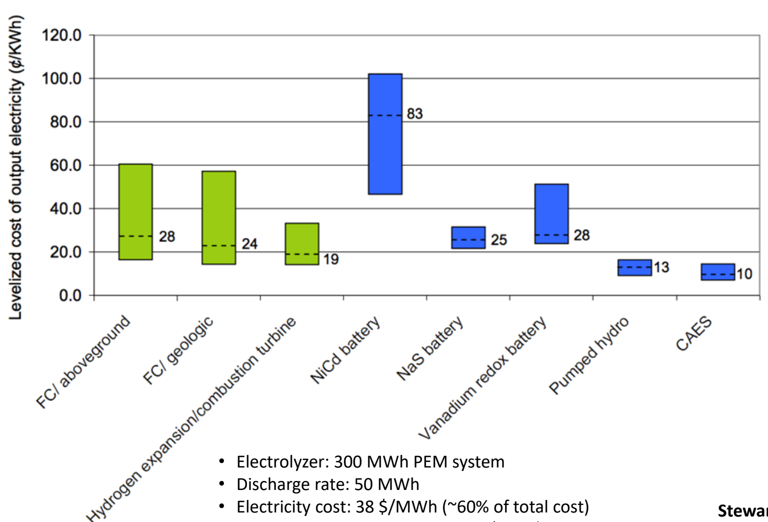
- Uninstalled cost of $430/kWe
- Installed cost of $612/kWe (total capital investment includes engineering, permitting, contingency, land cost, etc.)

Economic modeling:

- Nuclear Power Plant operating cost of $30/MWh (cost of electricity for H_2 production; cost is subtracted from LMP to determine revenues from electricity "byproduct" sales)
- H_2 selling price does not include credit for capacity payments or O_2 byproduct sales

7

NREL Projections from 2009

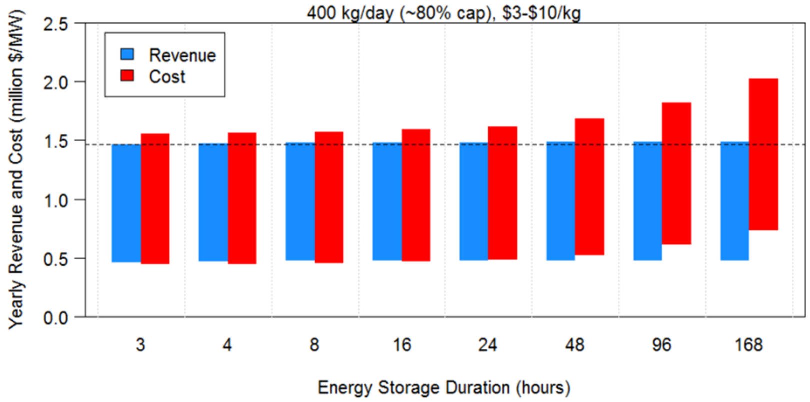


- Electrolyzer: 300 MWh PEM system
- Discharge rate: 50 MWh
- Electricity cost: 38 $/MWh (~60% of total cost)
- Predicted mid H2 cost for ~2014: $4.69/kg
    - *Note: current projections are much lower*
- Predicted mid storage cost for ~2014: 15 $/kWh

Steward et al, (2009)
NREL/TP-569-46719

8

NREL 2016 Projection for CAISO Market



Storage capacity sensitivity

- Based on CAISO 2012 market
- Hydrogen is produced using 1 MW PEM electrolyzer
- Electricity is produced using fuel cell
- Revenue includes capacity and ancillary services

Profits are maximized by

- Selling hydrogen in favor of electricity
- Participating in energy, ancillary, and capacity markets
- Employing storage capacity of less than 16 hours

Eichman, Townsend, Melaina, (2016) NREL/TP-5400-65856

Summary

- **Hydrogen markets are rapidly growing (doubling in the next 10 years)**
- **Hydrogen storage is feasible for 1-100 GW and is suitable for hours or days**
- **Hybrid nuclear/hydrogen production plant is projected to sell hydrogen for <$2/kg (with electricity price of $30/MWh)**
- **Profits are maximized for short-term hydrogen storage**
  - o Short-term hydrogen storage (<16 hours)
  - o Priority for selling hydrogen rather than electricity

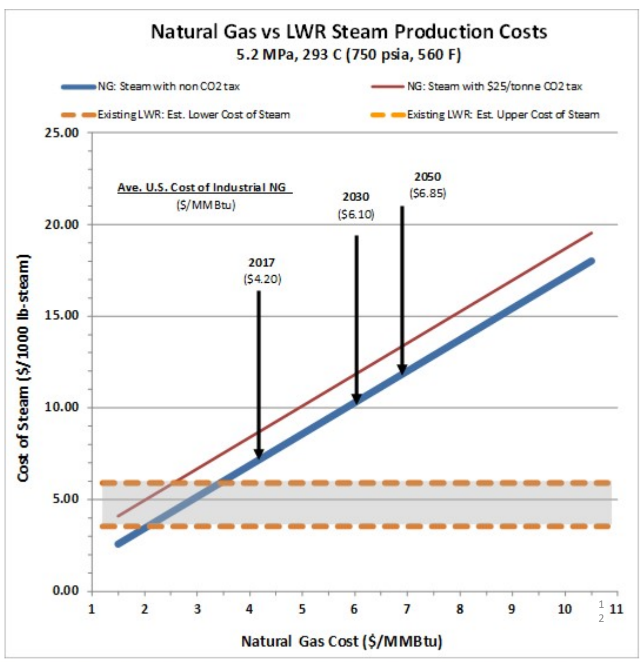
LWRS LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

lwrs.inl.gov

11

- Nuclear reactors outcompete natural gas when producing steam (and heat).
- Nuclear energy is clean and sustainable
- LHPs can exploit stable, non-volatile, low-cost electricity produced by LWRs

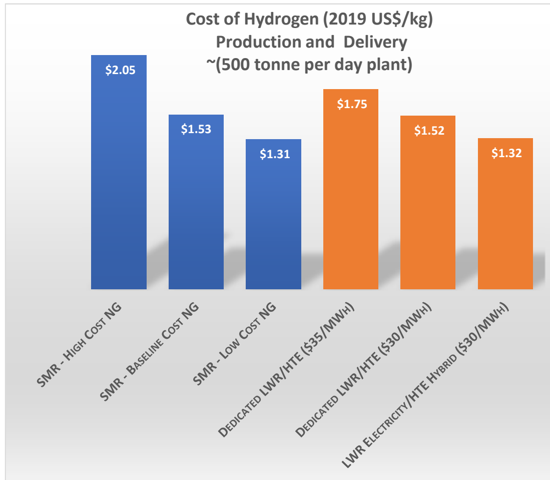


12

Large-Scale Hydrogen Plant Costs

Key assumptions:

- Steam Methane Reforming (SMR) hydrogen plant, 90% on-line capacity
- High Temperature Electrolysis (HTE) plant, 95% on-line capacity
- Electrolysis stack costs and balance of plant for 'nth-of-a-kind" plant
- Hybrid electricity/hydrogen plant sells electricity to grid 1.5% of year

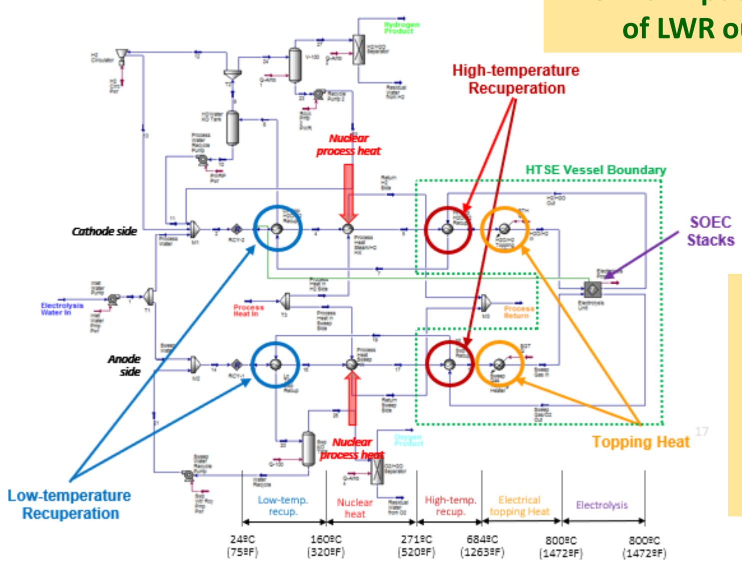


Source: R. Boardman, INL; Evaluation of Non-electric Market Options for a light-water reactor in the Midwest (Light Water Reactor Sustainability Market Study, March 2019)

13

HTSE Process Heat Integration

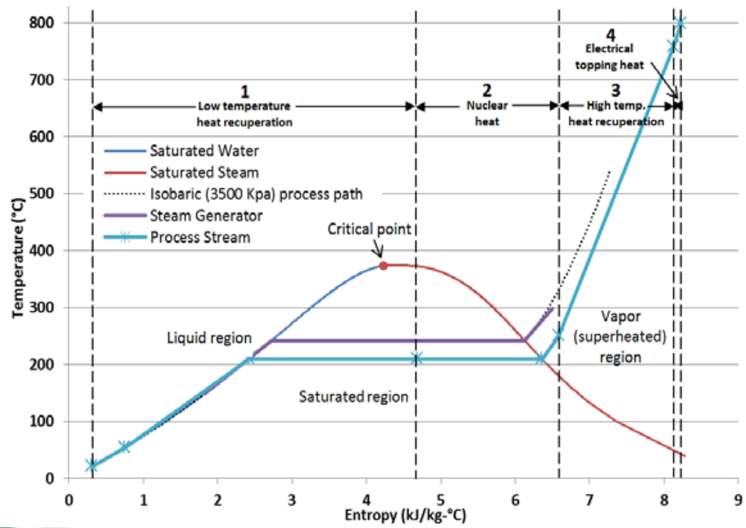
Thermal input is just 9% of LWR output



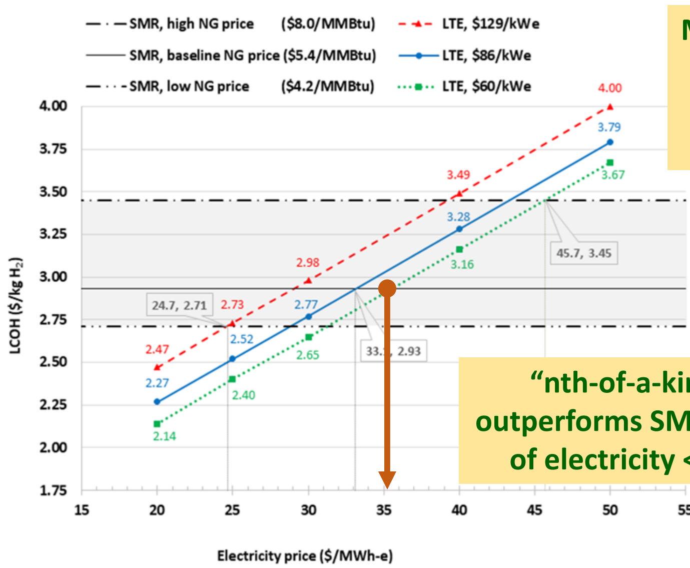
Less than 3% of LWR power is used for topping heat

14

Heat recuperation + Nuclear heat + Electrical topping heat

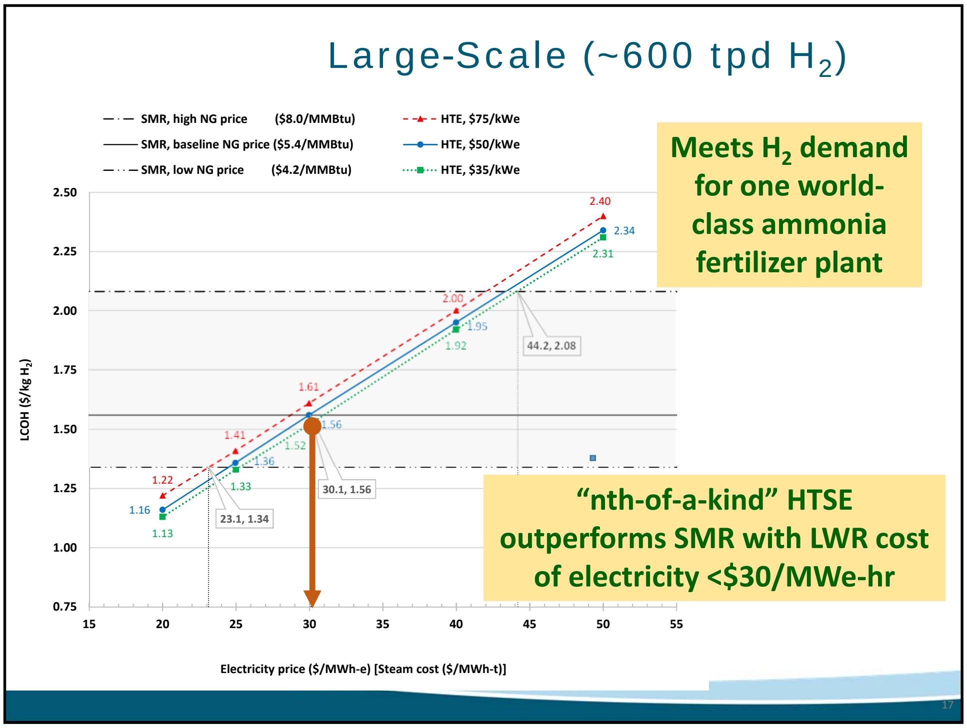


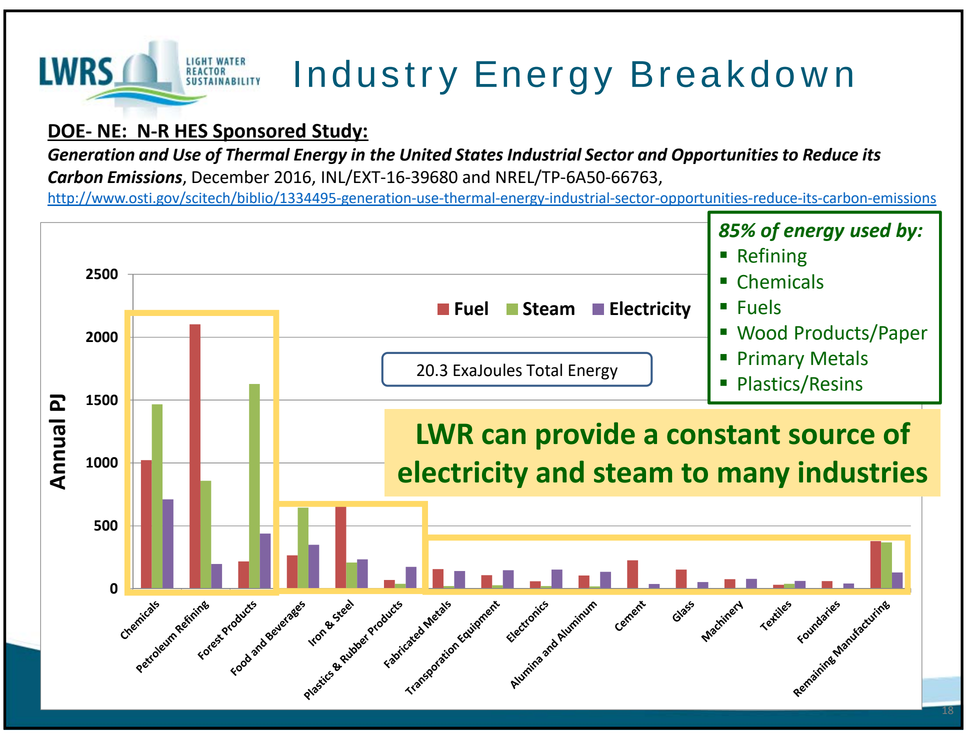
Small-Scale (24 tpd H_2)



Meets H_2 demand for FCV filling stations up to ~2030

"nth-of-a-kind" LTE PEM outperforms SMR with LWR cost of electricity <$35/MWe-hr


Large-Scale (~600 tpd H2)
SMR, high NG price ($8.0/MMBtu)
SMR, baseline NG price ($5.4/MMBtu)
SMR, low NG price ($4.2/MMBtu)
HTE, $75/kWe
HTE, $50/kWe
HTE, $35/kWe
LCOH ($/kg H2)
Electricity price ($/MWh-e) [Steam cost ($/MWh-t)]
44.2, 2.08
30.1, 1.56
23.1, 1.34
Meets H2 demand for one world-class ammonia fertilizer plant
"nth-of-a-kind" HTSE outperforms SMR with LWR cost of electricity <$30/MWe-hr
17


LWRS LIGHT WATER REACTOR SUSTAINABILITY
Industry Energy Breakdown
DOE- NE: N-R HES Sponsored Study:
Generation and Use of Thermal Energy in the United States Industrial Sector and Opportunities to Reduce its Carbon Emissions, December 2016, INL/EXT-16-39680 and NREL/TP-6A50-66763,
http://www.osti.gov/scitech/biblio/1334495-generation-use-thermal-energy-industrial-sector-opportunities-reduce-its-carbon-emissions
85% of energy used by:
Refining
Chemicals
Fuels
Wood Products/Paper
Primary Metals
Plastics/Resins
Fuel Steam Electricity
20.3 ExaJoules Total Energy
LWR can provide a constant source of electricity and steam to many industries
Annual PJ
Chemicals
Petroleum Refining
Forest Products
Food and Beverages
Iron & Steel
Plastics & Rubber Products
Fabricated Metals
Transportation Equipment
Electronics
Alumina and Aluminum
Cement
Glass
Machinery
Textiles
Foundaries
Remaining Manufacturing
18

Millard County

S. Barney

Population: 12,503

3rd Largest County in Utah

Major Industries: AG (Alfalfa, Delta Egg Farm, Dairy, LiquaDry, Great Lakes Cheese) Graymont lime plant, Ashgrove Cement plant, Materion Berylium

IPP

Newer Industries: Magnum NGL's, Solar, Norbest, Smithfield (in permitting process)

"Utah's Industrial County"

INTERMOUNTAIN POWER PROJECT

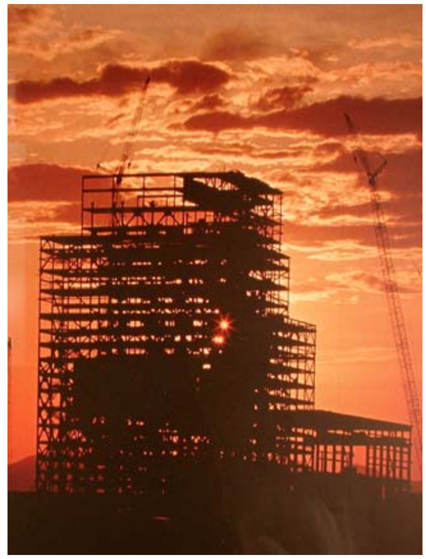
Station Overview and History

rev 10/3/16

Plant History

Owner
Intermountain Power Agency
Operating Agent
LADWP
Construction

- Construction began 1982
- LADWP – Project Manager
- Black & Veatch - A/E
- Bechtel- Construction Manager
- Unit 1 Commercial Oper 1986
- Unit 2 Commercial Oper 1987



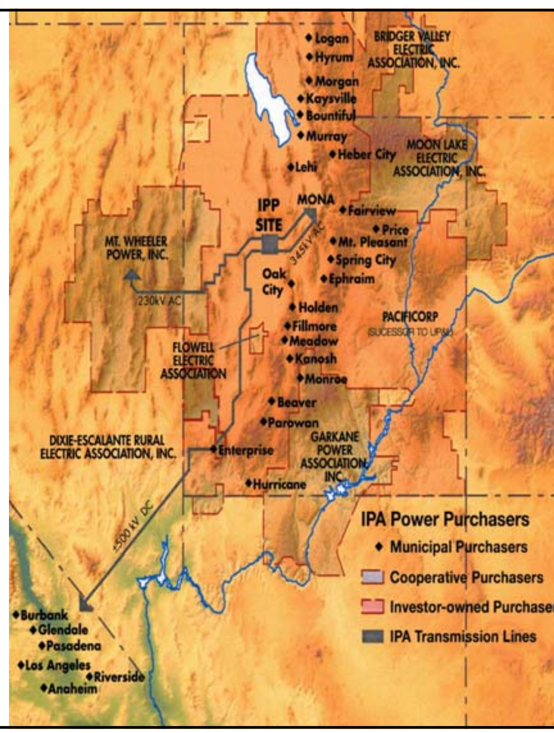
IPP 36 Original Participants

23 Utah Municipalities

6 Rural Co-ops

6 California Municipalities

1 IOU (Pacificorp)



Generation Entitlement Shares

California Purchasers	
Los Angeles Department of Water and Power	44.617%
City of Anaheim	13.225%
City of Riverside	7.617%
City of Pasadena	4.409%
City of Burbank	3.371%
City of Glendale	1.704%
Total - 6 California Purchasers	74.943%
Utah Cooperative Purchasers	
Moon Lake Electric Association, Inc.	2.000%
Mt. Wheeler Power, Inc.	1.786%
Dixie-Escalante Rural Electric Association, Inc.	1.534%
Garkane Power Association, Inc.	1.267%
Bridger Valley Electric Association	0.230%
Flowell Electric Association	0.200%
Total - 6 Cooperative Purchasers	7.017%
Utah Investor-Owned Purchasers	
Utah Power & Light Company (PacifiCorp)	4.000%
Utah Municipal Purchasers	
Murray City	4.000%
Logan City	2.469%
The City of Bountiful	1.695%
Kaysville City	0.739%
Heber Light & Power Company	0.627%
Hyrum City	0.551%
Fillmore City	0.512%
The City of Ephraim	0.503%
Lehi City	0.430%
Beaver City	0.413%
Parowan City	0.364%
Price	0.361%
Mount Pleasant	0.357%
City of Enterprise	0.199%
Morgan City	0.190%
City of Hurricane	0.147%
Monroe City	0.130%
The City of Fairview	0.120%
Spring City	0.060%
Town of Holden	0.048%
Town of Meadow	0.045%
Kanosh	0.040%
Town of Oak City	0.040%
Total - 23 Municipal Purchasers	14.040%

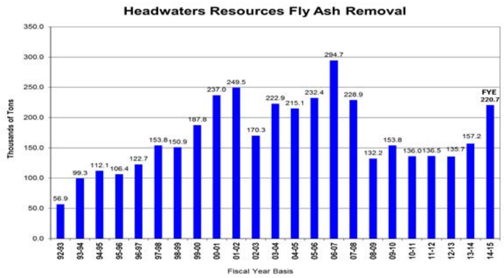
5

Intermountain Power Project

- Intermountain Generating Station (2 units)
- Electrical Switchyard/Converter Station (ICS-ACS)
- Transmission Systems (AC & DC)
- Railcar Facility Springville (own & maintain 4 unit trains with 431 cars)
- Utah - water rights for 4 units, rent unused to agriculture
- Site - zero discharge, with onsite disposal and storage
- Fly Ash Sales to contractor (Headwaters)

6

Fly Ash Collection and Sales



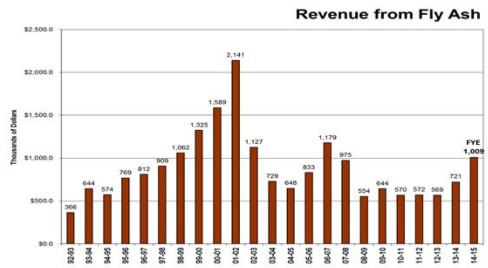
Fly ash storage & loading

Fly ash sold 2015-16 FYE totaled 226.1 ktons.

Revenue 2015-16 FYE was $1,110,000 plus eliminated ash handling costs.

Total flyash sold life of project 4.2 million tons.

Total flyash revenue life of project $21.5 million.

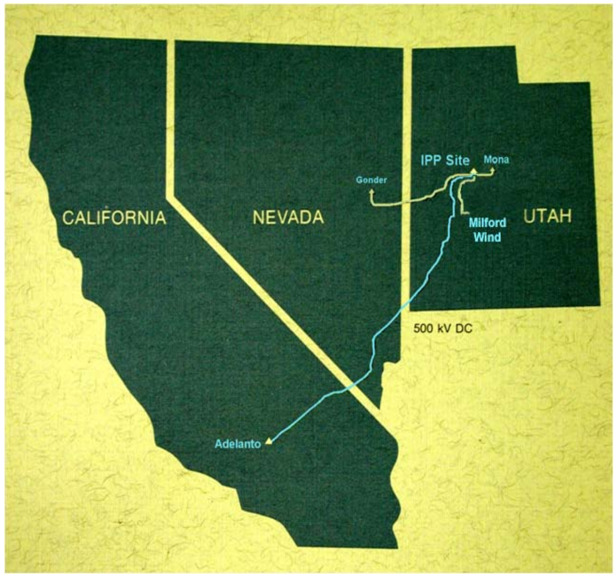


7

Transmission System

- AC Switchyard
- 345 KV AC Transmission Line to Mona, UT – Rocky Mountain Power
- 230 KV AC Transmission Line to Gonder, NV – NV Energy
- 345 KV AC Transmission Line to Milford UT Wind Farm
- AC to DC conversion with 2400 MW DC line to California

Intermountain Power Plant Site



9

DC Transmission line to California

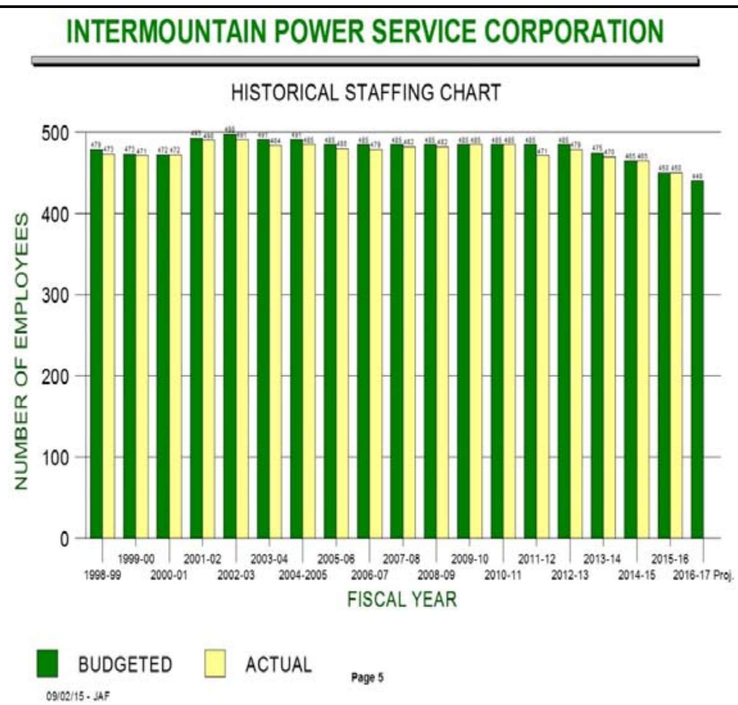
10

Plant Operation

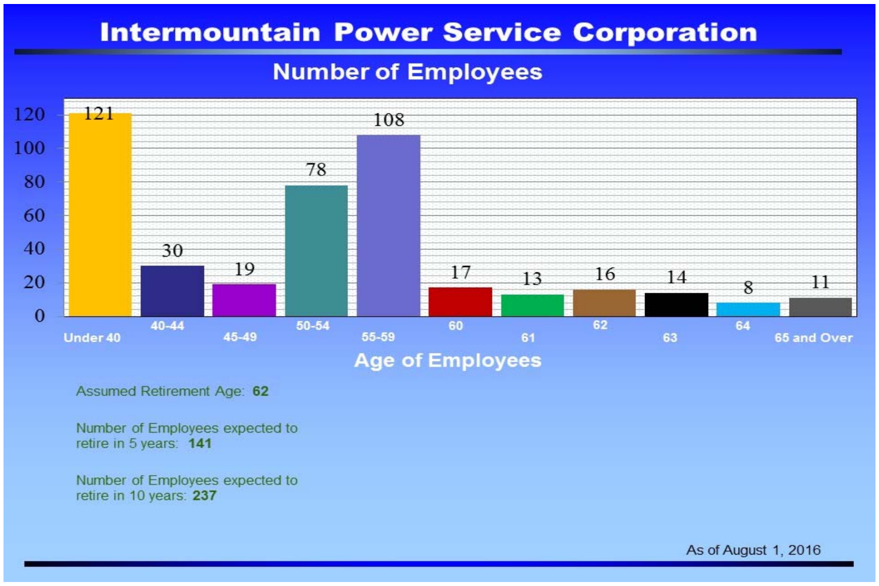
Intermountain Power Service Corporation

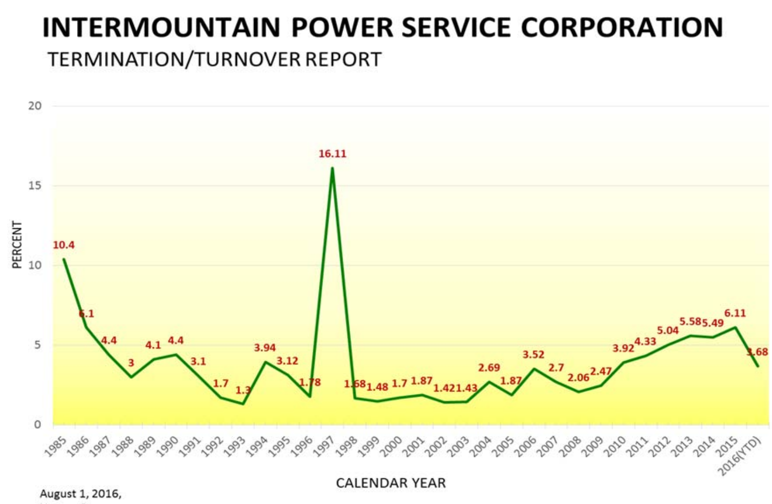
- Self-Contained Contract Service Organization
- 440 Employees
- Operations, Safety-Training, and Convertor Station
- Maintenance, Railcar, and Warehouse
- Engineering, Environmental, Computer Services
- Human Resource, Accounting, and Purchasing

11



IPSC Employee Age





14

Local Economic Benefit

Payroll: IPSC employs 385 residents of Millard County who had a gross payroll of $39,704,261 in 2015. The total gross payroll for the current 440 employees and the 24 retirees in 2015 was $46,146,892.

Business and Commerce: For the calendar year 2015, IPSC purchased $5,093,512 worth of goods and services from individuals, businesses, and vendors located in Millard County.

Chamber of Commerce Gift Certificates: To date, IPSC has purchased $93,050 worth of gift certificates which are redeemable at Chamber of Commerce business members.

Local Economic Benefit

Property Taxes, paid in calendar year 2015:

- Millard School District $6,836,423
- Millard County General Fund $3,555,633
- County Assessing & Collecting $403,606
- State Assessment/Collection Fees $12,985
- Fire District $350,586
- Mosquito Abatement $491,420
- Other $105
- Total **$11,650,758**

This was approximately 42% of all taxes collected in Millard County

State Economic Benefit

IPP'S State Tax Payments & Payments Made In Lieu of taxes

	Sales & Use	Gross Receipts	Fees in Lieu	Total
2015 TAXES	413,569	4,869,322	12,220,173	**$17,503,064**
Cumulative	26,436,667	136,648,819	452,301,182	**$615,386,668**

State Economic Benefit

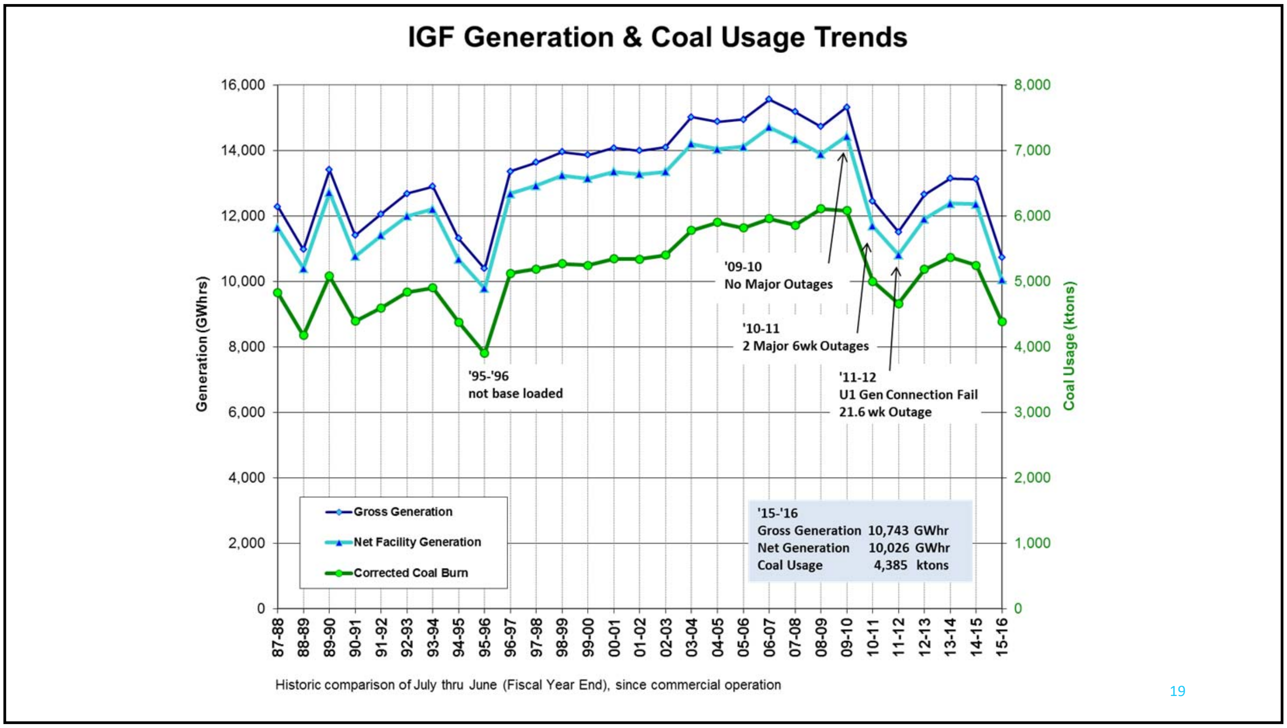
Economic and Fiscal Impact Analysis of IPP

December 6th, 2010 Utah Foundation Report

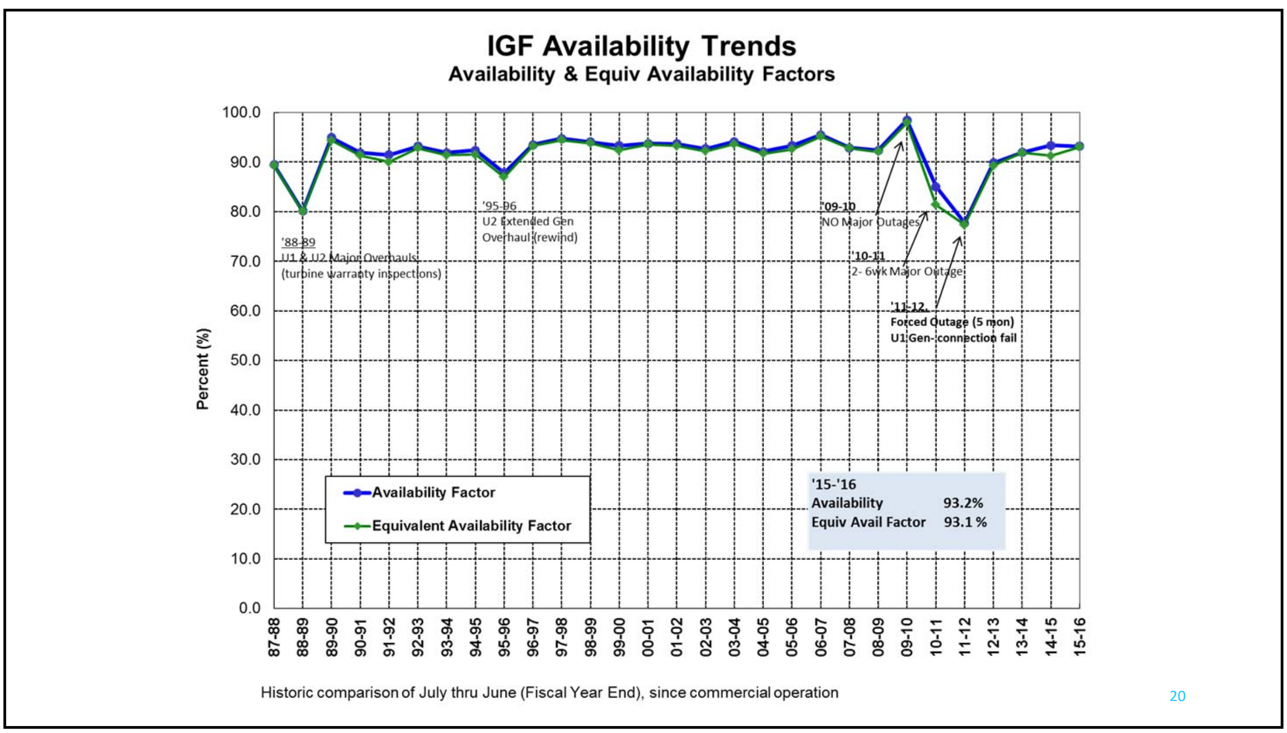
IPP generates more than 13,000,000 MWhr of energy each year from its 2 coal-fired units. In 2008, IPP contributed about $627,000,000 in economic activity, 3,350 jobs, and $147,000,000 in household earnings to Utah's economy.

Through the year 2026, IPP may continue to contribute in the magnitude of 0.60% of state GDP, 0.25% of state employment, and between 0.25% and 0.30% of Utah's total household earnings each year.

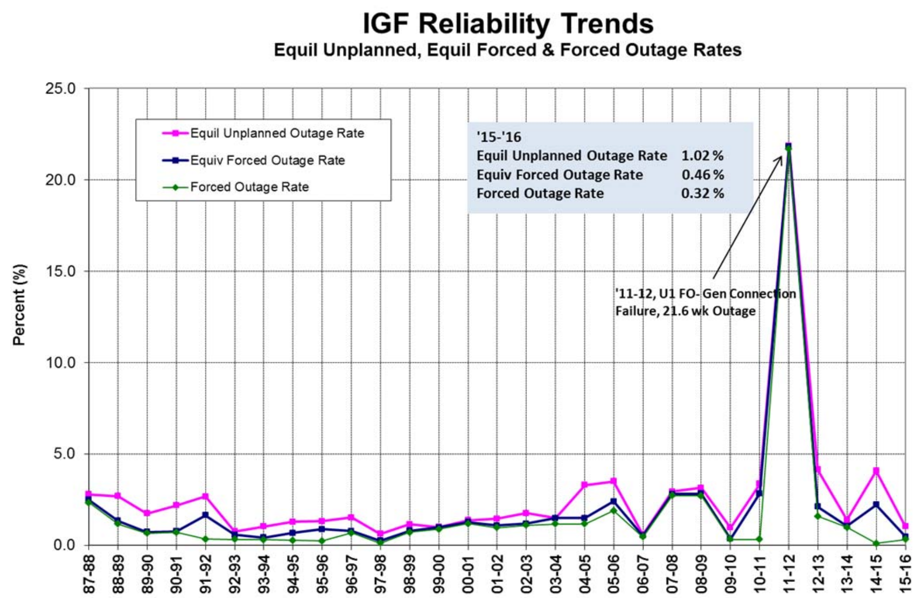
This equates to an average contribution per year of $866,000,000 in economic activity to the state, 4,600 non-farm jobs, and $222,000,000 in household earnings.



IGF Generation & Coal Usage Trends
Generation (GWhrs)
Coal Usage (ktons)
'09-10
No Major Outages
'10-11
2 Major 6wk Outages
'11-12
U1 Gen Connection Fail
21.6 wk Outage
'95-'96
not base loaded
Gross Generation
Net Facility Generation
Corrected Coal Burn
'15-'16
Gross Generation 10,743 GWhr
Net Generation 10,026 GWhr
Coal Usage 4,385 ktons
Historic comparison of July thru June (Fiscal Year End), since commercial operation
19



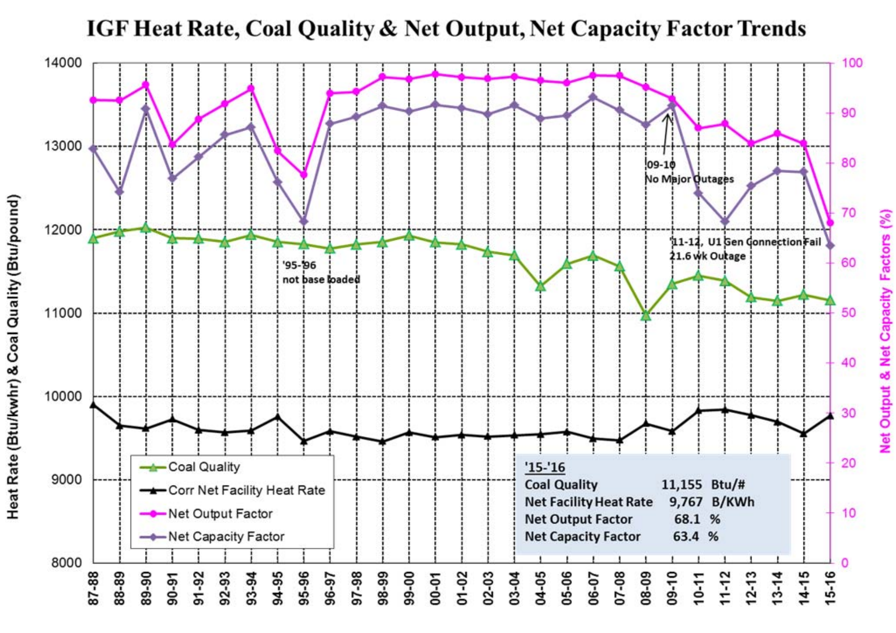
IGF Availability Trends
Availability & Equiv Availability Factors
Percent (%)
'88-89
U1 & U2 Major Overhauls
(turbine warranty inspections)
'95-96
U2 Extended Gen
Overhaul (rewind)
'09-10
NO Major Outages
'10-11
2- 6wk Major Outage
'11-12
Forced Outage (5 mon)
U1 Gen- connection fail
Availability Factor
Equivalent Availability Factor
'15-'16
Availability 93.2%
Equiv Avail Factor 93.1 %
Historic comparison of July thru June (Fiscal Year End), since commercial operation
20



Historic comparison of July thru June (Fiscal Year End), since commercial operation

NOTES: Equivalent Unplanned Outage Rate includes forced outages, maintenance outages, plus all derates, but excludes annual pre-planned unit overhauls. Equivalent Forced Outage Rate is the total time charged to forced outages and unit derates. Forced Outage Rate is the time charged just to forced outages (unit trips).

21

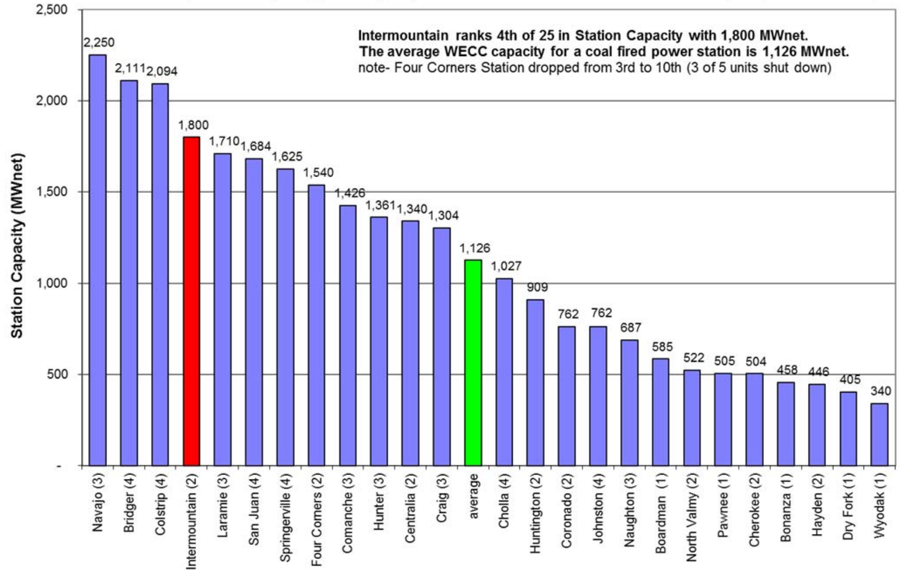


Historic comparison of July thru June (Fiscal Year End), since commercial operation

22

STATION CAPACITY COMPARISON

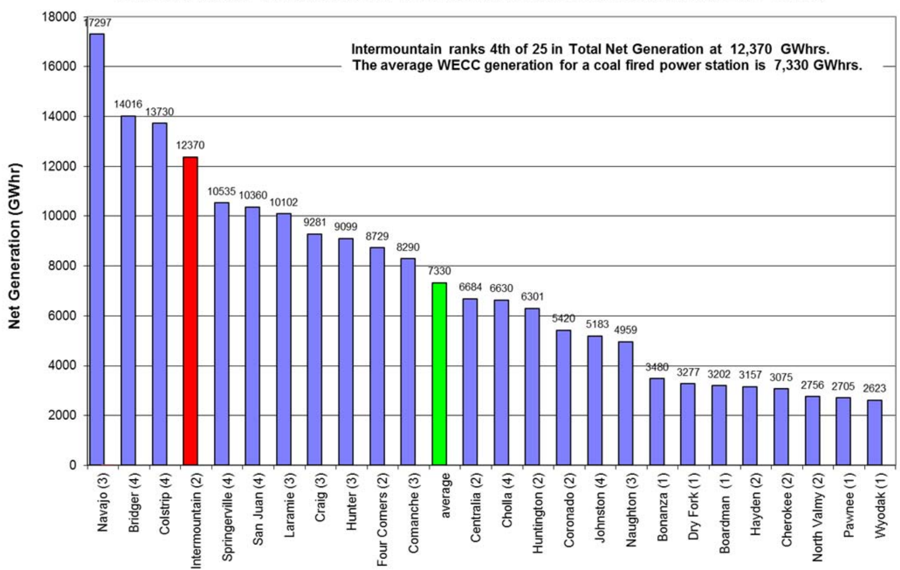
Data ranked by Station Capacity (MWnet), Top 25 Coal Fired Plants from the Western Region (NERC- WECC)



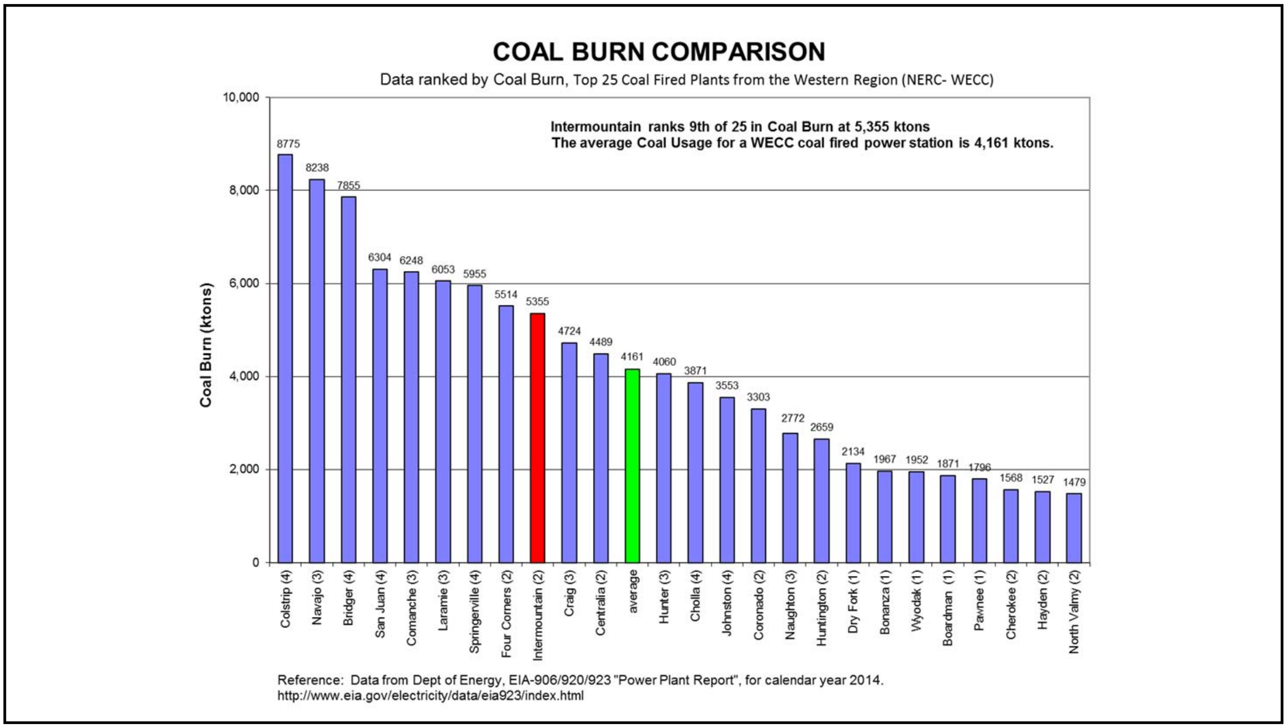
Reference: Data from Dept of Energy, EIA-860, for calendar year 2014
http://www.eia.gov/electricity/data/eia860/index.html

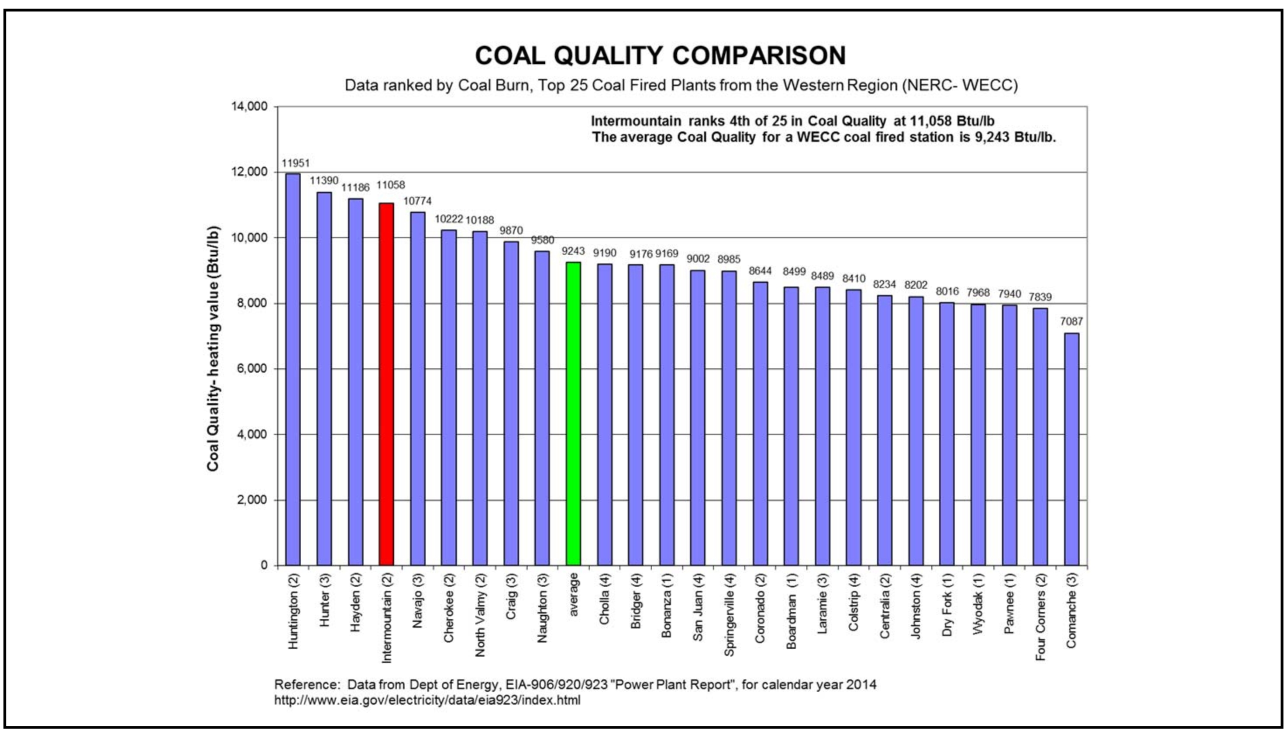
NET GENERATION COMPARISON

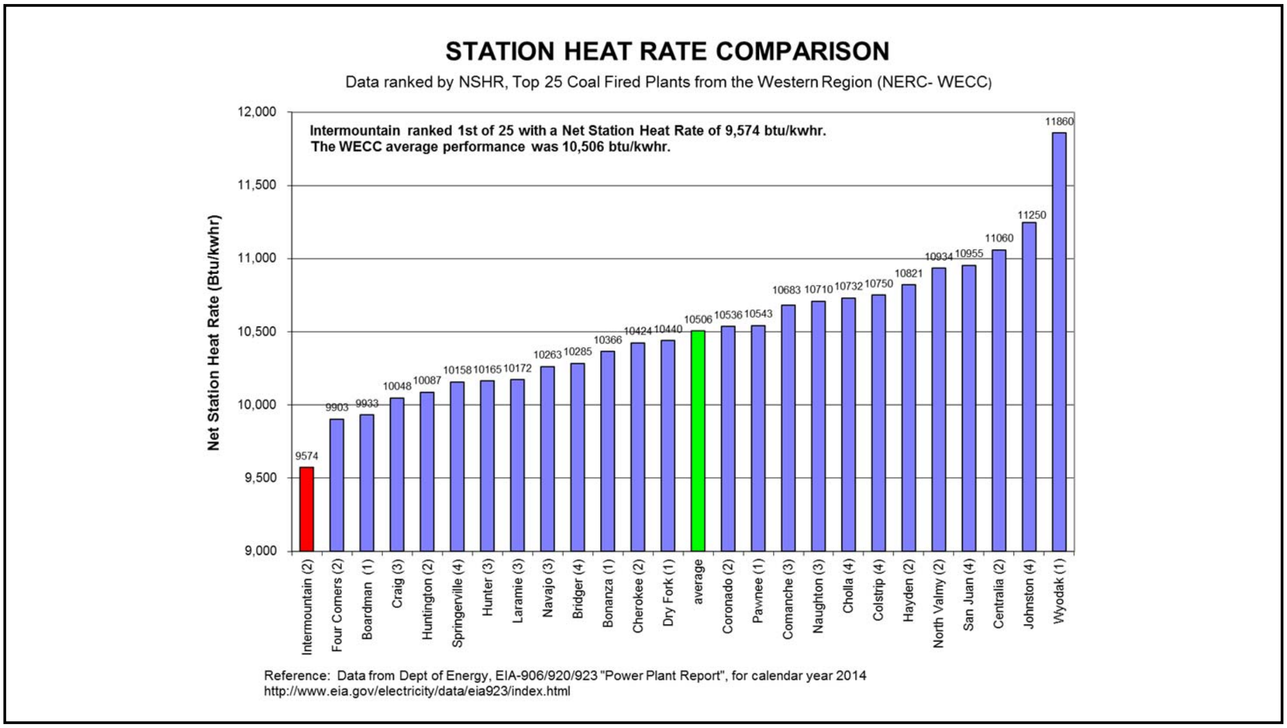
Data ranked by Net Generation, Top 25 Coal Fired Plants from the Western Region (NERC- WECC)

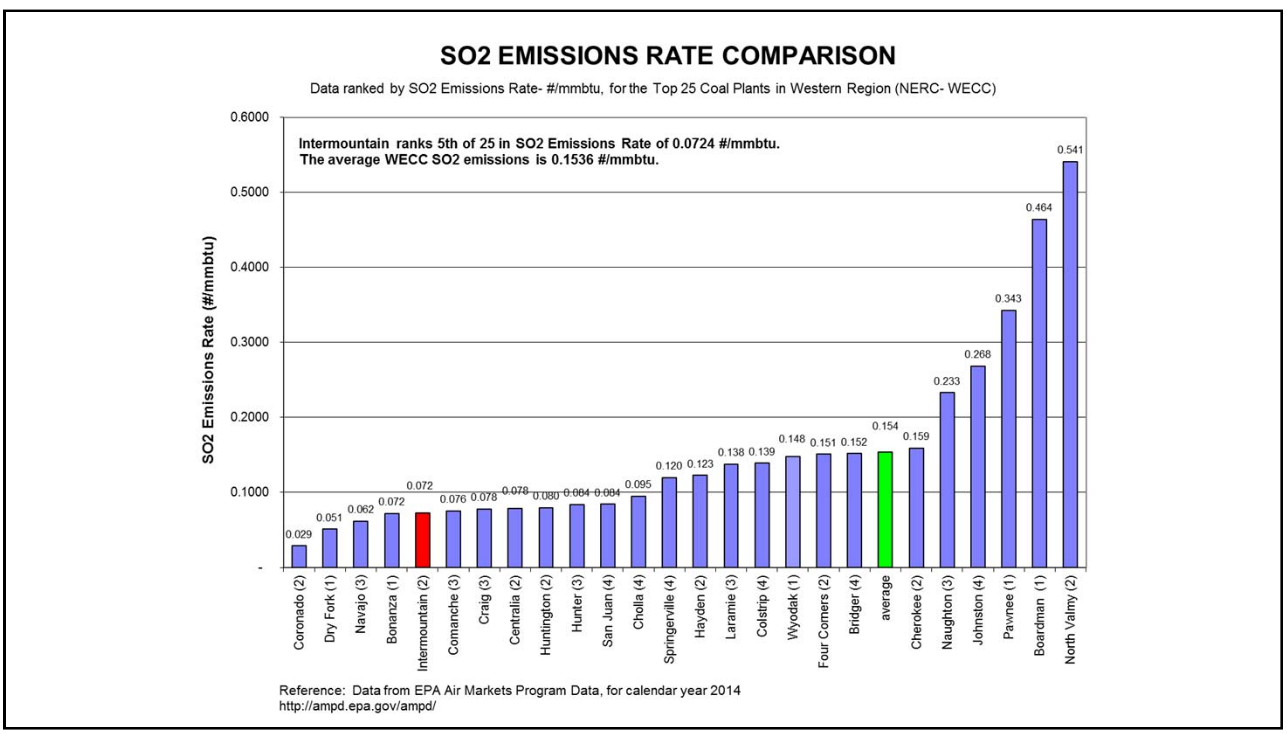


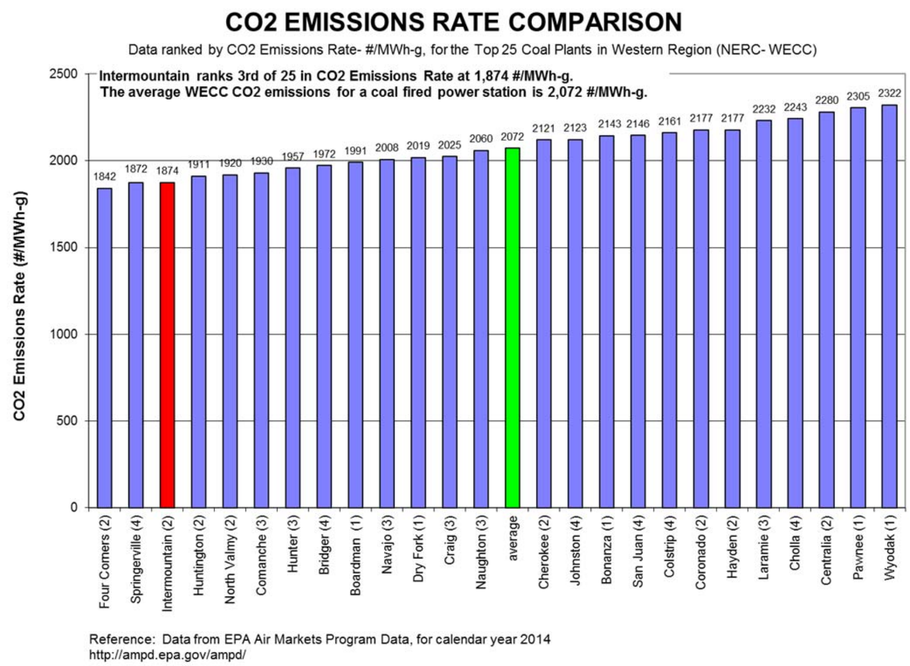
Reference: Data from Dept of Energy, EIA-906/920/923 "Power Plant Report", for calendar year 2014
http://www.eia.gov/electricity/data/eia923/index.html


COAL BURN COMPARISON
Data ranked by Coal Burn, Top 25 Coal Fired Plants from the Western Region (NERC- WECC)
Intermountain ranks 9th of 25 in Coal Burn at 5,355 ktons
The average Coal Usage for a WECC coal fired power station is 4,161 ktons.
Coal Burn (ktons)
10,000
8,000
6,000
4,000
2,000
0
8775
8238
7855
6304
6248
6053
5955
5514
5355
4724
4489
4161
4060
3871
3553
3303
2772
2659
2134
1967
1952
1871
1796
1568
1527
1479
Colstrip (4)
Navajo (3)
Bridger (4)
San Juan (4)
Comanche (3)
Laramie (3)
Springerville (4)
Four Corners (2)
Intermountain (2)
Craig (3)
Centralia (2)
average
Hunter (3)
Cholla (4)
Johnston (4)
Coronado (2)
Naughton (3)
Huntington (2)
Dry Fork (1)
Bonanza (1)
Wyodak (1)
Boardman (1)
Pawnee (1)
Cherokee (2)
Hayden (2)
North Valmy (2)
Reference: Data from Dept of Energy, EIA-906/920/923 "Power Plant Report", for calendar year 2014.
http://www.eia.gov/electricity/data/eia923/index.html


COAL QUALITY COMPARISON
Data ranked by Coal Burn, Top 25 Coal Fired Plants from the Western Region (NERC- WECC)
Intermountain ranks 4th of 25 in Coal Quality at 11,058 Btu/lb
The average Coal Quality for a WECC coal fired station is 9,243 Btu/lb.
Coal Quality- heating value (Btu/lb)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
11951
11390
11186
11058
10774
10222
10188
9870
9580
9243
9190
9176
9169
9002
8985
8644
8499
8489
8410
8234
8202
8016
7968
7940
7839
7087
Huntington (2)
Hunter (3)
Hayden (2)
Intermountain (2)
Navajo (3)
Cherokee (2)
North Valmy (2)
Craig (3)
Naughton (3)
average
Cholla (4)
Bridger (4)
Bonanza (1)
San Juan (4)
Springerville (4)
Coronado (2)
Boardman (1)
Laramie (3)
Colstrip (4)
Centralia (2)
Johnston (4)
Dry Fork (1)
Wyodak (1)
Pawnee (1)
Four Corners (2)
Comanche (3)
Reference: Data from Dept of Energy, EIA-906/920/923 "Power Plant Report", for calendar year 2014
http://www.eia.gov/electricity/data/eia923/index.html


STATION HEAT RATE COMPARISON
Data ranked by NSHR, Top 25 Coal Fired Plants from the Western Region (NERC- WECC)
Intermountain ranked 1st of 25 with a Net Station Heat Rate of 9,574 btu/kwhr.
The WECC average performance was 10,506 btu/kwhr.
Net Station Heat Rate (Btu/kwhr)
12,000
11,500
11,000
10,500
10,000
9,500
9,000
9574
9903
9933
10048
10087
10158
10165
10172
10263
10285
10366
10424
10440
10506
10536
10543
10683
10710
10732
10750
10821
10934
10955
11060
11250
11860
Intermountain (2)
Four Corners (2)
Boardman (1)
Craig (3)
Huntington (2)
Springerville (4)
Hunter (3)
Laramie (3)
Navajo (3)
Bridger (4)
Bonanza (1)
Cherokee (2)
Dry Fork (1)
average
Coronado (2)
Pawnee (1)
Comanche (3)
Naughton (3)
Cholla (4)
Colstrip (4)
Hayden (2)
North Valmy (2)
San Juan (4)
Centralia (2)
Johnston (4)
Wyodak (1)
Reference: Data from Dept of Energy, EIA-906/920/923 "Power Plant Report", for calendar year 2014
http://www.eia.gov/electricity/data/eia923/index.html


SO2 EMISSIONS RATE COMPARISON
Data ranked by SO2 Emissions Rate- #/mmbtu, for the Top 25 Coal Plants in Western Region (NERC- WECC)
Intermountain ranks 5th of 25 in SO2 Emissions Rate of 0.0724 #/mmbtu.
The average WECC SO2 emissions is 0.1536 #/mmbtu.
SO2 Emissions Rate (#/mmbtu)
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
-
0.029
0.051
0.062
0.072
0.072
0.076
0.078
0.078
0.080
0.084
0.084
0.095
0.120
0.123
0.138
0.139
0.148
0.151
0.152
0.154
0.159
0.233
0.268
0.343
0.464
0.541
Coronado (2)
Dry Fork (1)
Navajo (3)
Bonanza (1)
Intermountain (2)
Comanche (3)
Craig (3)
Centralia (2)
Huntington (2)
Hunter (3)
San Juan (4)
Cholla (4)
Springerville (4)
Hayden (2)
Laramie (3)
Colstrip (4)
Wyodak (1)
Four Corners (2)
Bridger (4)
average
Cherokee (2)
Naughton (3)
Johnston (4)
Pawnee (1)
Boardman (1)
North Valmy (2)
Reference: Data from EPA Air Markets Program Data, for calendar year 2014
http://ampd.epa.gov/ampd/



UTILITY RELIABILITY COMPARISONS

IGS vs NERC UTILITY COMPARISON DATA

2010 - 2014	Intermountain ('10-14 data)	Coal fired, 800-999 MW	Difference (IGS better than "like" units)
# Units	2	36	
Availability Factor	88.3	85.2	3.2
Equiv Availability Factor	86.9	83.5	3.4
Net Output Factor	87.0	85.0	2.0
Net Capacity Factor	**76.8**	**68.6**	8.3
Forced Outage Rate	5.02	4.52	-0.50
Equiv Forced Outage Rate	6.06	5.76	-0.30

Note- IGS #'s recovering from 11-1228 U1 Gen Stator Connection Failure, 5.0 months duration which BIAS numbers UP

Intermountain Power Project

Lifetime Highlights - 30 years of Operation

(since U1 commercial operation on 7/1/1986, through 6/30/2016)

- **Net Generation** 368,077 GWhr
- **Coal Usage** 151,914 ktons
- **Coal Quality** 11,644 btu/#
- **Net Facility Heat Rate** 9,601 btu/kwh

- **Availability Factor** 91.57 %
- **Forced Outage Rate** 1.72 %
- **Net Capacity Factor** 83.31 %
- **Net Output Factor** 90.94 %

Intermountain Power Project

Lifetime Highlights - 30 years of Operation

(since U1 commercial operation on 7/1/1986, through 6/30/2016)

- **Net Generation** 368,077,277,000 KWhr
  electricity at $0.05/kwhr, valued at $18,403,863,850

- **Coal Usage** 151,914,000 tons
  coal at 40 $/ton, valued at $6,076,560,000

IPP Challenges to Continued Operation

- EPA Clean Air Act Section 114 Audit
- EPA CCR Final Rule published April 18, 2015
- EPA Clean Power Plan (111(d) carbon rule)
- California Carbon Tax and RPF
- Low Price of Natural Gas
- California Legislation Limiting GHG, loss of customers

33

Future Plan

34

Proposed Solar Project West of IPP, desiring to connect to Southern California.

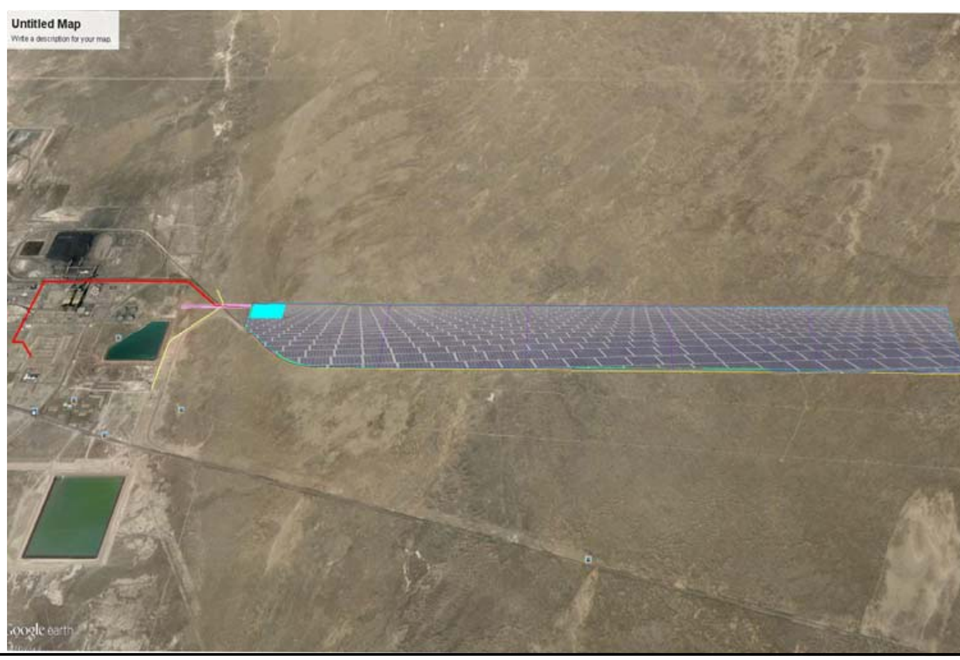
Notch Peak Solar Project

BayWa r.e. | BayWa r.e. Solar Projects LLC

Company presentation Slide 13

35

Proposed Solar Project East of IPP, desire to connect to Southern California, ECG/EDF



36

37

Salt Cavern Storage

Magnum Salt Dome is One-of-a-Kind:

- Only salt dome in the Western U.S.
- At the crossroads of energy and transportation infrastructure
- Strategic asset for the State of Utah and the West

Salt is the Ideal Storage Medium:

- Recognized by the U.S. Government (Strategic Petroleum Reserve)
- Broadly utilized by the energy industry

Salt Caverns Store a Wide Range of Energy Products:

- Natural Gas
- CAES (Compressed Air Energy Storage)
- Natural Gas Liquids
- Petroleum Products
- CO_2

Strategic Location:
At the Crossroads of Significant Existing Infrastructure

Connected to Multiple Power Markets:
- Significant existing onsite transmission connectivity to Mona (2 x 345KV – Utah), Gonder (230KV - Nevada) and Los Angeles (500DC)

Kern & Questar Natural Gas Pipelines:
- FERC 7C & BLM permitted 36-inch header to interconnect at Goshen, with backhaul capabilities to multiple other pipelines at Opal

UP Railroad Mainline:
- 7-mile existing rail lead to Union Pacific Railroad Mainline

UNEV Pipeline:
- Adjacent to site; refined products pipeline with maximum capacity of 118,000 bpd; ability to transport NGLs in batches from Salt Lake refineries and beyond

I-15 and I-80 Highways:
- Direct access to interstate highway system and enough land to accommodate as many trucks as needed

Salt Cavern Storage Basics

Magnum's Salt Dome Can Accommodate the Creation of a 100+ Caverns
- Each cavern contains a dedicated product
- Each cavern is custom designed
- Each cavern is solution mined by injecting water
- Brine is stored in double-lined leak detected ponds
- 1000s of salt caverns are in use around the world

Magnum's Western Energy Hub

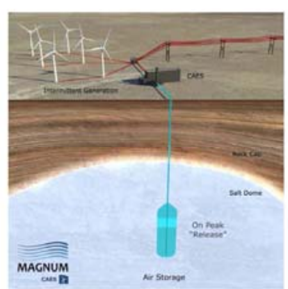
Business Platforms:

MAGNUM Gas Storage | MAGNUM NGLs | MAGNUM Power | MAGNUM CAES | MAGNUM Salt

Magnum CAES

Compressed Air Energy Storage

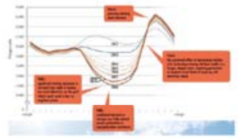
- Proven technology
  - Electric compressors w/ modified gas turbine
- Can be used to firm and shape intermittent power generation – renewable integration
- Optimize existing infra-structure
- Two operating facilities
  - McIntosh, Alabama (in-service 1991)
  - Huntdorf, Germany (in-service 1978)
    - Created directly above solution mined caverns on a salt dome
    - Salt dome also contains high deliverability gas storage
- Magnum CAES
  - 150 mW units that can be easily expanded as demand increases
    - Capex similar to CCGT
    - Can generate or store



Renewable Integration is Driving Storage Demand

California Sets Targets for Energy Storage Deployment for IOUs

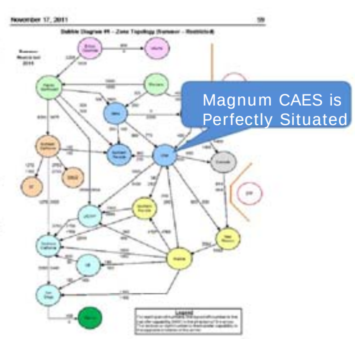
- World's Largest Procurement Commitment for Electricity Storage Solutions.



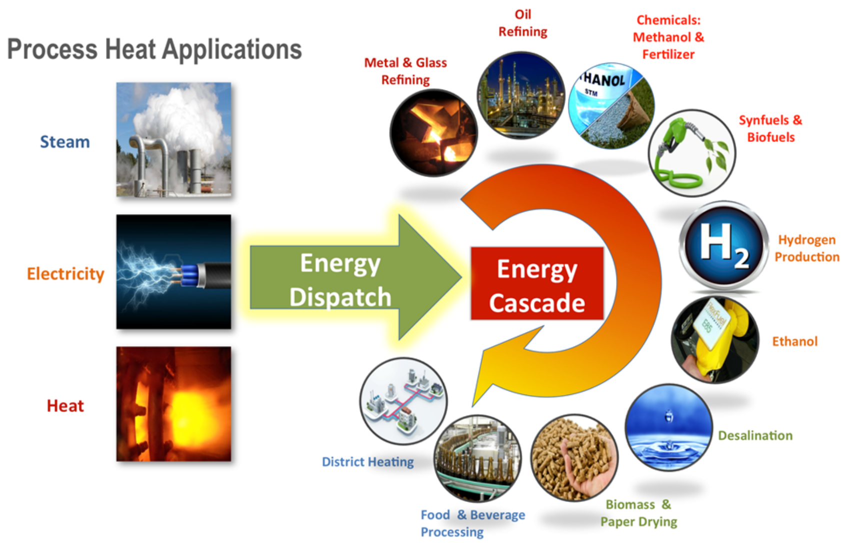
STORAGE GRID DOMAIN POINT OF INTERCONNECTION	2014	2016	2018	2020	TOTAL
Southern California Edison					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal SCE	**90**	**120**	**160**	**210**	**580**
Pacific Gas and Electric					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal PG&E	**90**	**120**	**160**	**210**	**580**
San Diego Gas and Electric					
Transmission	10	15	22	33	80
Distribution	7	10	15	23	55
Customer	3	5	8	14	30
Subtotal SDG&E	**20**	**30**	**45**	**70**	**165**
TOTAL - ALL 3 UTILITIES	**200**	**270**	**365**	**490**	**1,325**

7

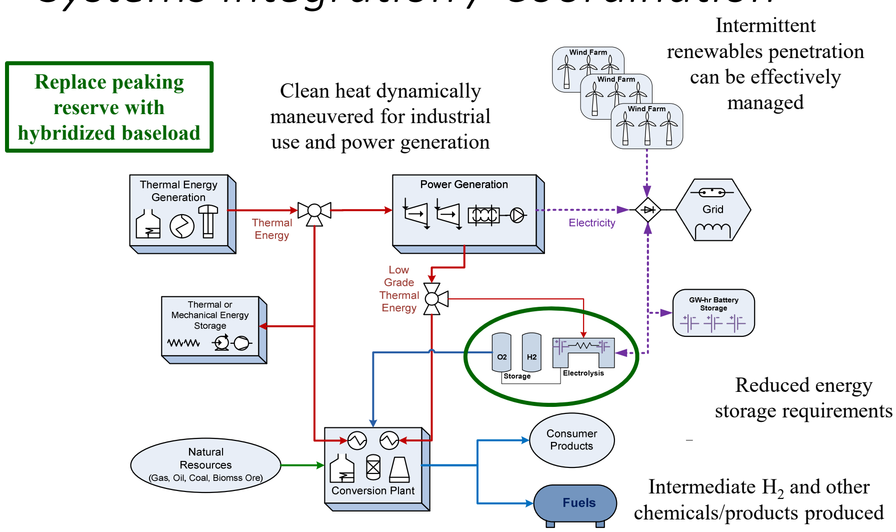
...The Good News is that Magnum CAES Lies in the Heart of the WECC Grid



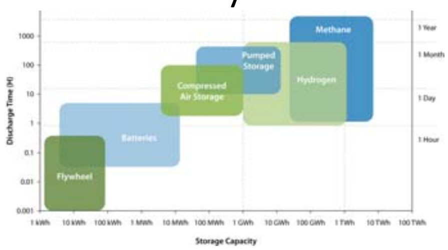
Integrated Energy System Heat Applications:



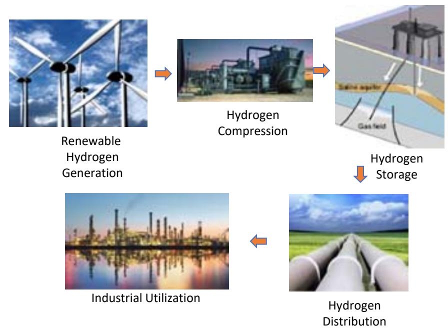
Systems Integration / Coordination

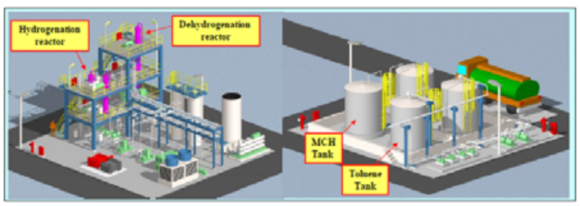


Grid Scale Hydrogen Storage & Delivery



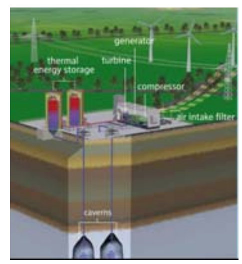
Hydrogen Excellent Energy Storage Medium





Chemical Storage

Geologic Storage



Cast-Iron Hexagons With Cladding for Heat Storage in Sodium, Salt, Lead and Helium Cooled Reactors

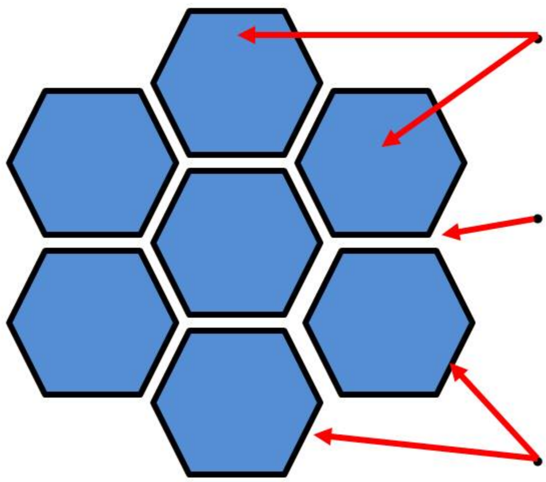
Charles Forsberg (cforsber@mit.edu)
Department of Nuclear Science and Engineering
Massachusetts Institute of Technology

Piyush Sabharwall (piyush.sabharwall@inl.gov)
Idaho National Laboratory, Idaho Falls, ID

Takeaway Messages

- As a heat storage material, iron is cheap and can operate from 100 to 700/900°C
- Steel cladding can be chosen for helium, sodium, lead or salt (fluoride, nitrate or chloride) environment—universal storage material
- Cast iron sets an upper limit on storage costs for sensible heat storage

Cast Iron Storage for Any Coolant In Primary or Secondary Loop

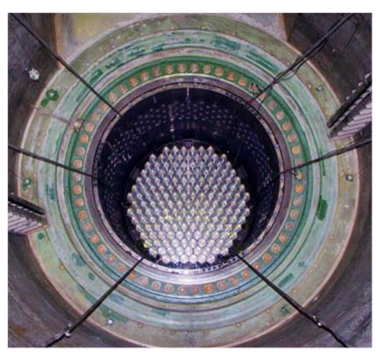


- Cast iron hexagons up to 20 meters high, Hundreds of hexagons
- Vertical coolant flow channels
  - Width dependent upon coolant
  - Tabs on assemblies to space array
- Corrosion Resistant Wrapper

3

Cast Iron Storage In Tank Is Similar to Hexagonal Fuel Assemblies in Sodium and Russian Light Water Reactors

- We know how to design hexagonal structures in close-packed arrays
- Practical experience with different coolants



Russian VVER Core

Massachusetts Institute of Technology

4

Characteristics of Cast Iron Storage

- Sensible heat storage with cast iron. Clad metal chosen for corrosion resistance to primary or secondary reactor coolant (sodium, salt, lead or helium)
- Temperature range from 100 to 700/900°C
- Low cost
- Layout: hexagonal assemblies 10 to 20 meters high in close-pack array
  - Maximize storage heat capacity with >95% of volume in hexagonal solid assemblies
  - Minimize primary or secondary coolant fraction to minimize cost and maximize safety (sodium case)

5

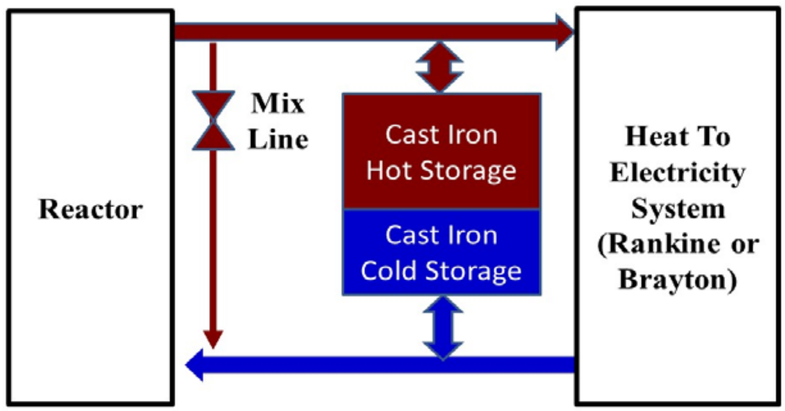
Cast Iron Constraints

- Peak temperature limit is a tradeoff between performance and cost. Design constraints
  - Cast iron (iron + carbon) phase change with significant expansion 727 °C
  - Pure iron phase change at 917°C
  - Loose strength at higher temperatures
- Minimizing costs requires design with fabricator where minimum-cost design may depend upon fabricator facilities—manufacturing cost determines design

Massachusetts Institute of Technology

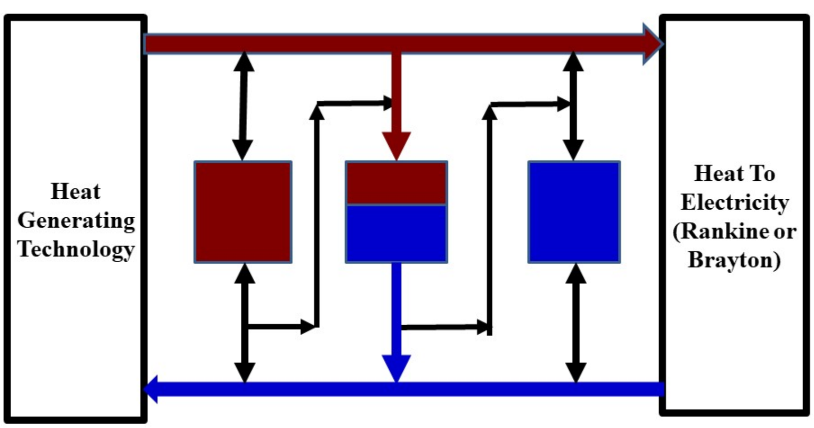
6

Cast Iron Storage with Small Temperature Drop Across Reactor and Large Temperature Drop Across Cast Iron to Minimize Storage Cost

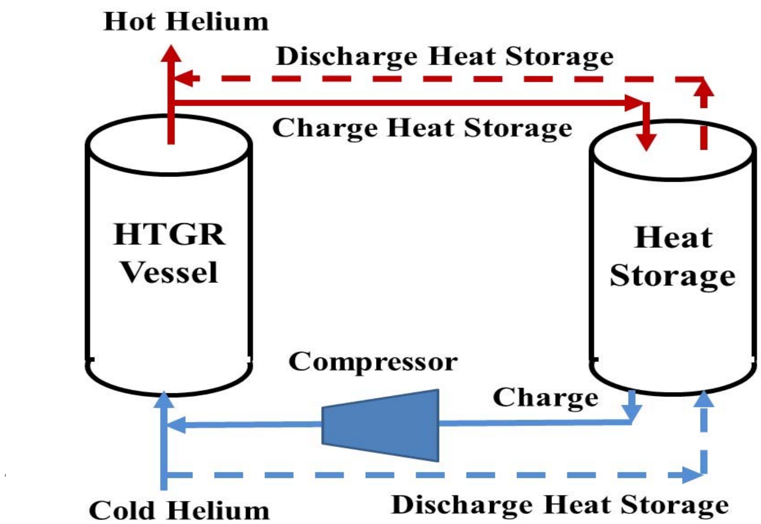


Sodium or Salt-Cooled Reactor Intermediate Loop

Cast Iron Heat Storage Can Be Placed in Series to Minimize Conductive Heat Loses in the Vertical Direction



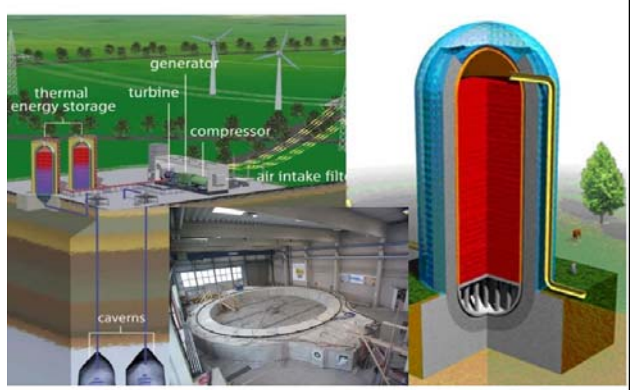
Integrating Cast Iron With Primary Helium in High-Temperature Gas-Cooled Reactor



9

Large Pressure Vessels Being Developed for Adiabatic Compressed Air Storage

- Primary system minimizes temperature losses
- Fast response to variable electricity prices
- Steam or Brayton cycle



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

10

Size and Cost of Cast Iron Heat-Storage System is Reasonable

- Gigawatt-hour of cast iron with 100°C Delta T
  - 80,000 metric tons
  - 10,000 m^3
  - If 15 meters high, Diameter 29 m
- Cast iron capital cost: $500/ton (plus cladding and system)
  - $40/kWh if 100°C Delta T
  - $13/kWh if 300°C Delta T

Massachusetts Institute of Technology

11

Can the Steel Clad Be Filled with Other Heat Storage Materials?

- Potentially other storage materials
  - Firebrick, alumina, phase-change, etc.
  - Requires thicker steel cladding (container) to provide structural
- Cast iron with cladding fabrication: Integrated piece
  - Cast iron
  - Fit cladding over cast iron
  - Pull vacuum and heat to bond into single structure (other fabrication options exist)

Massachusetts Institute of Technology

12

Conclusions

- Cast iron storage is compatible with all coolants if use appropriate cladding
- Cast iron
  - Can be used in primary or secondary loop of reactor
  - Minimizes risk by minimizing total inventory of reactive coolants such as sodium (reduced inventory)
  - Reduces cost if expensive coolant (sodium, many salts)
- Brute force, low technology option
- No detailed engineering studies

Massachusetts Institute of Technology

13

References

1. C. W. Forsberg, "Sodium-Steel Heat Storage for Variable Energy Output from Nuclear and Solar Power Systems," *Transactions of the 2018 American Nuclear Society Winter Meeting held in Orlando, Florida: 11-15 November 2018.*
2. C. W. Forsberg, "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology* March 2019. https://doi.org/10.1080/00295450.2018.1518555
3. C. Forsberg and P. Sabharwall, *Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Operations*, ANP-TR-181, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology, INL/EXT-18-51329, Idaho National Laboratory
4. Charles Forsberg, Stephen Brick, and Geoffrey Haratyk, "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Base-Load Reactor Operation, *Electricity Journal*, **31**, 23-31, April 2018, https://doi.org/10.1016/j.tej.2018.03.008
5. C. Forsberg, K. Dawson, N. Sepulveda, and M. Corradini, *Implications of Carbon Constraints on (1) the Electricity Generating Mix for the United States, China, France and the United Kingdom and (1) Future Nuclear System Requirements*, MIT-ANP-TR-184 (March 2019)

Massachusetts Institute of Technology

14

Chemical Heat Pumps

Vivek P. Utgikar[1], Brian M. Fronk[2], and Piyush Sabharwall[3]

[1]University of Idaho, Moscow, ID 83844
(208) 885-6970, vutgikar@uidaho.edu

[2]Oregon State University, Corvallis, OR 83844
(541) 737-3952, brian.fronk@oregonstate.edu

[3]Idaho National Laboratory, Idaho Falls, ID 83415
(208) 526-6494, piyush.Sabharwall@inl.gov

Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors

Idaho Falls, ID
July 23-24, 2019

University of Idaho

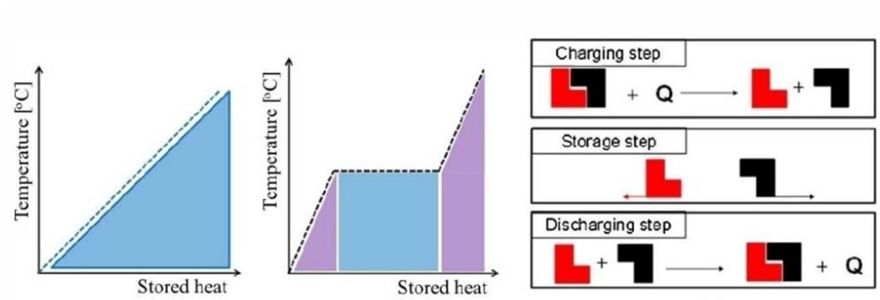
, USA

Contents

College of Engineering

University of Idaho

Thermal Energy Storage (TES) Technologies



Sensible Heat | Latent Heat | Thermochemical

Sarbu and Sebarchievici, *Sustainability*, **2018**, 10, 191

College of Engineering

University of Idaho

Comparison of TES Technologies

Characteristic	Sensible TES	Latent TES	TCS
Energy density	Low (0.2 GJ/m^3)	Medium (0.3-0.5 GJ/m^3)	High (0.5-3 GJ/m^3)
Heat loss	Significant heat loss over time	Significant heat loss over time	Small heat loss
Temperature range	Charging step temperature	Charging step temperature	Ambient temperature
Lifetime	Long	Limited	Depends on reactant degradation and side reactions
Transport	Small distance	Small distance	Unlimited theoretically
Advantages	Low cost and mature technology	Small volume and short distance transport possibility	High storage density, long distance transport possibility, low heat losses
Disadvantages	Significant heat loss over time; large volume needed	Small heat conductivity, materials corrosion, significant heat losses	Technically complex, high costs
Technical complexity	Simple	Medium	Complex

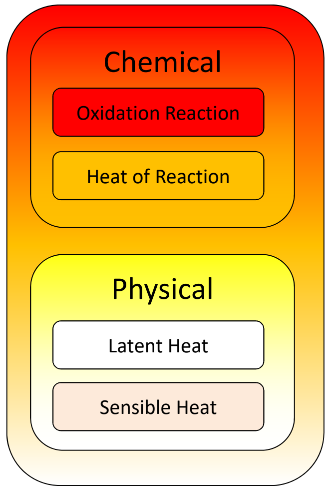
Liu et al, *Int. J. Energy Res.*, **2018**, 42, 4546

College of Engineering

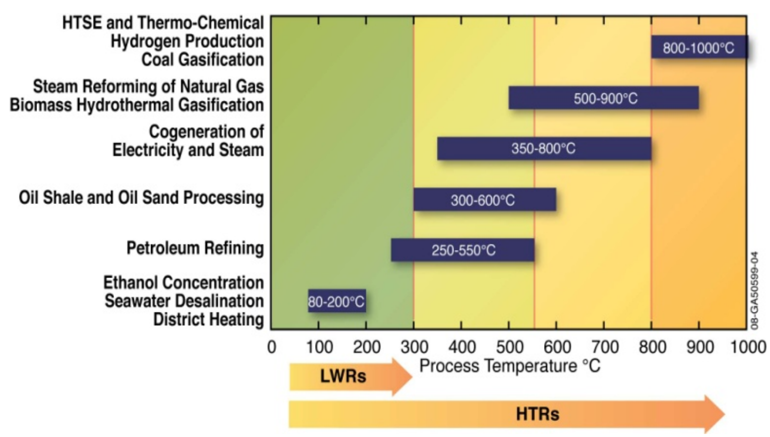
University of Idaho

Energy Storage Density Diagram

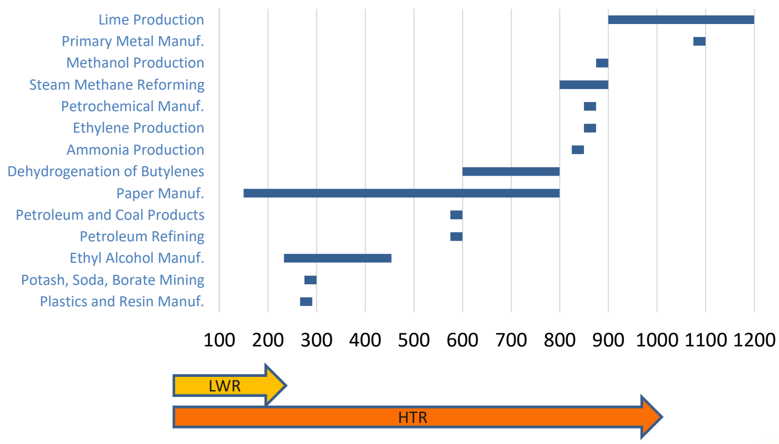
Sensible heat < latent heat < chemical reaction < oxidation reaction



Process Heat Applications



Process Heat Applications



McMillan *et al.*, 2016, NREL/TP-6A50-66763

College of Engineering

University of Idaho

7

Motivation

In order to realize the benefits of nuclear hybrid energy systems with the current reactor fleets, selection and development of a complimentary temperature upgrading technology is necessary

- Potential of production of synthetic fuels based on indigenous carbon sources using nuclear energy
- Process temperature requirements: pyrolysis and hydrotreatment/hydrocracking – 500ºC; gasification and reforming – 800ºC
- Conventional LWRs outlet temperatures:~300°C

College of Engineering

University of Idaho

8

Technology Requirements and Selection for Temperature Upgrading

- Ability to upgrade reactor outlet temperature to levels required for process heat applications (500-800°C)
- Ability to integrate with nuclear hybrid energy systems (tolerant of dynamic or transient operation)
- Economic viability, reliability, and operational safety
- Direct utilization of nuclear heat with minimal energy conversion steps

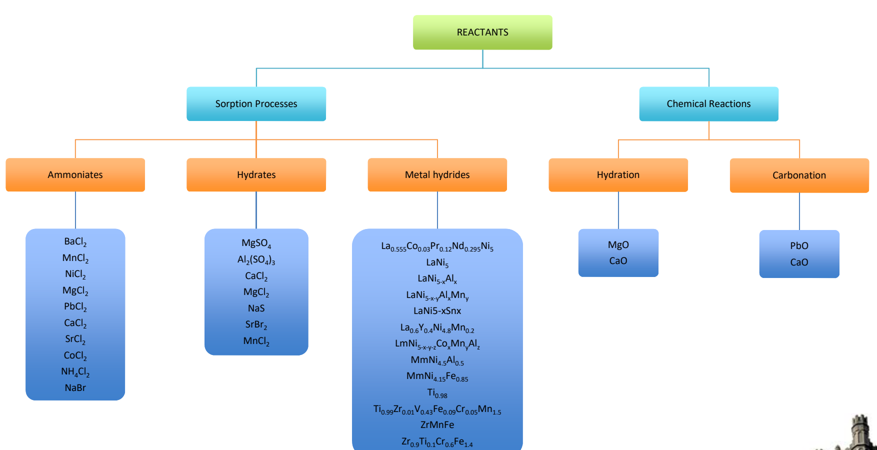
Temperature Upgrading Technologies

- Mechanical Heat Pumps
  - Reverse power cycle (Rankine, Brayton)
  - Low temperature upgrade (up to 200°C)
  - Requires mechanical power source
- Vapor Absorption Heat Pumps
  - Low temperature upgrade (up to 260°C)
  - Driven by thermal energy sources
  - Higher efficiency with few moving parts
- Solid State Heat Pumps
  - Use magnetic or thermoelectric effects to achieve thermal energy transport
  - Require electrical power input
  - Best suited for refrigeration and space heating and cooling applications
- Chemical Heat Pumps (CHPs)
  - Use reversible chemical reactions to change the temperature level of the thermal energy stored by the chemicals
  - High temperature upgrade possible

Chemical Heat Pump Types

- Sorption processes
  - Heating and cooling applications
  - Heat and mass transfer limitations
  - Relatively low temperature (range)
- Chemical reactions
  - Heating and cooling applications
  - Heat and mass transfer limitations
  - Storage of medium and high grade heat (>400°C)

Overview of working pairs



Cot-Gores et al, *Renewable Sustainable Energy Rev.*, **2012**, 16, 5207

Advantages of CHPs

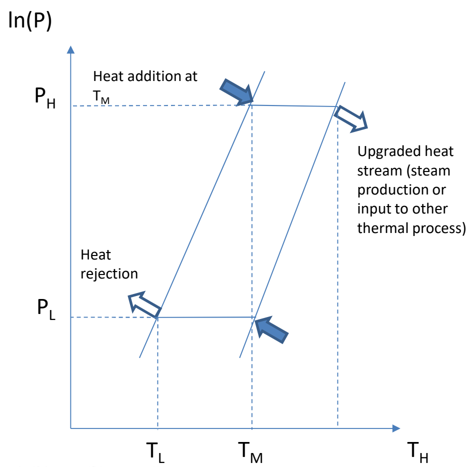
- Operating temperature range higher than mechanical heat pumps
- Reversible reactions (oxidation reactions have higher energy density but are irreversible)
- Possible to operate without mechanical energy input (Hasatani 1992)
- Energy storage potential
  - High energy density relative to sensible or latent heat storage (large energy storage per unit mass)
  - Energy storage without heat loss as in case of sensible or latent heat storage (no insulation required as energy is stored as chemical potential energy)
  - Potential to operate with thermal energy at various temperatures (Hasatani 1992)
- Reaction materials metal oxides/carbonates tend to be inexpensive and non-toxic

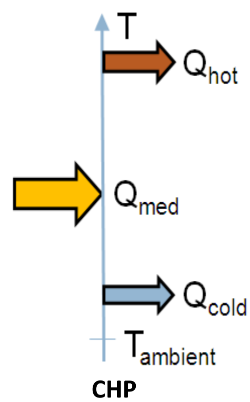
Hasatani M. (1992). Highly developed energy utilization by use of chemical heat pump. In Global Environmental Protection Strategy Through Thermal Engineering, Hemisphere Publishing, New York, pp. 313-322.

Disadvantages/Issues

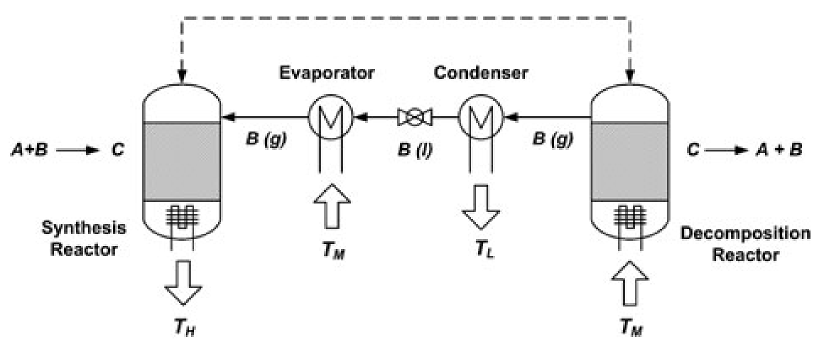
- Inorganic solid/gas CHPs operate as batch processes
- Heat transfer limitations associated with packed bed reactors and solid/gas phase reactions
- Materials stability and durability issues
- Transient systems with temperature fluctuations leading to generation of thermodynamic irreversibility

CHP Operation





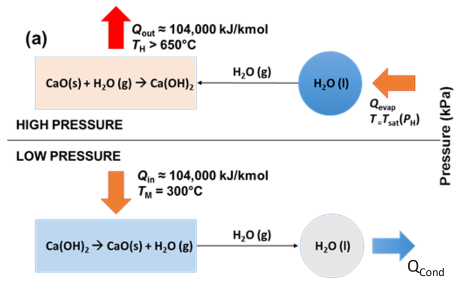
For Continuous Operation: Multiple Reactors



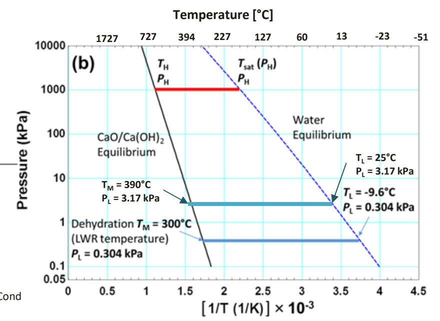
More reactors could also provide sensible heat recuperation to improve heat integration, reducing the thermodynamic losses.

Arjmand et al, *Int. J. Energy Res.*, **2013**, 37, 1122

Dehydration-Hydration CHP

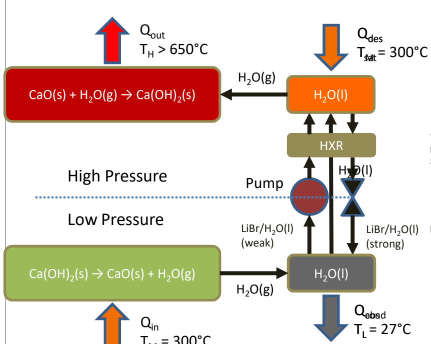


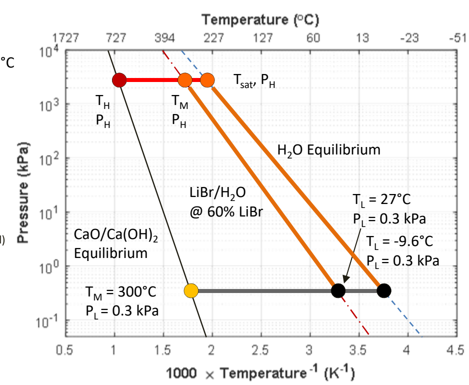
Schematics of component of CHP system



Heat pump cycle on Clausius-Clapeyron diagram showing equilibrium of $CaO/Ca(OH)_2$ and $H_2O_{(L)}/H_2O_{(G)}$

Chemical / Absorption Heat Pump





Sabharwall *et al.*, 2013

Research Effort and Collaboration

- University of Idaho
  - Transient heat and mass transfer and reaction kinetics of CaO
  - Material characterization of CaO
- Oregon State University
  - Transient high temperature heat pump performance
  - Model and evaluate entire system
  - Design, build, and test absorption heat pump subsystem
- Idaho National Laboratory
  - Facilitate university collaboration
  - Enable system integration tests

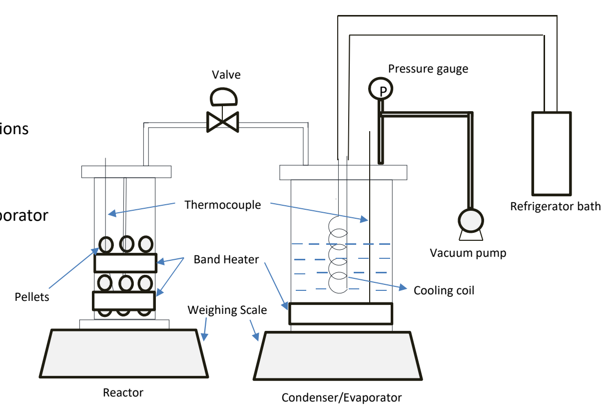
University of Idaho

Oregon State University

INL Idaho National Laboratory

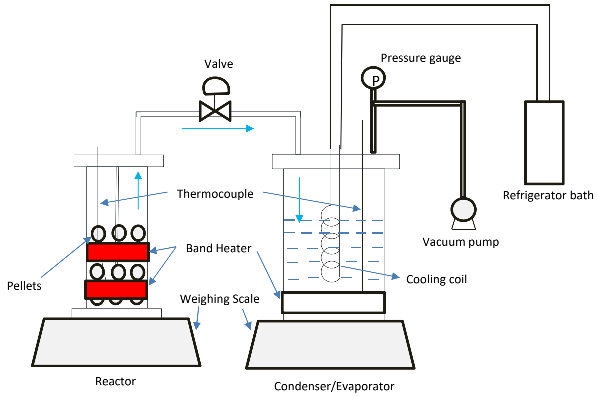
Materials and Methods

- Reactor Dimensions
  ID – 2.5"
  Height – 9"
- Condenser/Evaporator Dimensions
  ID – 4.4"
  Height – 8"



Materials and Methods

Materials and Methods



Materials and Methods

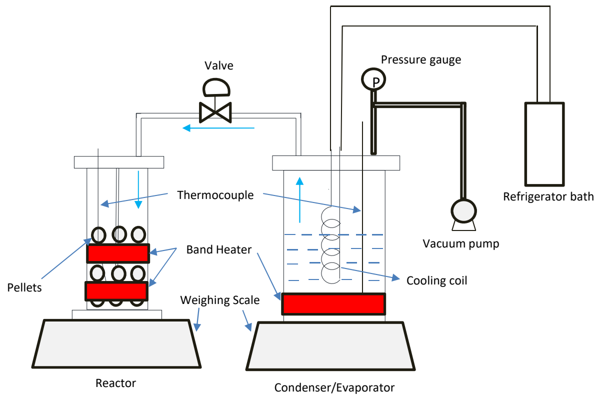


Figure 7 : Schematic of Experimental Setup

Preliminary Results

TABLE III. Change in the reading of weighing scale and unconverted mole fraction with time during dehydration process

Time (min)	Weighing Scale Reading (g)		Unconverted mole fraction
	Reactor	Condenser	
0	0	0	0
118	-3	2	0.95
120	-8	7	0.88
124	-15	13	0.78
126	-30	28	0.57
128	-34	32	0.51
132	-51	48	0.27
135	-60	57	0.14
140	-68	64	0.03

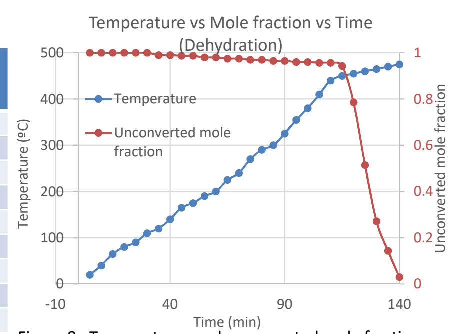


Figure 8 : Temperatures and unconverted mole fraction during dehydration reaction P = 3.17 kPa

Preliminary Results

- Hydration

$CaO(s) + H_2O(g) \leftrightharpoons Ca(OH)_2(s) + \Delta\hat{H}_r \qquad \Delta\hat{H}_r = 104.4\ kJ\ mol^{-1}$

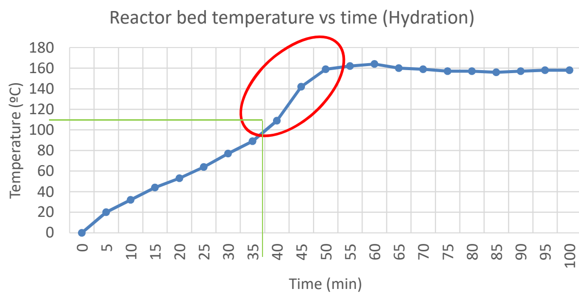


Figure 10 : Temperature profile during hydration process

Observations and Conclusions

- Dehydration process
  - Nearly complete decomposition of $Ca(OH)_2$ in ~150 min
- Hydration process
  - Temperature increase due to exothermic recombination of CaO and H_2O observed
- Absorber-Desorber Modeling
  - Thermal pathway increases exergetic efficiency to >80%
  - Absorber inlet conditions greatly impact performance

Future Work

- Experimental investigation of performance change for repeated dehydration/hydration cycles
- Validation of experimental data with theoretical analysis
- Dynamic chemical/absorption heat pump model development
- Experimental investigations of absorber-desorber system

College of Engineering

University of Idaho

27

Acknowledgement

This research is being performed using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Program. Graduate students supported on the project: Aman Gupta (UI), Paul Armatis (OSU)

NEUP Nuclear Energy University Program

U.S. Department of Energy

College of Engineering

University of Idaho

28

Appendix D
Posters

Appendix D

Posters presented at the Heat Storage for Gen IV Reactors Workshop July 23-24, 2019

1. **MIT / INL / Exelon Workshop, Heat Storage for Gen IV Reactors for Variable Electricity from Base-load Reactors**
    - MIT Co-Chair: Charles Forsberg
    - INL Co-Chairs: Hans D. Gougar, Piyush Sabharwall

2. **Results from: Light Water Reactor Heat Storage for Peak Power and Increased Revenue: Focused Workshop on Near-Term Options**
    - Charles Forsberg, MIT

3. **Phenomenon Identification Ranking Table Development for Identifying Thermal Energy Storage for Near-Term Integration with Light Water Reactors**
    - Daniel M. Mikkelson, North Carolina State University

4. **Optimizing a Heat Storage Retrofit to a Nuclear Power Plant under Market Uncertainty**
    - W. N. Mann (Neal), University of Texas Austin
    - K. Ramirez-Meyers, University of Texas Austin
    - S. Bisett, University of Texas Austin
    - C. Bagdatlioglu, University of Texas Austin
    - S. Landsberg, University of Texas Austin
    - M. E. Webber, University of Texas Austin

5. **OU model acts as a surrogate to the demand power and provide NPPs a knob to control the level of fluctuations for safe and economical operation.**
    - Molly Ross, Kansas State University
    - Abhinav Gairola, Kansas State University
    - Hitesh Bindra, Kansas State University

6. **Cast-Iron with Wrapper for Heat Storage in Sodium, Salt, Lead and Helium**
    - Charles Forsberg, MIT
    - Piyush Sabharwall, Idaho National Laboratory

7. **Alumina particle beds can be durable and economical thermal energy storage media with nitrate salt as HTF.**
    - Brendan Ward, Kansas State University
    - Hitesh Bindra, Kansas State University

Appendix D

8. **Molten Salt Corrosion for Energy Storage**
    - Brendan D'Sonza, Virginia Polytechnic Institute
    - Shaoqiang Guo, Virginia Polytechnic Institute
    - Jinsuo Zhang, Virginia Polytechnic Institute

9. **Progress on the Reheat Air Combined Cycle Coiled Tube Air Heater Design**
    - Shane Gallagher, University of California, Berkeley
    - Per Peterson, University of California, Berkeley

10. **H_2 and Battery Storage Solutions**
    - Tim Stack, Framatome

11. **Metal Hydride TES for CSP and Nuclear Applications**
    - Jamison Couture, Brayton Energy

12. **Markets, Design, and Experiments for Firebrick Resistance – Heated Energy Storage (FIRES)**
    - Daniel C. Stack, MIT
    - Charles Forsberg, MIT

13. **Latent Heat Thermal Energy Storage System**
    - Amey Shigrekar, University of Idaho
    - Piyush Sabharwall, Idaho National Laboratory
    - Richard Christensen, University of Idaho
    - Matt Memmott, Brigham Young University

14. **Solid-Liquid Phase Change Materials for High-Temperature Nuclear Reactor Heat Storage**
    - W. N. Mann (Neal), University of Texas at Austin
    - S. Landsberger, University of Texas at Austin
    - M. E. Webber, University of Texas at Austin

15. **Ceramic Encapsulated Metal Phase Change Material for Tunable, High Temperature Thermal Energy Storage**
    - J. W. McMurray, Oak Ridge National Laboratory
    - B. C. Jolly, Oak Ridge National Laboratory
    - S. S. Raiman, Oak Ridge National Laboratory
    - A. T. Schumacher, Oak Ridge National Laboratory
    - K. M. Cooley, Oak Ridge National Laboratory
    - E. Lara-Curzio, Oak Ridge National Laboratory

Appendix D

16. Experimental Investigation and Analysis of Ca $(OH)_2$ / CaO Cemical Heat Pump for Thermal Energy Storage

- Aman Gupta, University of Idaho
- Paul D. Armatis, Oregon State University
- Piyush Sabharwall, Idaho National Laboratory
- Vivek Utgikar, University of Idaho
- Brian M. Fronk, Oregon State University

17. Nuclear Energy Thermal Energy Upgrade with a Chemical – Absorption Heat Pump

- Paul D. Armatis, Oregon State University
- Aman Gupta, University of Idaho
- Piyush Sabharwall, Idaho National Laboratory
- Vivek Utgikar, University of Idaho
- Brian M. Fronk, Oregon State University

18. Welcome, Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors

MIT/INL/Exelon Workshop

Heat Storage for Gen IV Reactors for Variable Electricity from Base-load Reactors

Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

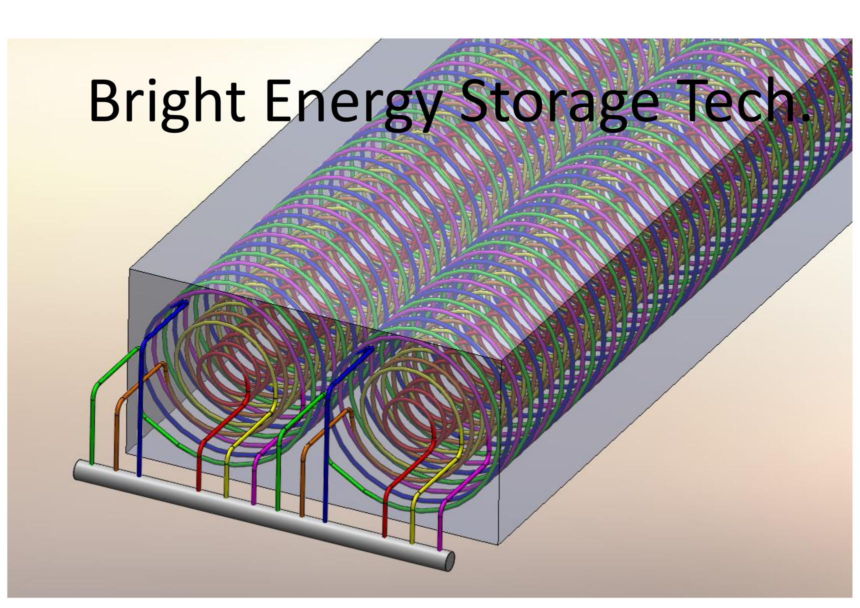
Bennion Student Union Building, Idaho State University, Idaho Falls, Idaho

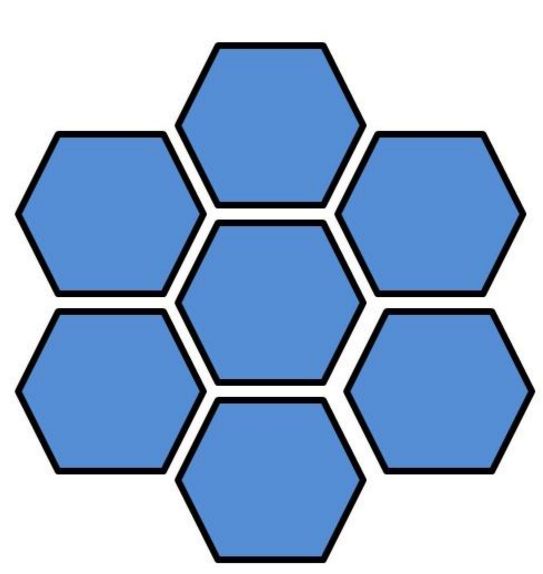
July 23, 2019: 8:15 am to 5:00 pm (plus dinner)

July 24, 2019: 8:30 to 12:00 Noon

The workshop will examine heat storage coupled to Generation-IV reactors (helium, sodium/lead and salt coolants) to enable variable electricity output while the reactor operates at base-load. The goal of the workshop is to develop a strategic path forward to incorporate heat storage and assured peak generating capacity into GenIV reactors to enable them to be competitive in the changing electricity market. The workshop addresses heat storage options associated with higher-temperature GenIV reactor systems that allow larger hot-to-cold temperature swings in storage with less storage mass per unit of stored heat. Higher-temperature stored heat allows higher heat-to-electricity efficiency with less storage mass per unit of electricity. These factors lower the cost of heat storage for higher-temperature GenIV reactors.

The workshop will address (1) the requirements for variable power based on market considerations, (2) the storage technology options for helium, sodium/lead and salt reactors and (3) what is the path forward. The concentrated solar thermal power (CSP) community faces the same challenges. Thus, the workshop includes participants from the CSP community that is developing many of the same storage technologies. There are large incentives for cooperative GenIV reactor /CSP programs going forward in time—from the research community to the commercial suppliers. Below some heat storage examples (left) and heat storage system design (right) for variable heat and electricity with assured peak generating capacity

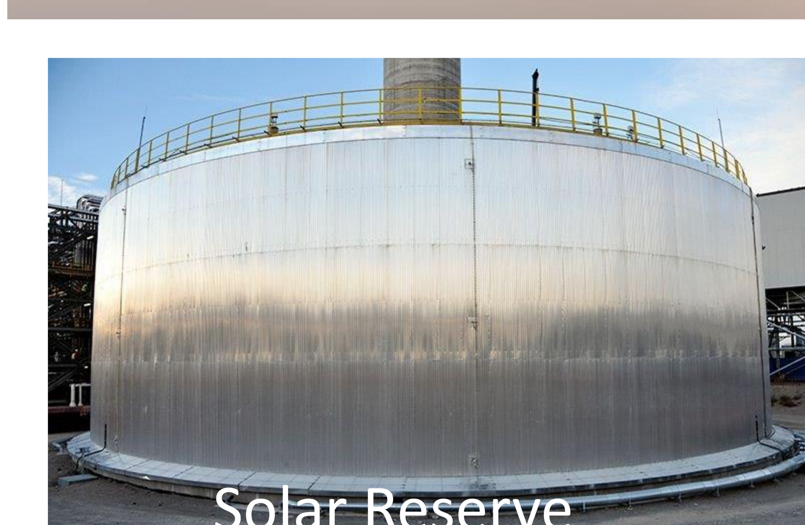


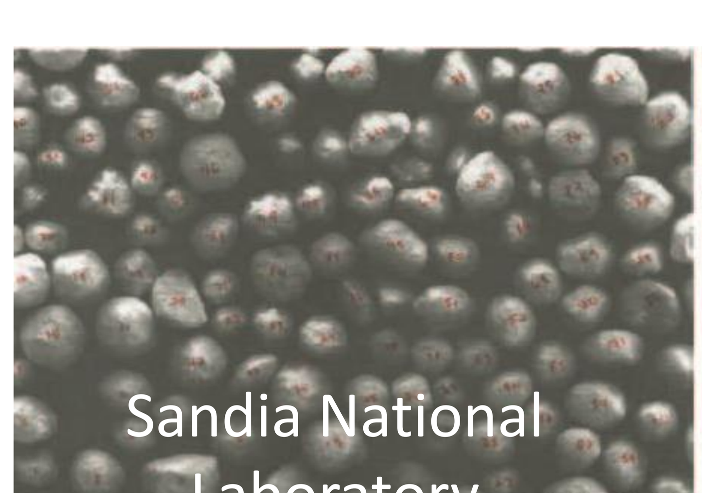


←Hot Concrete

←Hot Hexagonal Cast Iron Ingots

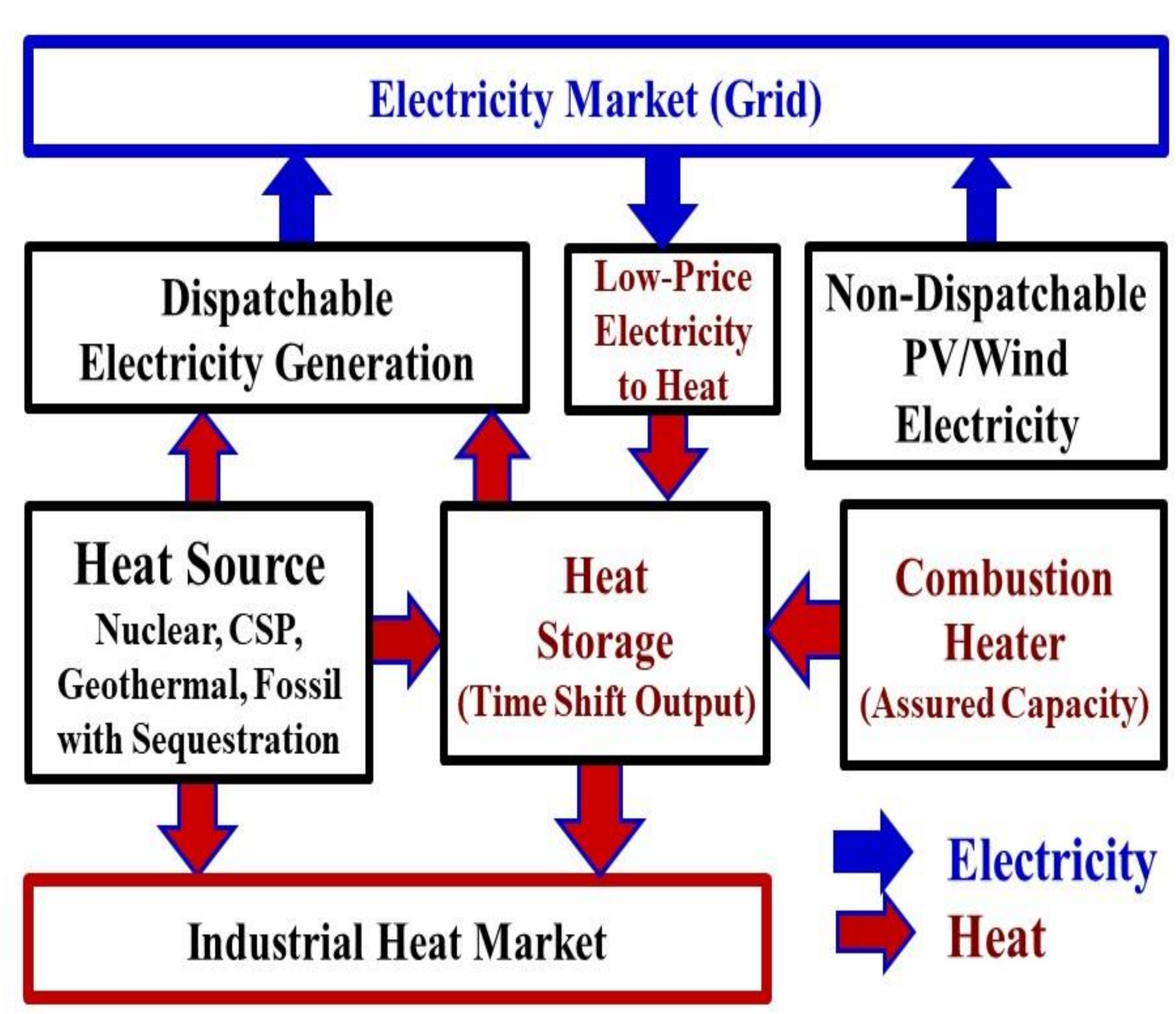
Heat Storage System Design→





←Hot Salt Nitrate or Chloride

←Hot Sand



MIT Co-Chair: Charles Forsberg (cforsber@mit.edu);
INL Co-Chairs: Hans D. Gougar (Hans.Gougar@inl.gov) and Piyush Sabharwall (Piyush.Sabharwall@inl.gov);

Results from: Light Water Reactor Heat Storage for Peak Power and Increased Revenue: *Focused Workshop on Near-Term Options*

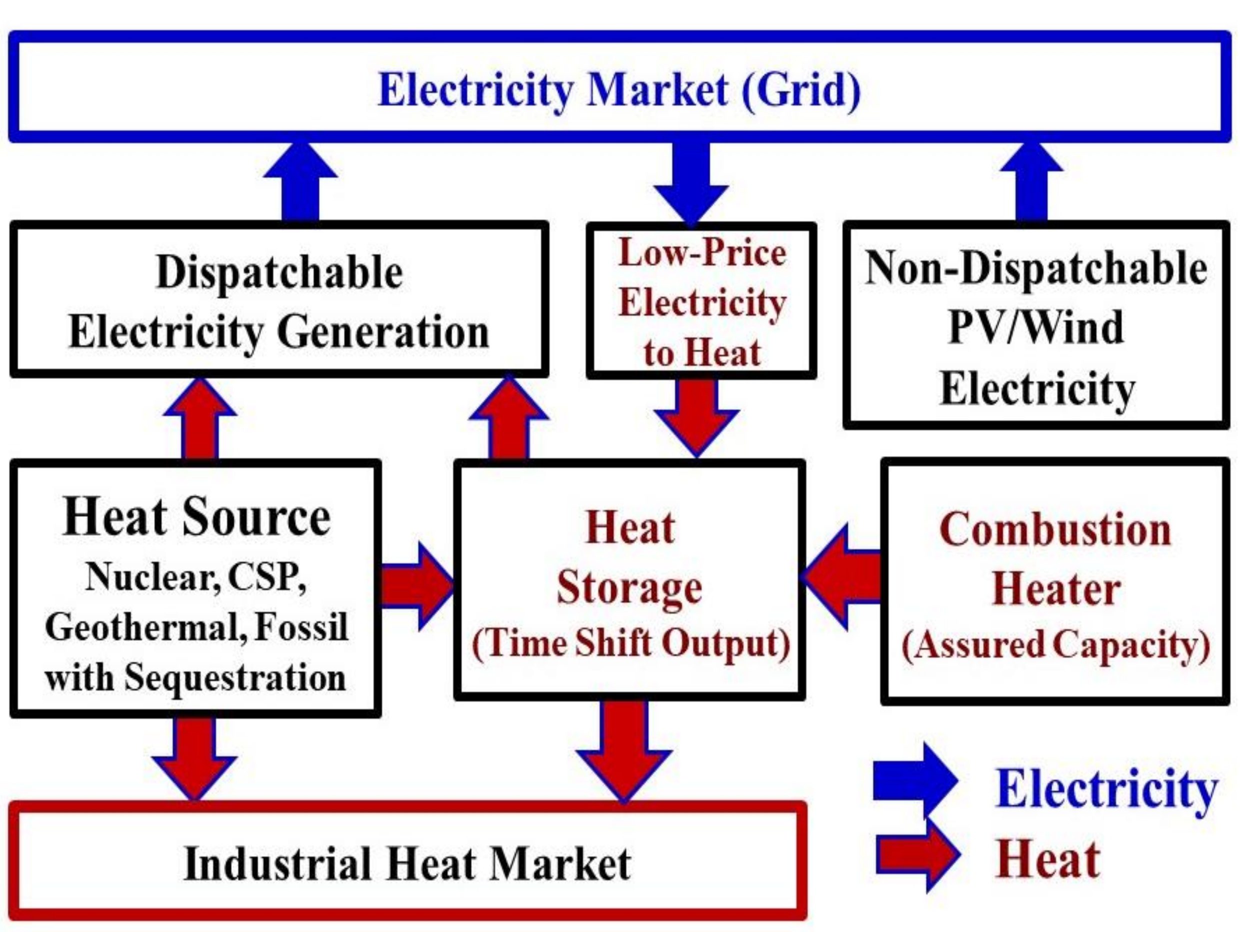
June 27-28, 2017; MIT, Cambridge, Massachusetts

Electricity Markets Are Changing Because of (1) Addition of Wind and Solar PV and (2) the Goal of a Low-Carbon Grid

- Fossil fuels provide three services
  - –Provide electricity (kWh)
  - –Energy storage (coal pile, oil tank, natural gas)
  - –Assured generating capacity—electricity when needed (Peak kW)
- Nuclear can provide all three services
- Non-dispatchable wind and solar PV only provides electricity
  - –Large-scale wind/solar collapses electricity prices, limits wind/PV
  - –Require other systems to provide storage and assured capacity

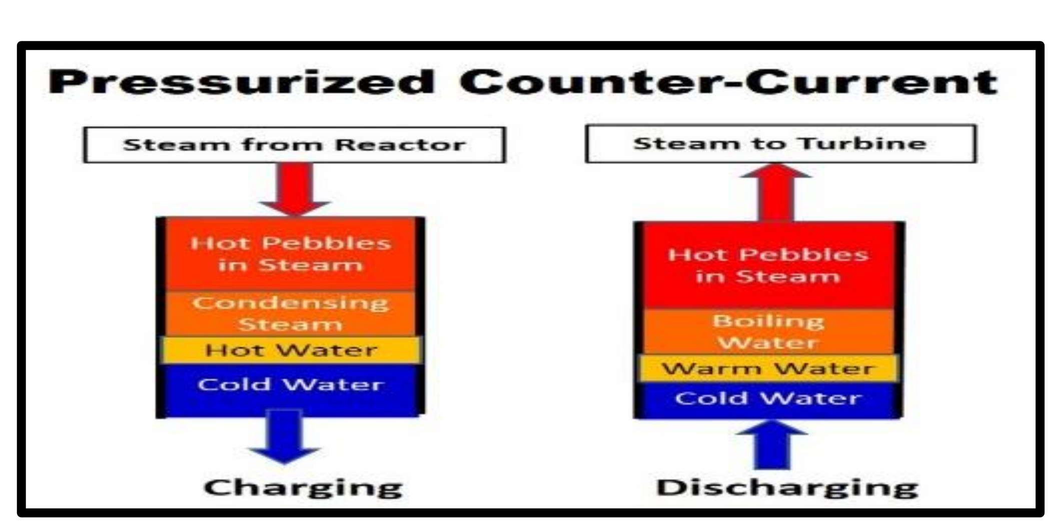
California Spring Day Electricity Prices Before and After Large-Scale PV Additions

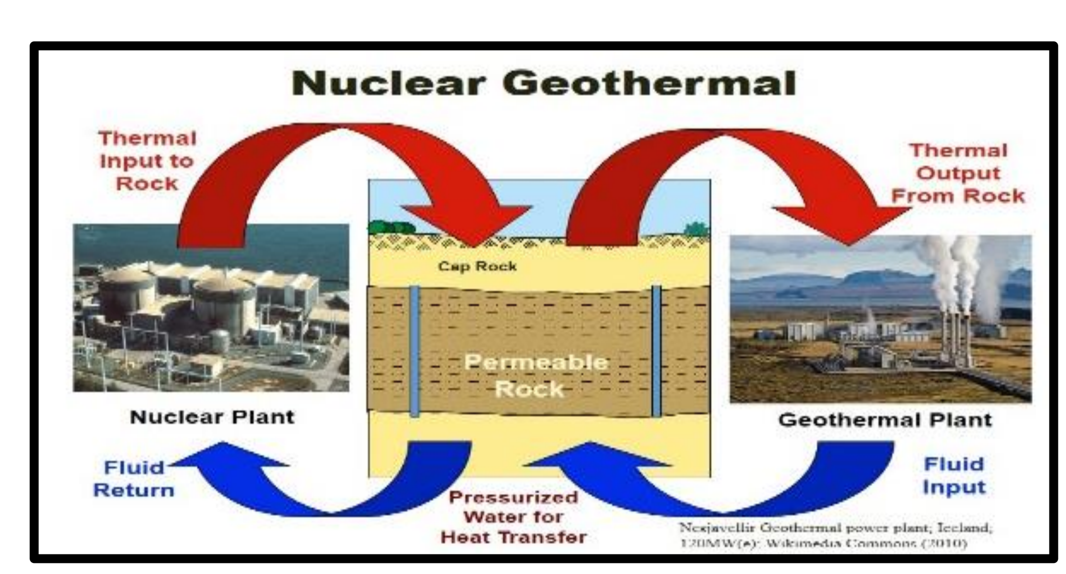
System Design Enables Base-Load LWR to Provide Variable Electricity to the Grid (Buy and Sell) with <u>Assured Peak Generating Capacity (What Needed)</u>



- Base-load LWR sends steam to turbine hall (electricity) and heat to storage depending upon demand for electricity. If very low or negative electricity prices, buy electricity and convert to heat for heat storage system.
- If high electricity prices, all steam from reactor and from heat storage sent to turbine to produce peak electricity greater than base-load capacity
- If heat storage depleted, combustion heater provides heat at same rate as storage to assure peak assured electricity generation. Low-cost and seldom used because usually heat storage provides peak energy demand
- Enables larger-scale economic PV and wind because provides economic storage and assured capacity functions that PV and wind can't provide.

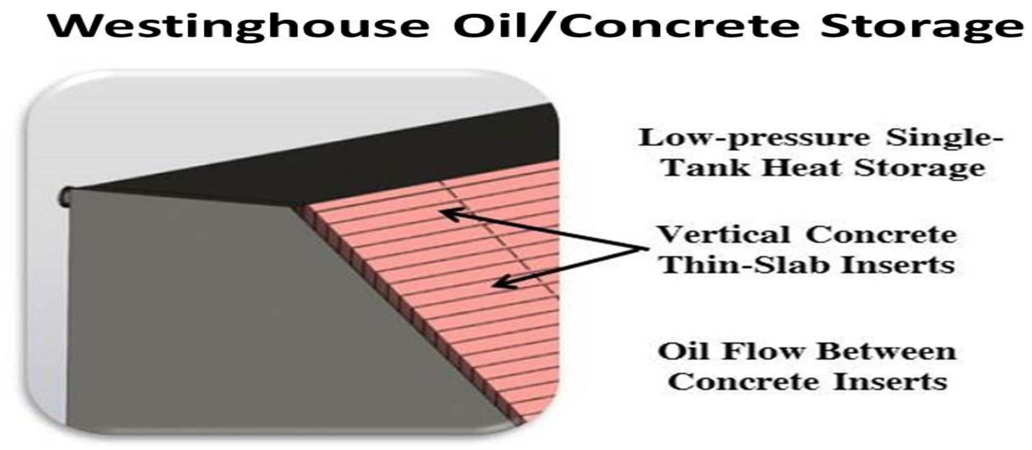
Many Heat Storage Options Where Choices Depend Upon Time-Varying Electricity Prices on an Hourly to Seasonal Basis (Outlined Options for Saturated Steam)





Cryogenic Air
Highview 5MW/15MWh Demonstration Plant

Westinghouse Oil/Concrete Storage



Latent Heat Storage (Nevada Solar One)

1. C. W. Forsberg, "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology* March 2019. https://doi.org/10.1080/00295450.2018.1518555
2. C. Forsberg (cforsber@mit.edu) et al. *Light Water Reactor Heat Storage for Peak Power and Increased Revenue: Focused Workshop on Near-Term Options*, MIT-ANP-TR-170, July 2017, http://energy.mit.edu/2017-canes-light-water-reactor-heat-storage-for-peak-power-and-increased-revenue

Phenomenon Identification Ranking Table Development for Identifying Thermal Energy Storage for Near-Term Integration with Light Water Reactors

Daniel M. Mikkelson
Department of Nuclear Engineering, NC State University dmmikkel@ncsu.edu

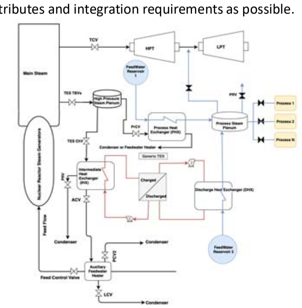
Introduction and Background

As electrical grids continue to integrate more intermittent renewable energy sources, the value of energy storage has increased. Concentrated solar power (CSP) plants have already implemented thermal energy storage, usually in the form of molten salt sensible heat storage. CSP plants use thermal energy storage to increase the capacity factor of those systems by allowing the heat produced during daylight hours to be discharged as needed over the full 24-hour period. The nuclear power industry's interest in energy storage is effectively the opposite of CSP methods. With increased penetration of intermittent renewables, traditionally baseload plants have been required to operate flexibly to avoid periods of electricity oversupply or selling electricity at a loss. Energy storage could allow nuclear reactors to avoid power cycling during these periods of low baseload demand, instead storing the energy in order to discharge it later.

Idaho National Laboratory, in conjunction with the Department of Energy, NuScale, and Utah Area Municipal Power Systems, is planning a Joint Use Modular Plant program that will allow use of one module within a small modular reactor (SMR) plant for research for research, development, and demonstration (RD&D) purposes. A primary research application for JUMP is to demonstrate energy storage connected to an SMR.

Rendering of conceptual 12-module NuScale power plant
(Figure reference: https://inl.gov/trending-topic/carbon-free-power-project/)

Nuclear reactors generate large amounts of thermal energy. To avoid losses that occur during energy transformations, thermal energy storage (TES) is pre-selected for coupling with the JUMP module. A ranking system must be established to select a specific technology to pursue in the engineering design phase, accounting for as many energy storage attributes and integration requirements as possible.



Pre-conceptual design of a possible two tank sensible heat storage system for load following

Phenomenon Identification Ranking Table Criteria

TRL: Is the technology ready for near term deployment? (3-5 years)

Charge: Can the TES directly accept heat from LWR steam?

Discharge: Can the TES store and discharge at high temperatures?

Ancillary Market: Will the TES open up grid ancillary market participation?

Capacity: Can the TES be made large enough? (400MWht)

Ramp: Can the TES change its discharge power quickly?

Frequency: How often can the TES completely charge and discharge?

Realignment: How often will the TES be unavailable in order to reset?

Cost: What is the price per unit energy of storage?

Lifetime: How long will the storage last?

Geography: Is the TES location specific?

Environment Impacts: Are there significant environmental concerns?

Turndown: Will the TES need minimum heat input?

Technology	TRL	Charge	Discharge	Ancillary Market	Capacity	Ramp	Cycle Frequency	Realignment	Geography Reqs.	Environment Impacts	Turndown Reqs.	Total
UTES	9	0	0	0	2	0	0	2	0	0	1	14
Hot/Cold Water	9	0	0	0	2	2	2	1	1	1	1	19
Concrete	5	2	2	1	2	2	2	1	1	1	1	20
Firebrick	3	0	2	1	2	2	1	1	1	1	0	14
Geothermal	2	1	2	0	2	1	2	1	0	0	0	11
Therm. Chemicals	4	1	2	0	2	0	0	1	1	1	0	12
Phase Change Materials	4	1	2	1	2	1	1	1	1	1	1	16
Thermocline Molten Salt/Thermal Oil	5	1	2	1	2	2	2	0	1	1/0	0/1	17
Two-Tank Molten Salt/Thermal Oil	9	2	2	1	2	2	2	1	1	1/0	0/1	23
Steam Accumulators	9	2	1	1	1	2	2	1	1	1	1	22

PIRT evaluation results table. Each of the numerical categories are presented above.

Thermal Energy Storage Options

Underground Thermal Energy Storage

Underground thermal energy storage uses aquifers or boreholes to seasonally store hot and cold water for municipal or HVAC purposes.

Hot and Cold Water Storage

Above ground chilled and heated water storage allows for daily production of necessary hot or cold water for later use.

Concrete Thermal Energy Storage

Specialized concrete cast around piping allows for heat to be stored in the concrete. By reversing flow direction in the piping, a thermocline system can be established in the concrete.

Firebrick

Ceramic bricks heated by resistance heaters to as high as 1850°C store heat until discharged via air blown through internal channels.

Geothermal

Deep caverns store high temperature water, pressurized near the ambient pressure at the storage depth.

Thermochemicals

Endothermic chemical reactions absorb heat, and the products are stored separately until they can be recombined for exothermic energy release.

Phase Change Materials

Latent heat of vaporization, fusion, or sublimation is stored as materials change from one phase to another with heat input or release.

Thermocline Sensible Heat Storage

A single tank contains cold and hot stores of a working medium separated by thin but steep thermal gradient.

Two Tank Sensible Heat Storage

Two tanks separately store cold and hot masses. Heat is stored in the temperature change in the storage medium.

Steam Accumulators

Steam accumulators store saturated mixtures in a pressure vessel, allowing for the liquid to flash into more steam during discharge.

Preliminary Results

Preliminary results of the PIRT suggest that **two-tank** molten salt or thermal oil systems, **steam accumulators**, and **concrete** TES systems should continue to be evaluated.

This research was supported by the DOE Office of Nuclear Energy Crosscutting Technology Development Integrated Energy Systems Program at Idaho National Laboratory under U.S. Department of Energy contract DE-AC-07-05ID14517.

References:

1. NuScale Standard Plant Design Certification Applicaiton, "Steam Power and Conversion System," (2008).
2. J. COLEMAN et al, Nuclear Science and Technology, Idaho National Laboratory, INL/EST-17-42420, 2017.
3. Z. ZHOU et al, "Survey of U.S. Ancillary Services Market," Argonne National Laboratory, ANL/ESD-16/1, 2016.
4. J. KIM et al, "Status report on the high-temperature steam electrolysis model developed in the Modelica framework (FYH2017)," Nuclear Science and Technology, Idaho National Laboratory, INL/EST-17-43056, 2017.
5. H. TRAN and E. VAKKILAINNEN, "The kraft chemical recovery process." Available: https://www.tappi.org/content/events/08kros/manuscripts/1-1.pdf
6. DEPARTMENT OF ENERGY, "Technology readiness assessment guide," DOE G 413.3-4A, 2001.
7. K. FRICK et al, "Modeling hybrid nuclear systems with chilled-water storage," *Nuclear Technology* **202**, 53-70, 2018.
8. SANDIA NATIONAL LABORATORY, "DOE Global Energy Storage Database"
9. WENDT et al, "Geologic thermal energy storage of solar heat to provide a source of dispatchable renewable power and seasonal energy storage capacity," *GRC Transactions*, **43**, (2019).
10. STACK et al. "Performance of firebrick resistance-heated energy storage for industrial heat applications and round trip electricity storage," *Applied Energy*, **242**, 782-796, (2019).
11. N. HOIVIK et al, "Demonstration of EnergyNest thermal energy storage (TES) technology," *Proc. IEEE*, **100**, (2012).
12. K. PIELICHOWSKA and K. PIELIECHOWSKI, "Phase change materials for thermal energy storage," *Progress in Materials Science,* **65,** 67-123, (2014).
13. A. DE JONG et al, "Thermochemical storage – system design issues," *Energy Procedia*, **48**, 309-319 (2014).
14. G. ANGELINI et al, "Comparison of thermocline molten salt storage performances to commercial two-tank configuration," *Energy Procedia*, **49**, 694-704, (2014).
15. M. DANIELS, "Integration of large-scale steam accumulators for energy storage in nuclear hybrid energy systems," North Carolina State University, Thesis, (2017).
16. C. HATCH, (2019, March 20). *JUMP presents big opportunities for nuclear scientists, industry*

Optimizing a Heat Storage Retrofit to a Nuclear Power Plant under Market Uncertainty

W. N. Mann*, K. Ramirez-Meyers, S. Bisett, C. Bagdatlioglu, S. Landsberger, M. E. Webber
Walker Department of Mechanical Engineering, Cockrell School of Engineering, The University of Texas at Austin, *nealmann@utexas.edu

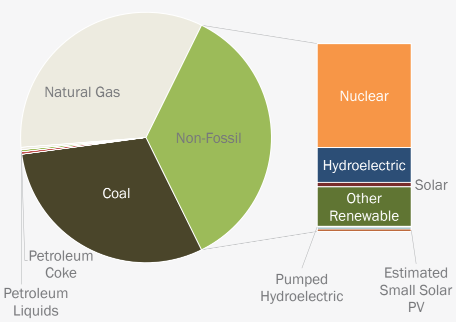
Objective

Find the optimal heat storage system for nuclear power plants as a hedge against uncertain future market conditions.

Background

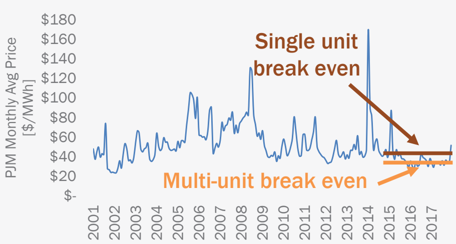
- Nuclear power is the biggest source of carbon-free electricity in the U.S.

U.S. Net Electricity Generation by Energy Source, 2016
Data: U.S. EIA



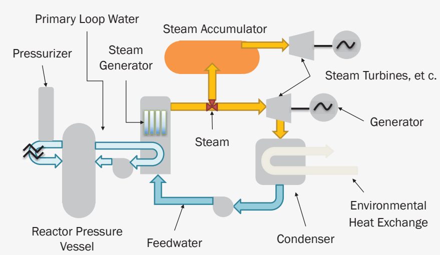
- Nuclear power plants are retiring due to low average prices, especially single-unit plants
- Low average electricity prices are driven by low natural gas prices and the expansion of wind and solar PV

PJM West Hub Monthly Average Prices, 2001–2017
Data: U.S. EIA



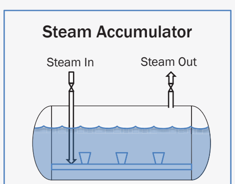
- Nuclear power plants typically operate continuously at 100% power (baseload)
- Flexible output may help economics in more volatile markets
- Heat storage enables variable electricity output with constant reactor power
  - Alternative to load following
  - Reduces ramping and curtailment of steam generator
  - Enables load shifting
  - Provides operating reserves or capacity reserves

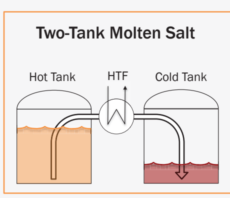
Example: Steam Accumulator Integration with PWR

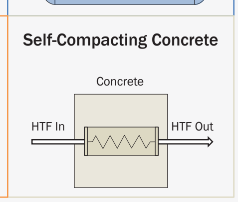


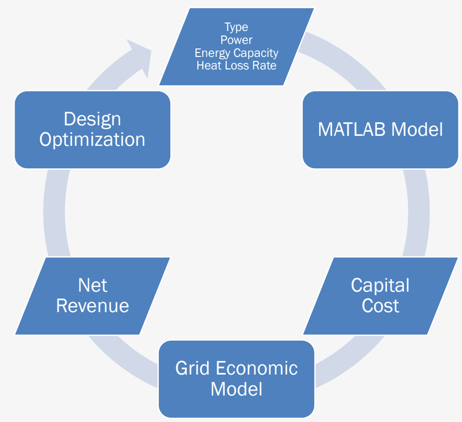
Methods

Three heat storage technologies were chosen for modeling based on their availability and compatibility:









- Market uncertainty is captured with variations in
  - Fuel prices (especially natural gas)
  - Historical or synthetic time series (load, solar PV, wind)
  - Peak load and demand growth
  - Capital cost declines for wind, solar PV, and batteries
  - Carbon prices

Expected Results

- Each scenario will produce one optimal energy storage system
- Recommendations will be made on the most optimal system based on the economic success criteria

Acknowledgements & Disclaimers

The authors acknowledge support from the U.S. Department of Energy, Office of Nuclear Energy (Nuclear Energy University Program, project 14-6950).

This material is based in part on work supported under an Integrated University Program Graduate Fellowship.

Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Department of Energy, Office of Nuclear Energy.

The University of Texas at Austin
Walker Department of Mechanical Engineering
Cockrell School of Engineering

Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors Workshop

23–24 July, 2019
Idaho Falls, ID
Sponsors: MIT, INL, Exelon

OU model acts as a surrogate to the demand power and provide NPPs a knob to *control the level of fluctuations for safe and economical operation*.

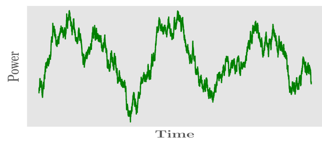
Sizing and control of advanced nuclear hybrid energy system

Molly Ross, Abhinav Gairola, Hitesh Bindra

Kansas State University

Load demand and Wind generation fluctuations

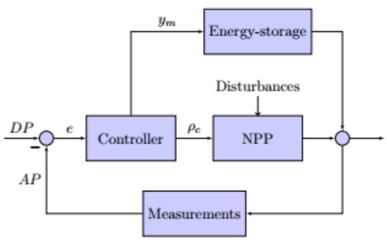
- Wind and Solar energy generation – Increase in load fluctuations.
- A data-driven stochastic surrogate for better forecasting– divide into long time behavior and short time fluctuations.

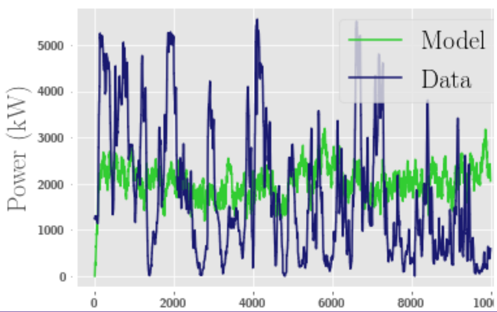


Sizing of Gen IV system and storage device

- NPP operation can be optimally controlled based on – reactor safety requirements; load requirements; and renewable generation.
- Ornstein-Uhlenbeck (OU) model – Surrogate to actual demand power – Provides a knob to control the level of fluctuations in reactor feedback based on economics and reactor safety.
- The rest of the demand is met by controlling the energy flow into or out from the storage device.

$\frac{dx}{dt} = -\gamma x + c\zeta$ **(OU process)** where, γ is drift or trend parameter obtained from auto-correlation and c estimates the fluctuation level.

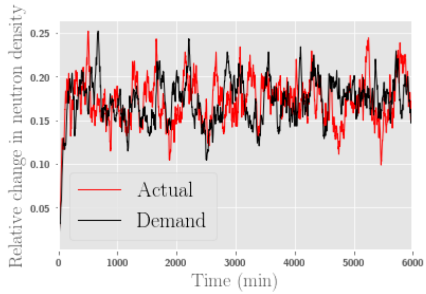


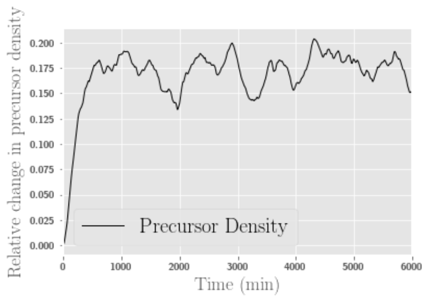


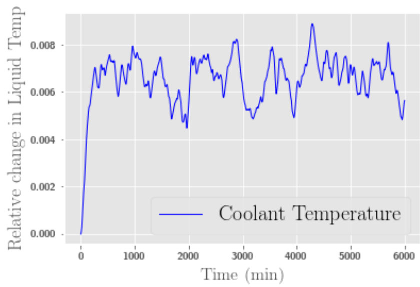
OU parameter c can be varied for stable reactor performance and excess energy is stored. Blue–Actual load fluctuations Green–Feedback to reactor based on safety constraints Figure shows model results with 20% of data driven c.

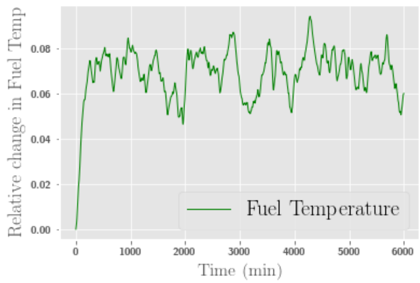
Model Results

- OU model is coupled to the reactor system model with the tunable controller. (For details download paper from link).









A robust stochastic control via OU process model can provide the optimal storage solution, improve economic proposition of NPPs and maintain safety constraints.

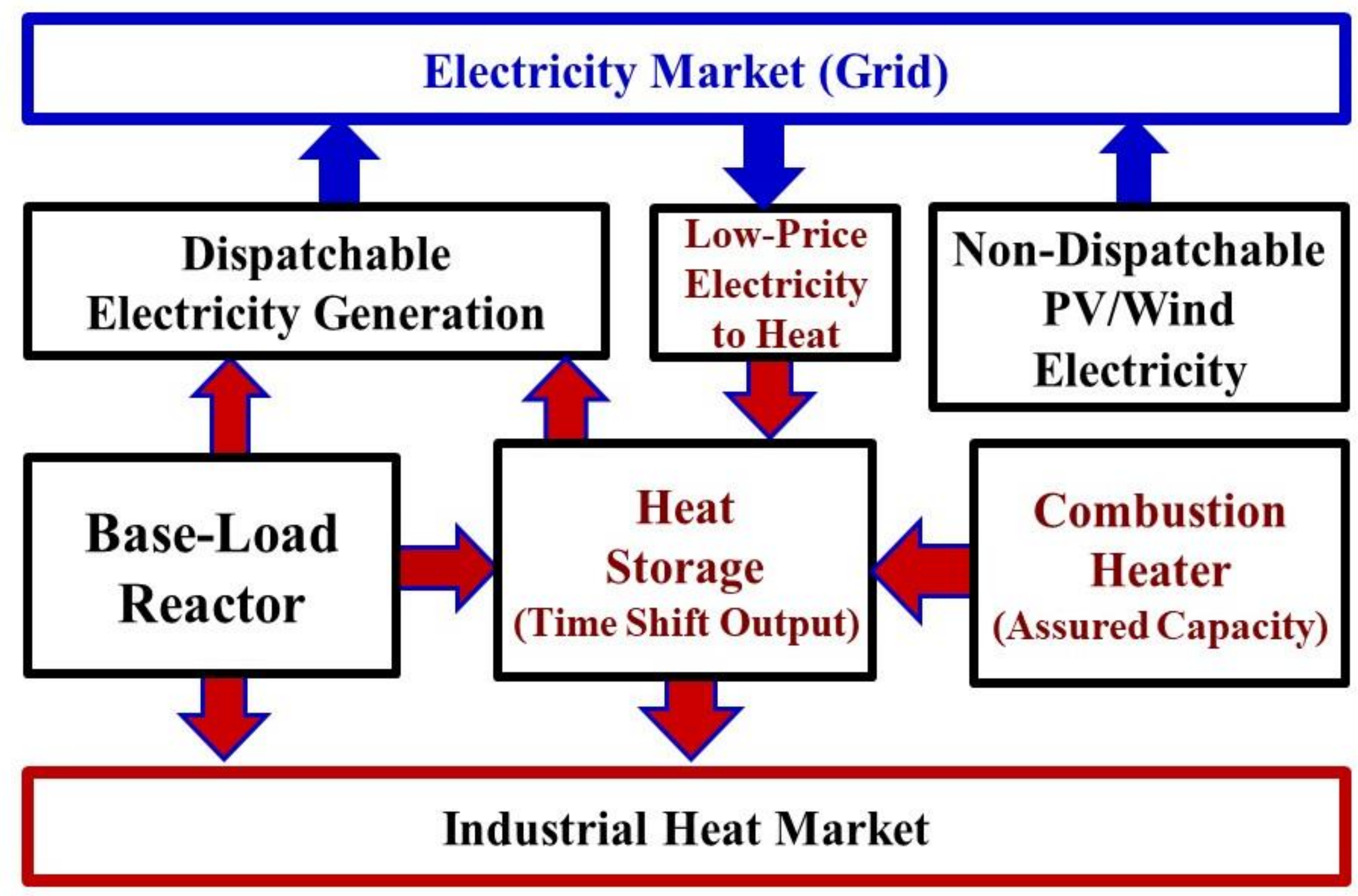
– Download the paper

Cast-Iron With Cladding for Heat Storage in Sodium, Salt, Lead and Helium Cooled Reactors

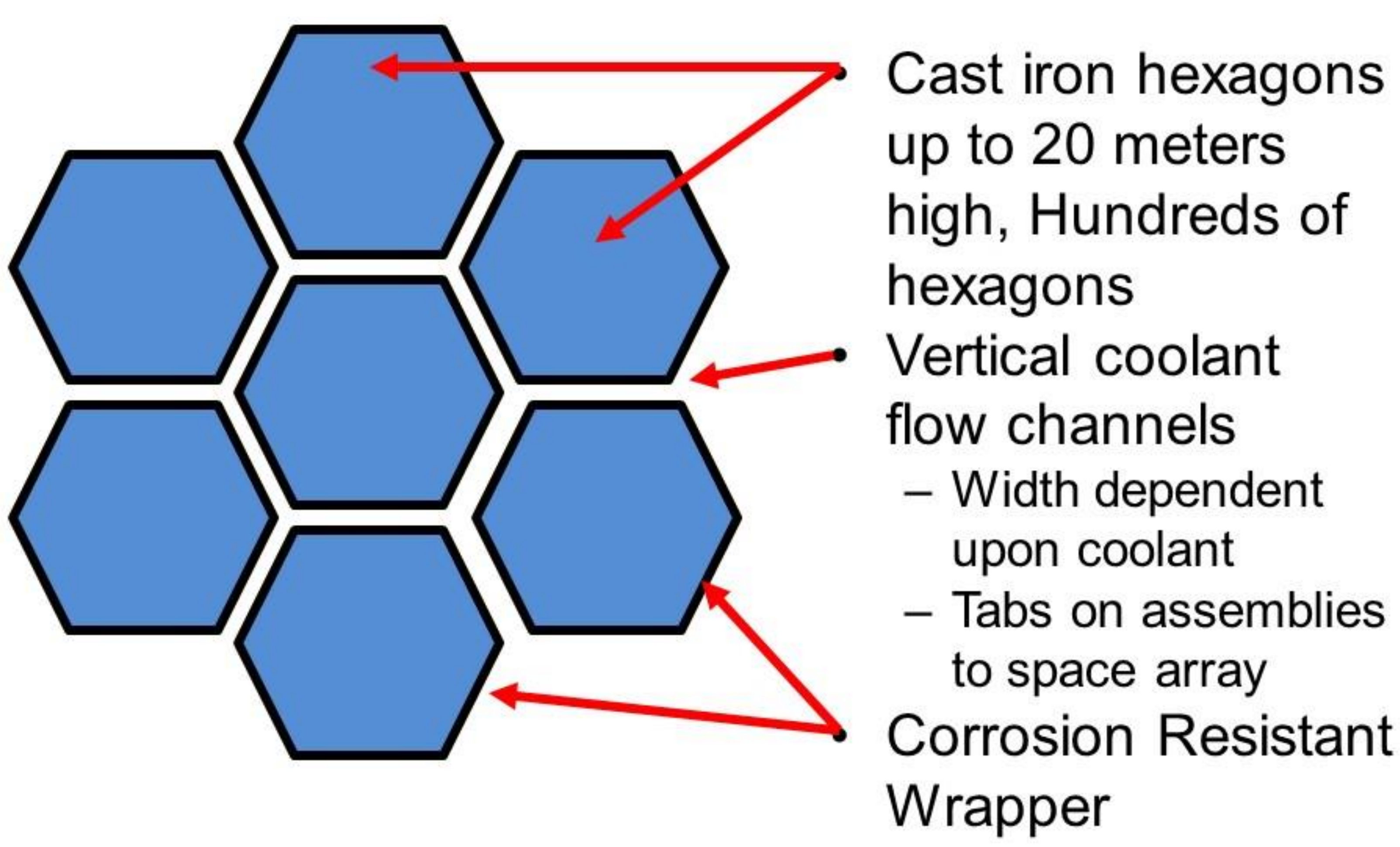
Charles Forsberg (cforsber@mit.edu) and Piyush Sabharwall (piyush.sabharwall@inl.gov)
Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA
Idaho National Laboratory, Idaho Falls, ID

Power System Design for Low-Carbon World

- Produce energy with heat from base-load reactor to steam turbine or storage depending upon electricity prices
- Variable electricity to grid with heat from reactor and heat storage to turbine
- If low-price electricity, convert excess electricity into stored heat
- Backup combustion furnace (natural gas, biofuels, hydrogen) if storage depleted for assured peaking capacity. Low cost relative to gas turbine and seldom used



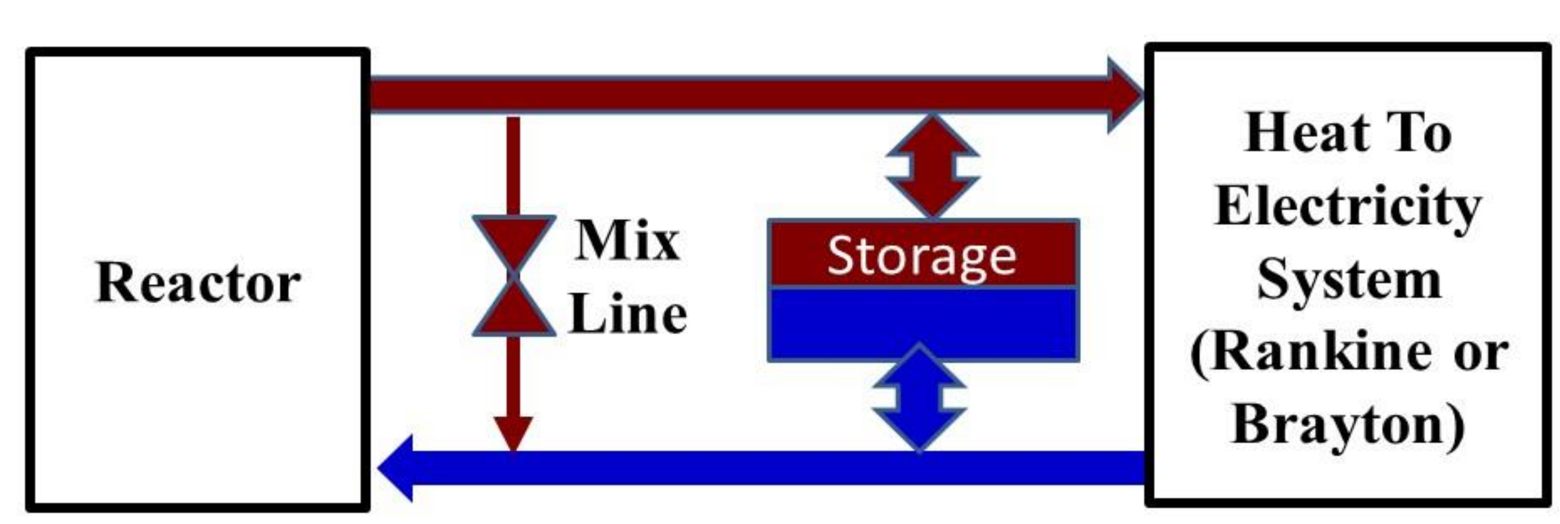
Cast Iron with Cladding Heat Storage

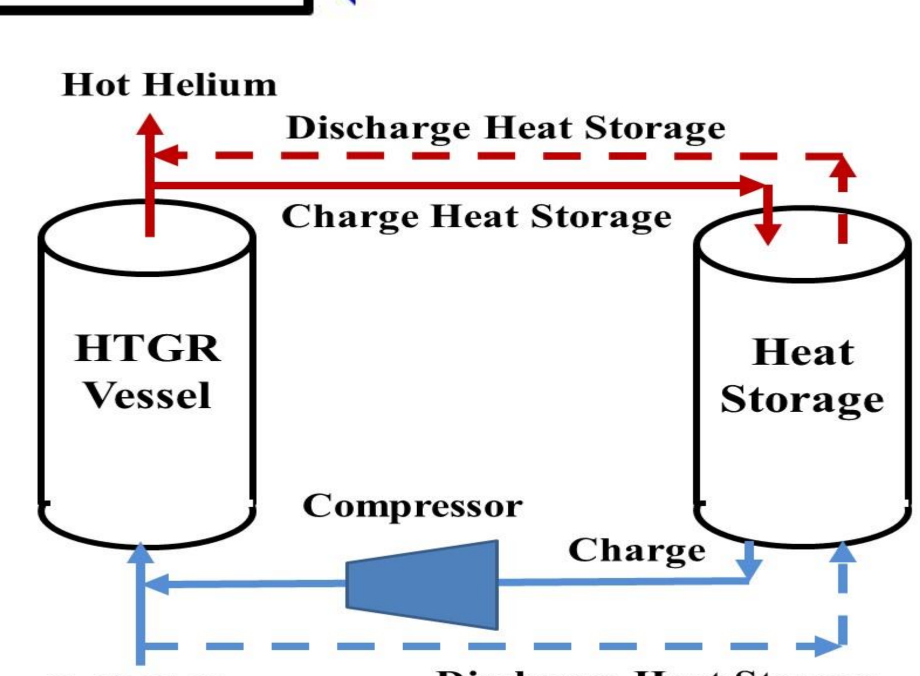


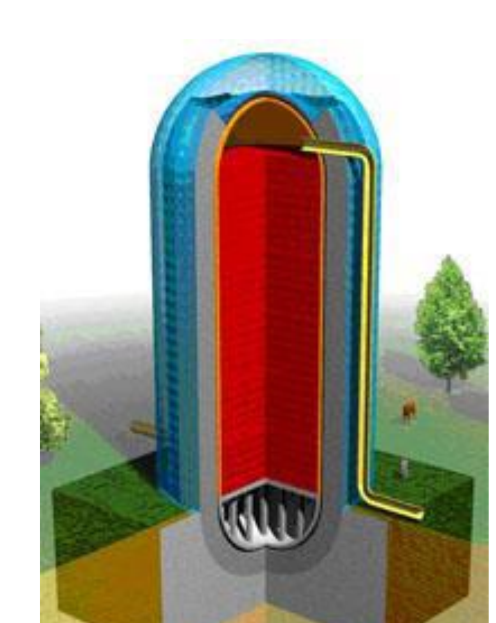
- Sensible heat storage with cast iron. Cladding metal chosen for corrosion resistance to primary or secondary reactor coolant (sodium, salt, lead or helium)
- Temperature range from 100 to 900° C
- Low cost
- Layout: hexagonal assemblies 10 to 20 meters high in close-pack array
  - Maximize storage heat capacity with >95% of volume in hexagonal solid assemblies
  - Minimize primary or secondary coolant fraction to minimize cost and maximize safety (sodium case)

System Design Considerations

- Economics improve if large temperature drop across storage system (double temperature difference and cost cut in half) but need to match reactor requirements (Sodium, lead, salt)
  - Heat storage can have large delta T
  - May require mix line to match cold return to reactor system requirements
- HTGR option to put storage in second pressure vessel in the primary reactor system
  - Hot helium to storage or power cycle
  - Large storage vessels are possible (GE Adiabatic Compressed Air Storage: Adele Vessel Right)







C. Forsberg and P. Sabharwall, *Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Operations*, ANP-TR-181, Center for Advanced Nuclear Energy, MIT, INL/EXT-18-51329, INL

Alumina particle beds can be durable and economical thermal energy storage media with nitrate salt as HTF.

Ceramic bed energy storage for Gen-IV reactors

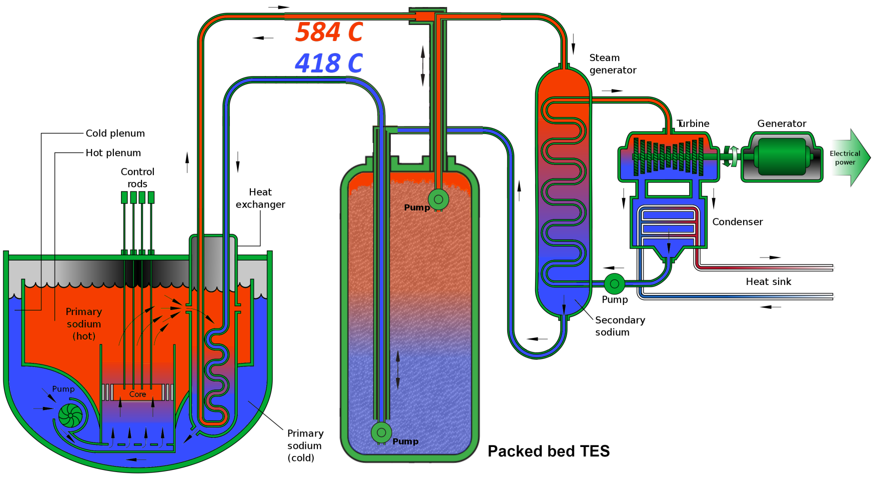
Brendan Ward, Hitesh Bindra
Kansas State University

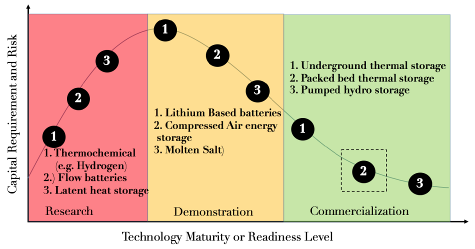
1 Many Gen IV systems use Intermediate Heat Transport System (IHTS) – SFRs, MSRs

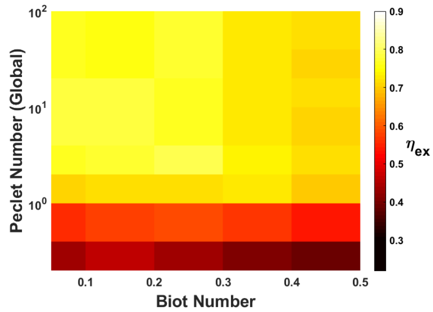
- Straightforward TES integration within IHTS loop
- Packed bed increases exergy efficiency

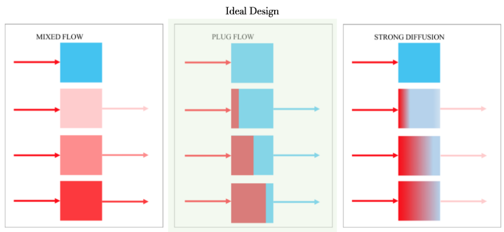
2 The single tank - packed ceramic bed storage

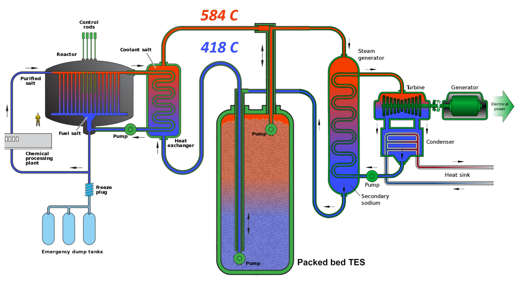
- IHTS $\Delta T = 166$ [C];
- $\rho C_p \Delta T \approx 87$ (salt), 95 (alumina) [kwh/m^3]
- Exergy efficiency = 0.79











Feasibility study of integrating thermal storage with Solar salt IHTS loop (**Kairos-FHR**) shows that the cost of energy storage using Alumina will be \$67/$kWh(e)$ as compared to \$80/$kWh(e)$ for two-tank Molten Salt.

– Project website

Molten Salt Corrosion for Energy Storage

Brendan D'Souza, Shaoqiang Guo, Jinsuo Zhang

Department of Mechanical Engineering, Virginia Polytechnic Institute and State University

Nuclear Materials and Fuel Cycle Center (NMFC)

1. INTRODUCTION

In Concentrated Solar Power (CSP) plants, molten salts are seen as an excellent replacement to the existing nitrate salts owing to their lower melting point and vapor pressure, and excellent heat transfer capabilities and stability at high temperatures (800°C). But they pose grave challenges in terms of material compatibility for ferrous and non-ferrous alloys, where they tend to react aggressively for temperatures ranging between 600 to 800°C.

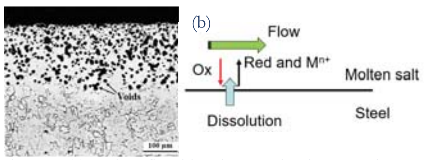


Figure 1. (a) Molten fluoride salt corrosion in Inconel 600 [ORNL-2349] (b) Corrosion kinetics in molten halide salt.

The formation of the passivating oxide layer becomes thermodynamically unfavorable in molten halide salts and corrosion proceeds as active metal dissolution, resulting in depletion of less noble alloying element and formation of voids. The corrosion kinetics at the interface is governed by a two-step process.

- Dissolution
- Mass Transfer (Convection or Diffusion)

Studies have also shown, corrosion in molten salt is an impurity (metallic and non-metallic like O, OH^-, H_2O) driven process. The presence of these species in the salt initiates corrosion in metals or alloys at an even faster rate [1] thus making it necessary to develop an appropriate purification process to remove the impurities from the salt.

2. OBJECTIVES

- Investigate the effects of salt impurities on material corrosion.
- Material selection - Corrosion studies to find alloys (i.e. Ni and Fe based alloys) that are compatible in molten chloride salt at higher temperatures (upto 800°C).
- Corrosion Mitigation Methods - Investigating the redox control method effects on mitigation of molten salt corrosion.
- Fission Product Effects - Investigating the effects of fission product (Eu) on corrosion.

3. MATERIALS AND METHODOLOGY

The dehydrated carnallite salt, KCl-$MgCl_2$-NaCl (43-53.4-3.6 wt.%) was obtained from ICL (Israel Chemicals Limited). Furthermore, high purity salt was also obtained, KCl (+99%) and NaCl (99.999%) from Sigma Aldrich and $MgCl_2$ (+98%, <2% moisture) from VWR

3. MATERIALS AND METHODOLOGY CONT'D

Hastelloy 230 was used as the baseline material to validate the purification technique. For the material compatibility tests, Ni based alloys, H230 and C276 and Fe based alloys, Alloy 709 (ANL material) were selected for the corrosion tests.

The static corrosion tests were conducted in the Ar filled glovebox using the muffle furnace and using the inhouse static system (Figure 2)

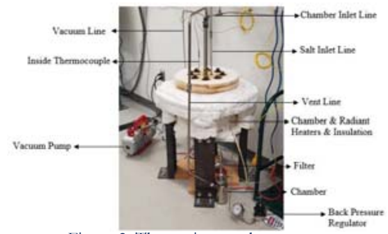


Figure 2. The static autoclave system.

Separation of impurities were accomplished through one of the following ways,

- Metallic - Electrochemical methods.
- Non-Metallic – Thermal and Chemical purification.

For thermal purification, a slow sequential heating schedule is adopted to vaporize moisture from the salt

For chemical purification, small Mg pieces (oxygen scavenger) are added to consume any residual oxygen (It will form MgO sludge and will settle at bottom of the crucible.

4. RESULTS

It is not possible to completely remove the impurities owing to the hygroscopic nature of $MgCl_2$. At higher temperatures, it thermally decomposes to $Mg(OH)_2$, MgO and Mg(OHCl) compounds with HCl (g) as the byproduct.

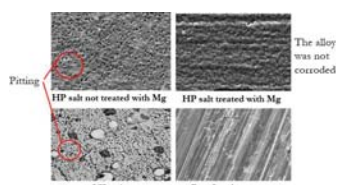


Figure 3. SEM surface images for H230 alloy after corrosion in KCl-$MgCl_2$-NaCl (800°C, 100 hours).

After purification, the oxide and hydroxide impurities in the salt reduces considerably. Furthermore, no corrosion was observed for H230 alloy in high purity chloride salt which was thermally and chemically purified.

4. RESULTS (CONT'D)

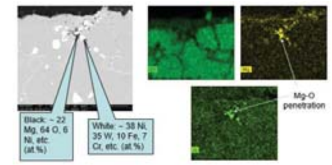


Figure 4. SEM cross sectional images for H230 alloy after vapor corrosion in KCl-$MgCl_2$-NaCl (800°C, 100 hours).

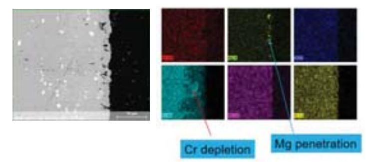


Figure 5a. SEM cross sectional images for H230 alloy after corrosion in KCl-$MgCl_2$-NaCl (without Mg addition, 800°C, 100 hours).

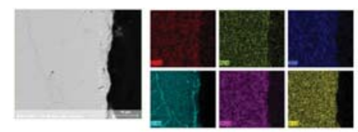


Figure 5b. SEM cross sectional images for H230 alloy after corrosion in KCl-$MgCl_2$-NaCl (with Mg addition, 800°C, 100 hours).

Table1. Corrosion attack details for H230 alloys.

Salt Details	Alloy	Depth of Attack (μm)	Corrosion Rate (mg/cm²)
Immersion Test-ICL Salt	H230	~47	3.5458
Immersion Test-HP Salt-Without Mg	H230	~37	0.7662
Immersion Test-HP Salt-With Mg	H230	No Attack	-
Vapor Test- ICL Salt	H230	~64	7.2096
Immersion Test-ICL Salt	C-276	4-16	0.7723
Immersion Test-ICL Salt	709-4B2	45-74	21.0569
Immersion Test-ICL Salt	709-RBB	~40	5.6528

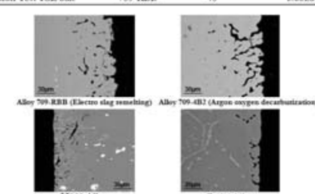


Figure 6. SEM cross sectional images for Ni Vs Fe based alloys after corrosion in KCl-$MgCl_2$-NaCl (800°C, 100 hours).

The surface analysis showed extensive pitting and surface cracks and severe material degradation. Corrosion in these alloys can be attributed to Cr depletion and dissolution from the alloy matrix.

4. RESULTS (CONT'D)

This is owing to Cr's strong electromotive force in molten chloride salt [1]. Ni based alloys showed better corrosion resistance than Fe based alloys. Furthermore, addition of inert elements like W and Mo increased the alloy resistance against chloride salt attack.

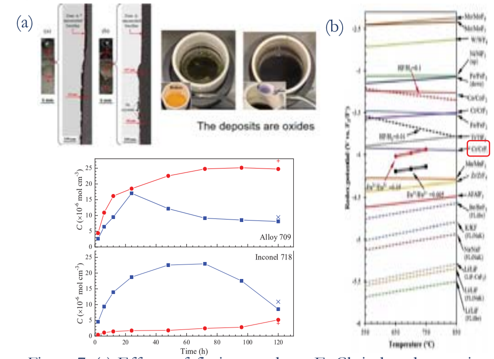


Figure 7. (a) Effects of fission products-$EuCl_3$ induced corrosion (b) Redox potentials Vs temperature in FLiBe and FLiNaK salts.

Eu(III)/Eu(II) was proposed as a soluble redox buffer agent for redox control in fluoride salts [2].

5. CONCLUSION

1. Both metal and non-metal impurities can induce corrosion.
2. Corrosion can be controlled and mitigated through salt purification and redox control method.
3. Salt vapor also leads to materials corrosion
4. Ni based alloys with Mo and W showed better resistance to chloride salt attack.
5. Eu in chloride salt increases material corrosion whereas in fluoride decreases material corrosion.

6. REFERENCES

1. Wenin Ding, Hao Shi et al. Hot corrosion behavior of commercial alloys in thermal energy storage material of molten $MgCl_2$/KCl/NaCl under inert atmosphere. J. of Solar Energy Materials and Solar Cells. 2018.
2. S. Guo, N. Shay et al. Measurement of europium (III)/europium (II) couple in fluoride molten salt for redox control in a molten salt reactor concept. J. of Nuclear Materials. 2017.

7. ACKNOWLEDGEMENT

- The authors would like to thank the Department of Energy for their valuable inputs and financial support.
- The authors would also like to acknowledge Dr. Xu Feng and Surface Analysis Lab at Virginia Tech for the XPS analysis.

Progress on the Reheat Air Combined Cycle Coiled Tube Air Heater Design

Shane Gallagher, Per Peterson
University of California, Berkeley

Introduction

The Reheat Air Combined Cycle (RACC) power conversion system is under investigation at the University of California, Berkeley. The RACC has many advantageous characteristics including:

1. Reduces water use by using air as working fluid
2. Produces rapidly dispatchable peaking power
3. Converts natural gas to electricity with 66% efficiency, significantly reducing CO2 emissions to produce peak power
4. Enables high-temperature thermal storage using electric-resistance heating with off-peak power

The RACC consists of a modified GE 7FB gas turbine, a novel salt to air heat exchanger called the Coiled Tube Air Heater (CTAH), a thermal energy storage system, and a heat recovery steam generator. An overview of the RACC is shown in Figure 1.

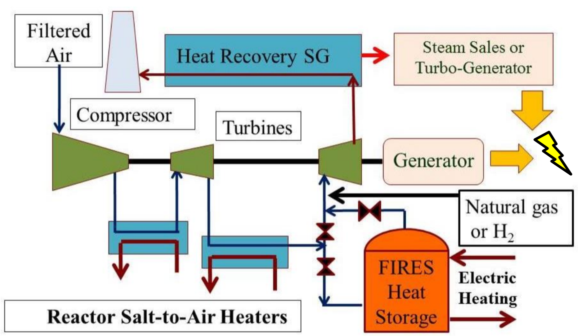


Figure 1. RACC Power Conversion System[1]

RACC Key Gaps

While there benefits of this technology are promising, there remains multiple key gaps which must be explored before the RACC can be commercialized. There remains:

1. Determining the validity of using internal insulation to reduce cost of CTAH shell material
2. Determining the maximum allowable creep deformation to maximize lifetime of CTAH tube bundle
3. Optimizing the design of the modified gas turbine to allow for one stage of reheat as well as co-firing
4. Dynamic system modeling to characterize RACC performance in transient scenarios

After considering our specific expertise and existing infrastructure, we have decided to focus our research efforts on key gaps 1, 2, and 4 while we encourage industry to focus efforts of developing the modified gas turbine. This poster focuses on key gaps 1 and 2.

CTAH Description

In a CTAH, molten fluoride salt on the tube side heats air on the shell side in a cross-counterflow arrangement, leading to high heat exchange effectiveness, while the coiled geometry provides good transient mechanical performance during thermal transients. An overview of the CTAH design is shown in Figure 2.

CTAH operating temperatures and pressures can be as high as 700 ºC and 20 bar. These conditions make creep deformation a significant concern. It is proposed to use internal insulation in order to keep the shell temperature sufficiently low to justify the use of a more economic material such as carbon steel. It is also important to determine how the tube to tube sheet joints will perform under these conditions. See Figure 3 for diagram of tube to tube-sheet.

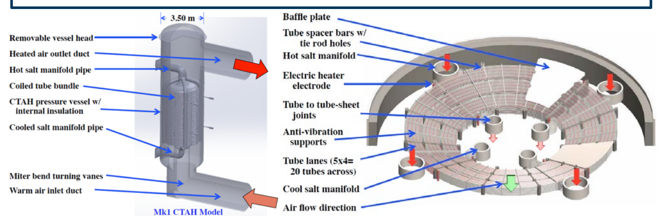


Figure 2. Isometric view of a reference CTAH assembly and sub-bundle 3D model with major components labeled [2]

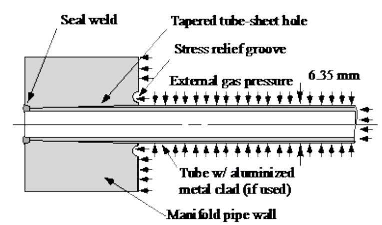


Figure 3. Tube to manifold joints and joint sample

Internal Insulation

Internal insulation is routinely used in the chemical industry in fluidized catalytic cracking units (FCCU). These units operate at temperatures and pressures similar to the CTAH conditions. Figure 4 shows examples of internally insulated expansion joints for FCCU application.

Figure 4. internal insulation for FCCU application[4]

Autoclave Experiment

The UC Berkeley Nuclear Engineering Thermal Hydraulics Lab has designed and constructed an autoclave for validating the use of internal insulation and to demonstrate the performance of the tube to tube-sheet joints.

Carbon steel was used for shell and structural components of the autoclave (Figure 5). The heater consists of a Kanthal wire on an alumina scaffolding (Figure 6). The heater is surrounded by firebrick blocks for internal insulation (Figure 7).

Samples are created by using industry standards for tube to tube-sheet manufacturing using a tube and collar. The collar is then capped (Figure 8). Samples are inserted through the bottom of the autoclave with the tube protruding from the bottom and the capped collar placed in the autoclave, in the heater. The interior of the tube is exposed to the atmosphere and the interior of the autoclave is pressurized, loading the sample in compression. By heating the samples above normal operating conditions, the rate of creep deformation is accelerated and performance of the tube to tube-sheet joints can be assessed.

Figure 5. CTAH Component Autoclave

Figure 6. Kanthal wire heater element on alumina

Figure 7. Firebrick internal insulation

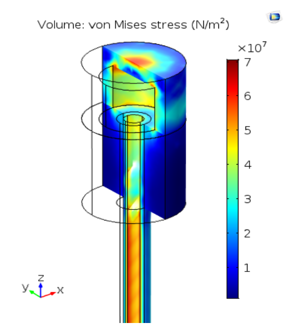


Figure 7. Sample geometer and model of induced stress

Contact

Shane Gallagher
University of California, Berkeley
Email: Shane.Gallagher@Berkeley.edu
Website: fhr.nuc.Berkeley.edu

References

1. C. Forsberg. "Fluoride-Salt-Cooled High-Temperature Reactors (FHRs) Base-load Reactor Operation with Variable Output, Electricity Storage (as Heat) and Grid Management." MIT. 2014.
2. C. Andreades, A. Cisneros, J. Choi, et-al, "Design Summary of the Mark-I Pebble-Bed, Fluoride-Salt-Cooled, High-Temperature Reactor Commercial Power Plant," Nuclear Technology, 195 (3), 223-238.
3. C. Andreades, "Dissertation: Nuclear Air-Brayton Combined Cycle Power Conversion Design, Physical Performance Estimation and Economic Assessment," University of California, Berkeley, Berkeley, CA, 2015.
4. http://eagleburgmann-ej.com/media/subsidiary-content/denmark/eagleburgmann-ke-a-s/expansion-joint-literature/ej-application-brochures/catalog-expansion-joints-for-fluid-catalytic-cracking-units-fccu

Department of Nuclear Engineering
University of California, Berkeley
Thermal Hydraulics Laboratory

H_2 and Battery Storage Solutions

Of the available storage technologies, lithium – ion batteries and hydrogen have the capacity required to complement renewable growth and nuclear generation in a low carbon future

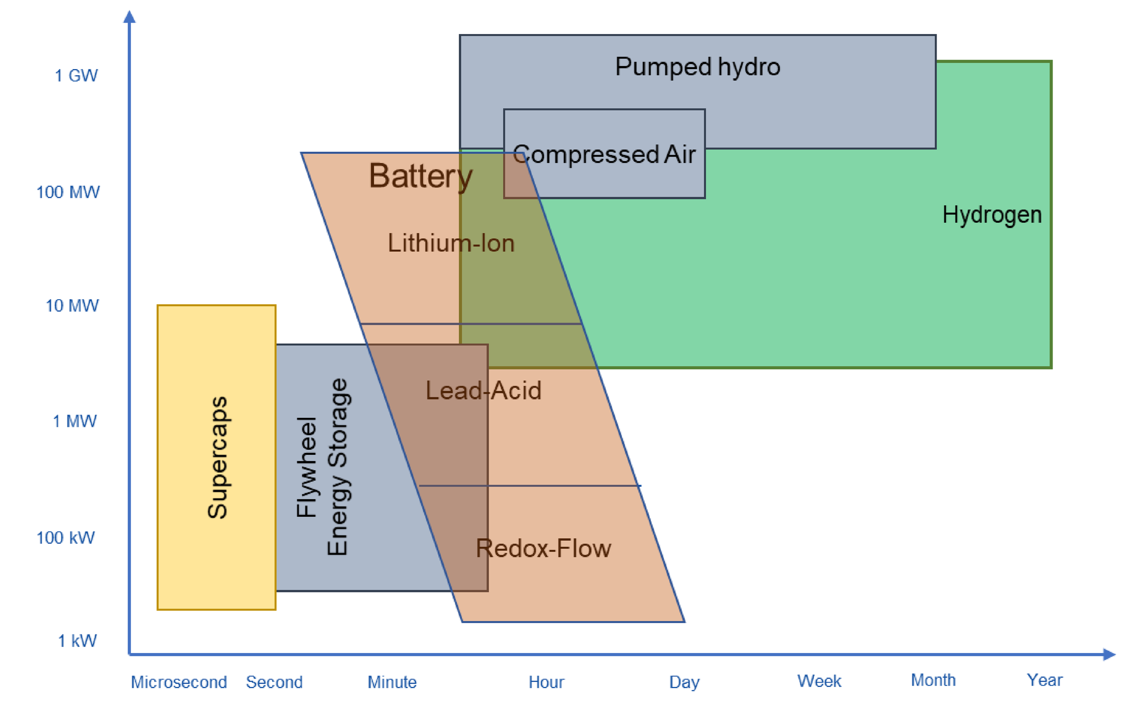


Fig 1: Overview of storage technologies

Hydrogen has an unparalleled ability to produce other forms of green energy

- Long-term, large-scale storage capabilities
- Broad spectrum of applications
- Large market potential
- First bankable applications in Europe at electricity prices in the 40 - 50€/MWh range
  → for H_2 mobility, refineries, chemical industry, gas injection

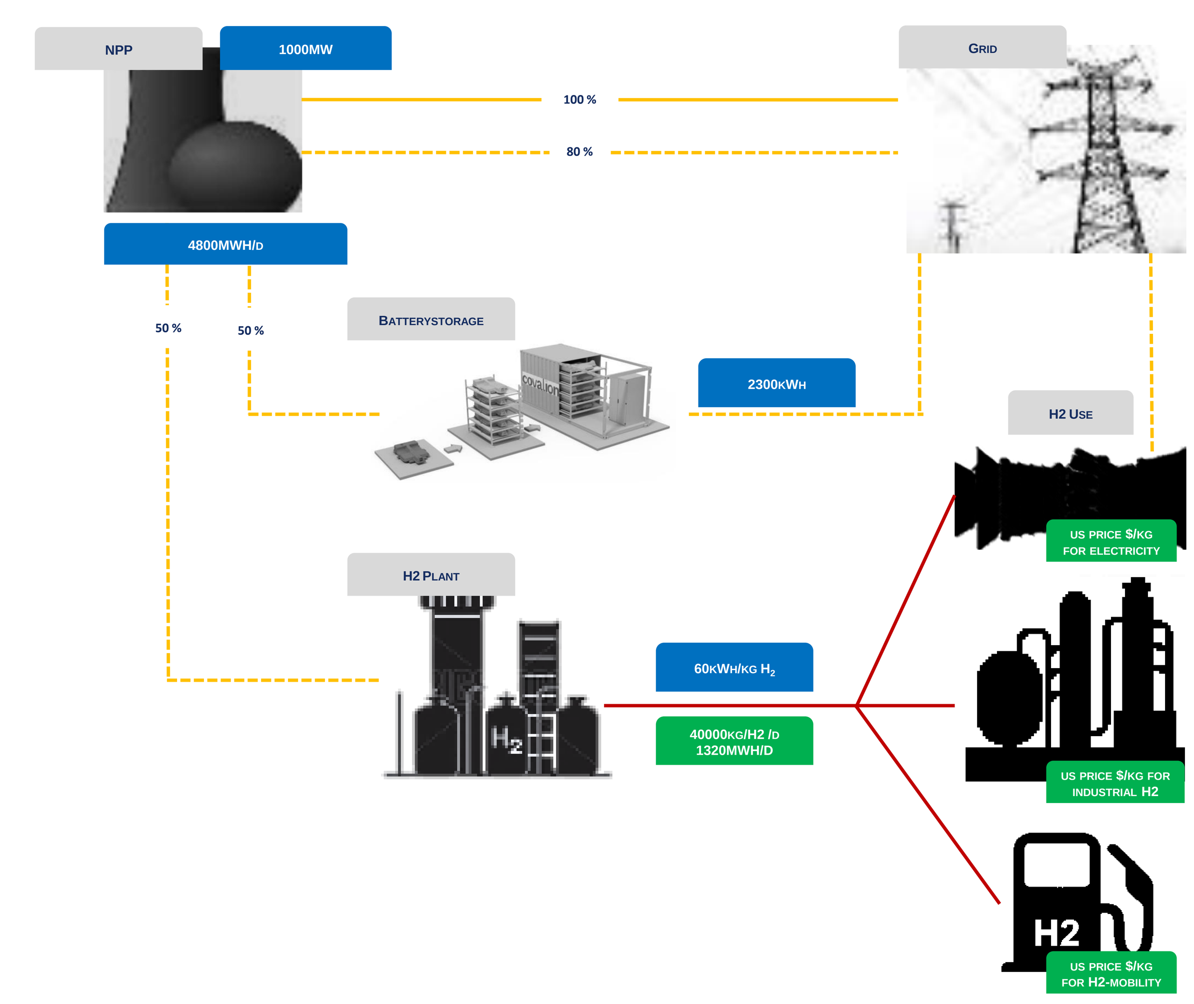


Fig 2: Storage solutions (H_2/Bat) coupled to NPP - Scheme

Nuclear cogeneration with H_2

- A H_2 plant is built in proximity to the nuclear plant
- Excess electricity from the nuclear plant (when renewable generation is high) is used for H_2 production via water electrolysis
- The H_2 produced is compressed and stored for sale to end users

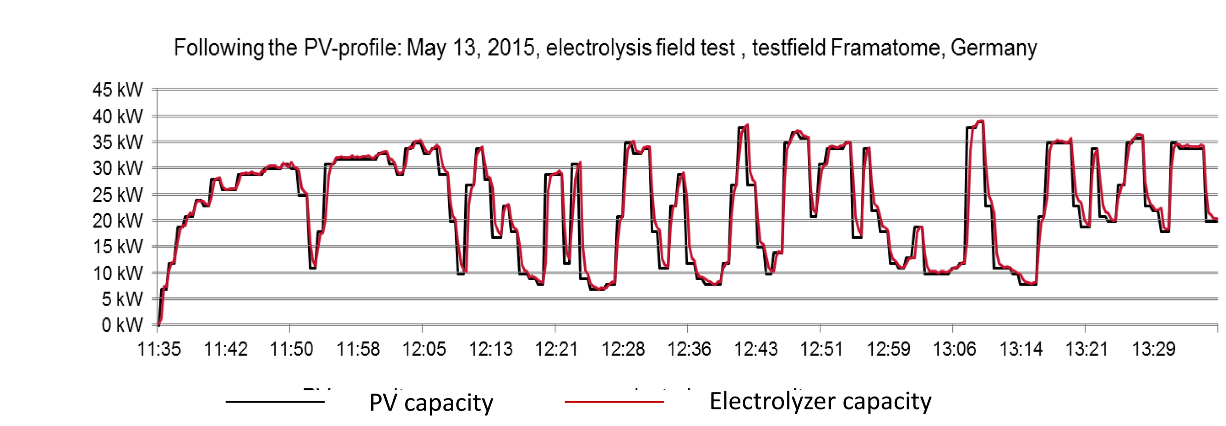


Fig 3: PEM electrolyzer dynamics: Following PV profile

Framatome H_2 Energy Storage Projects

Myrte, Corsica: Electrolyzers, fuel cells, gas storage stabilizing the grid

- H2 system (electrolyzer, fuel cell)
- storage

SCOPE

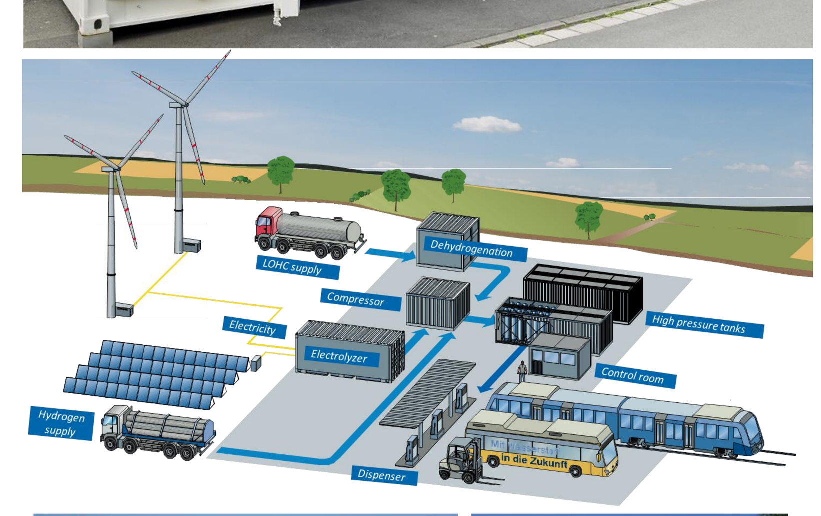
- 8 years (since 2011)

Operating

- CEA
- EDF
- University of Corse

CUSTOMER

H_2 storage, South Africa: LOHC* (innovative H_2 storage)
Public transport, Germany: Hydrogen refueling station



- LOHC (liquid organic hydrogen storage
- Containerized solution

H2 storage

- RVK public transport company, Germany

Customer

- < 2 years
- in operation Dec 2019

PROJECT Realization

- Hydrogen refueling station
- 500kg H2 per day (20 buses)

SCOPE

framatome

For more information, visit www.covalion.net
or contact Tim Stack at 704-805-2141 or tim.stack@framatome.com

Metal Hydride TES for CSP and Nuclear Applications

Jamison Couture
jamison.couture@braytonenergy.com
Brayton Energy
07118

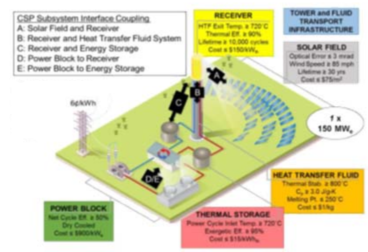
FUNDING PROGRAM: **APOLLO**

PROJECT NAME	Solar Receiver with Integrated TES for a sCO_2 Power Cycle
FUNDING OPPORTUNITY	DE-FOA-0001186 / CSP: Advanced Projects Offering Low LCOE Opportunities (APOLLO)
PRINCIPAL INVESTIGATOR	Shaun Sullivan
LEAD ORGANIZATION	Brayton Energy, LLC
PROJECT PARTNERS	• Savannah River National Laboratory • Greenway Energy, Inc.
PROJECT DURATION	42 months
BUDGET (DoE/Cost Share)	$ 3,249,948 ($ 2,599,959 / $ 649,990)

Apollo's Objectives

Meet DOE's $0.06/kW-hr CSP Energy target by 2020.

Conventional CSP Layout



+

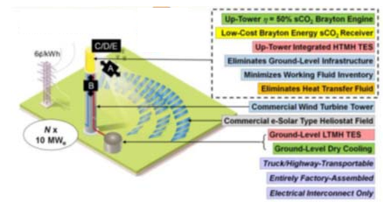
Metal Hydrides Energy Storage

Advance, Low Cost, and Scalable Solution

Promising applications for Base Load Nuclear Power Plants

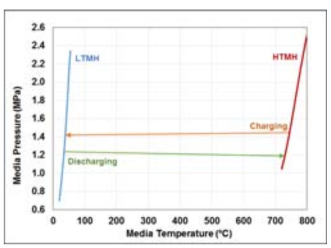
→

Apollo's Concept



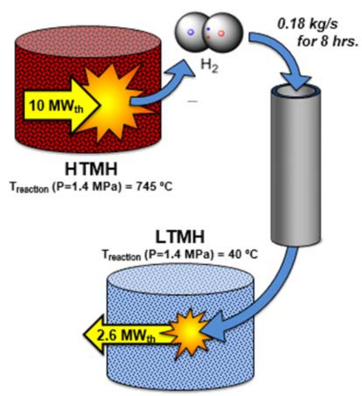
Metal Hydride Pairing

- A well-chosen pairing of metal hydrides will enable the free flow of hydrogen between the two media at the desired temperatures (600°C – 800°C)
- Connecting pipes must be sized for the appropriate pressure drop to maintain intended operating temperatures

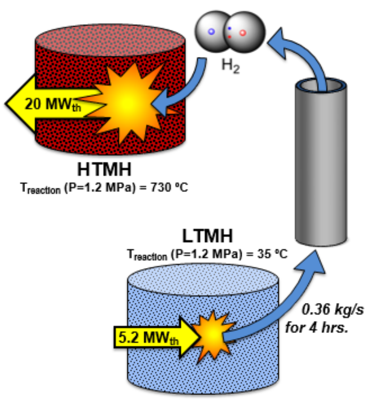


TES Charging

- Thermal (concentrated solar) energy is added to the HTMH, which *endothermically* releases hydrogen at its high reaction temperature
- The hydrogen flows into the LTMH, where it is *exothermically* absorbed at a lower reaction temperature
  - The released energy is absorbed by a flowing glycol loop, which then rejects it to ambient via an air cooled heat exchanger
- The energy is stored at low temperature in chemical bonds within the LTMH



TES Discharging

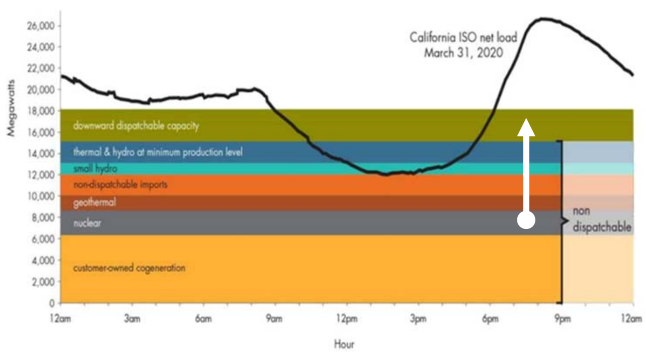


- Waste heat from the sCO_2 power cycle is absorbed into the same flowing glycol loop and transferred into the LTMH
  - This thermal energy is absorbed by the LTMH, which *endothermically* releases the stored hydrogen at its low reaction temperature
- The hydrogen flows back into the HTMH, where it is *exothermically* absorbed at a high reaction temperature
  - The released energy is transferred into the sCO_2 power cycle working fluid, heating it to the cycle turbine inlet temperature

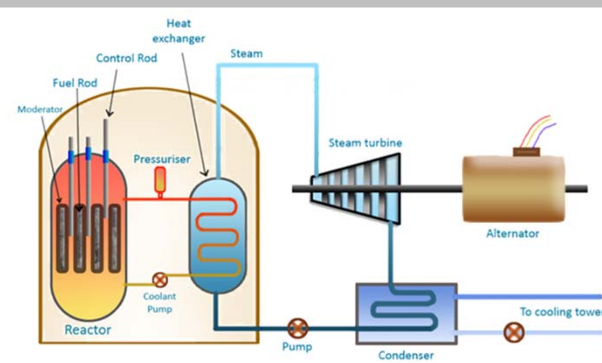
TES Sizing

	HTMH	LTMH
Compound	Ca_2Si	TiFe
ΔH (kJ/molH$_2$)	110	28
ΔS (kJ/molH$_2$-K)	130	114
Bulk Density (kg/m³)	1400	3129
Thermal Conductivity (W/m-K)	3.5	7
Weight Capacity (kg$_{H2}$/kg$_{MH}$)	0.023	0.0153
Specific Heat (J/kg-K)	950	500
Raw Material Cost ($/kg)	-	5.2

Market Demand for Dispatchable Energy

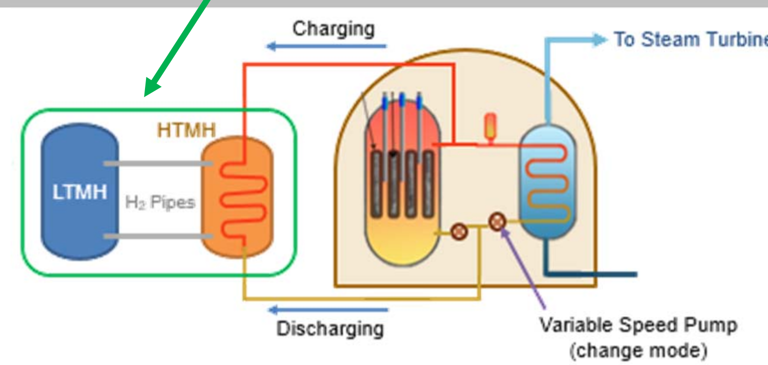


Base Load Nuclear Power Plant



With MH TES

Load Following Nuclear Power Plant



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY | SOLAR ENERGY TECHNOLOGIES OFFICE

BraytonEnergy

SRNL

GreenWayEnergy — POWERFUL EXPERTS

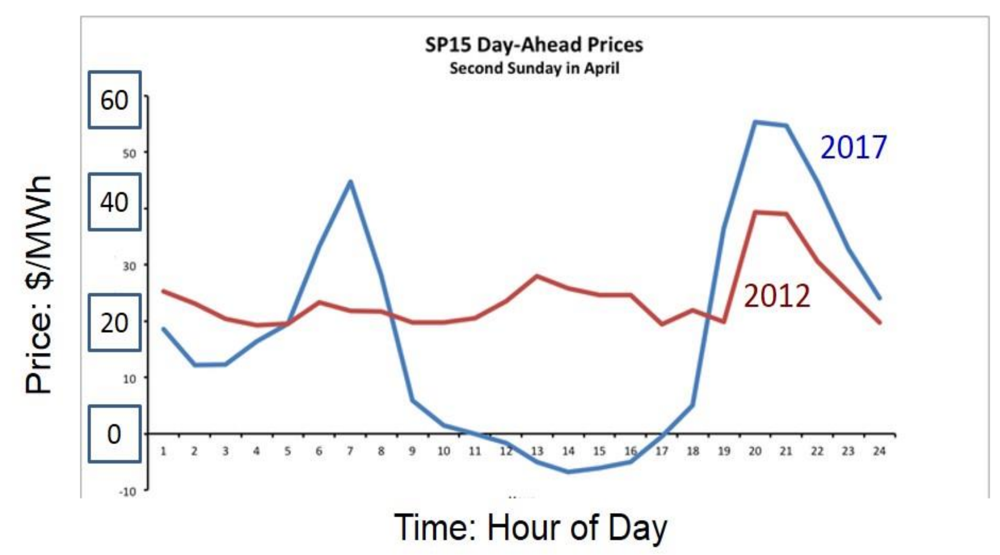
Markets, Design, and Experiments for Firebrick Resistance-Heated Energy Storage (FIRES)

Daniel C. Stack and Charles Forsberg
Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA

NSE Nuclear Science and Engineering
science : systems : society

Why Energy Storage?

- Society demands low-carbon energy to prevent climate change
- Addition of renewable generation to grid crashes price of electricity
- Damages low-carbon energy economics (including nuclear)
- Need large-scale, deployable, cheap energy storage to capture surplus energy
- **No such storage solution exists!**

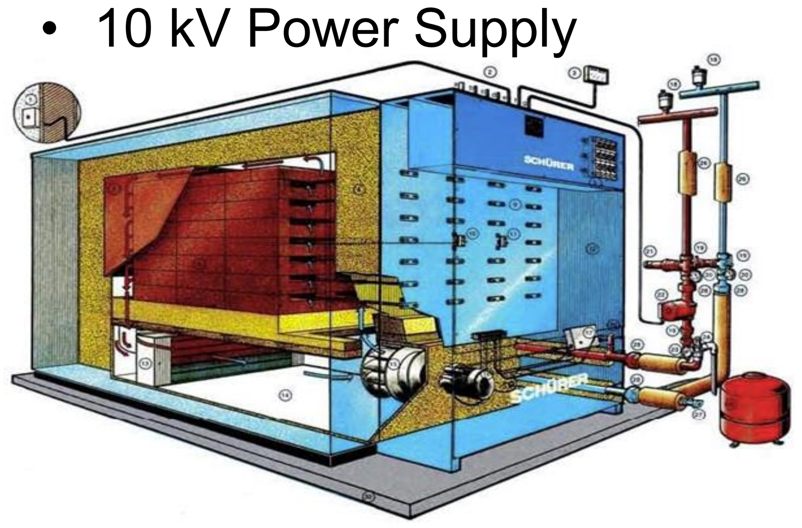


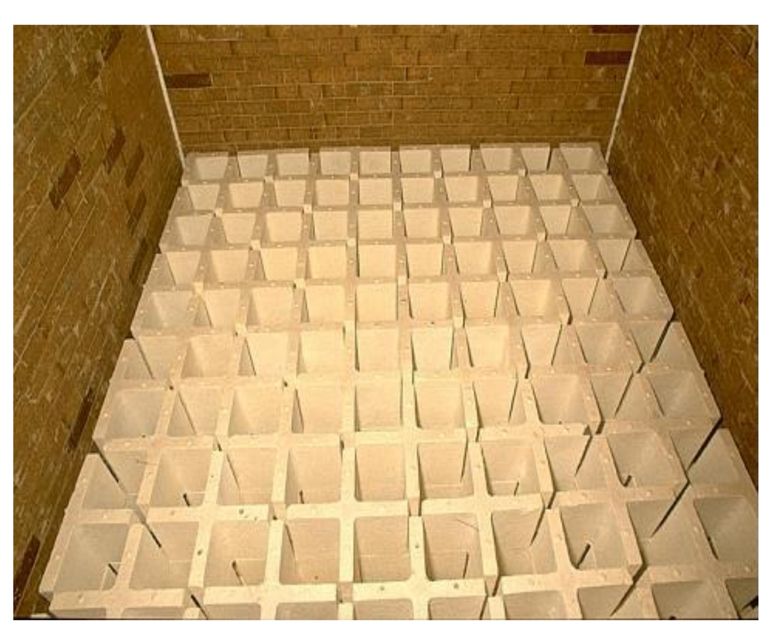
California Wholesale Prices Before and After Addition PV On Spring Day

Introducing FIRES

System Concept and Description

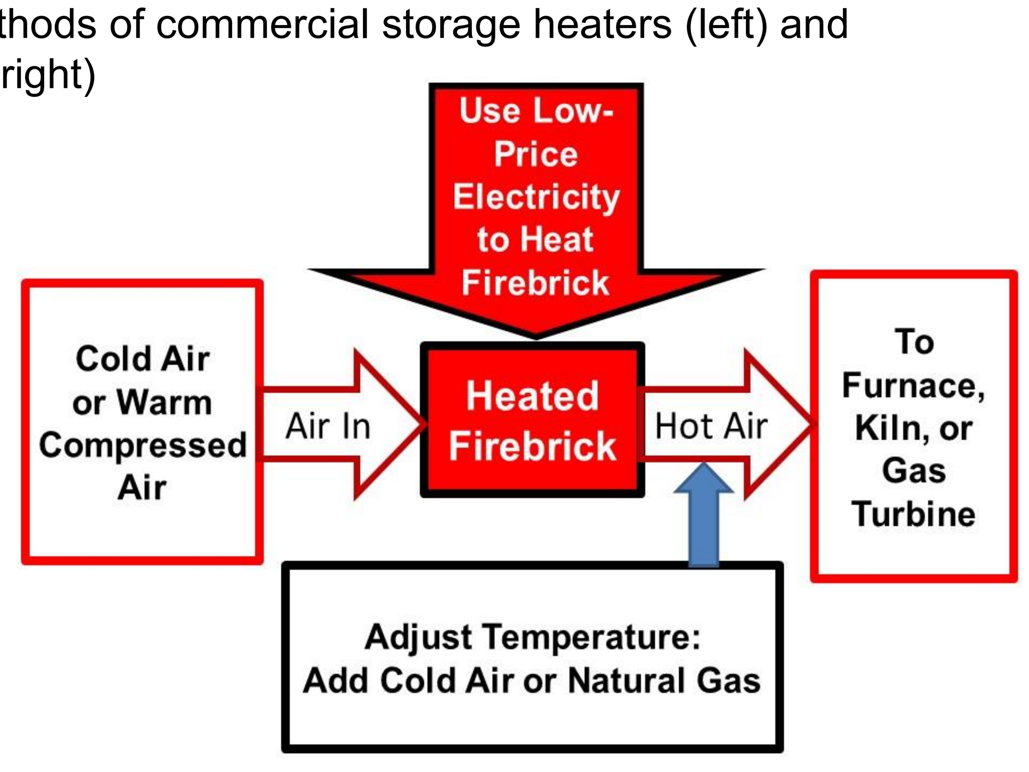
- Buy electricity when its price is less than price of natural gas
- Electrically heat insulated mass of firebrick to very high temperatures
- Discharge stored heat as hot air and use for (1) Industrial heat supply and (2) Peak electricity production
- State of the art (Atmospheric pressure): Deployed in China
  - 40 MWh
  - 600ºC
  - 10 kV Power Supply





FIRES combines the proven methods of commercial storage heaters (left) and industrial firebrick recuperators (right)

- FIRES is charged with low-price electricity
- Cold inlet air is blown through and heated by firebrick mass
- Temperature is adjusted by natural gas or cold air



- **Large Deployment: Prevent Electricity Price Collapse**

Storage Requirements

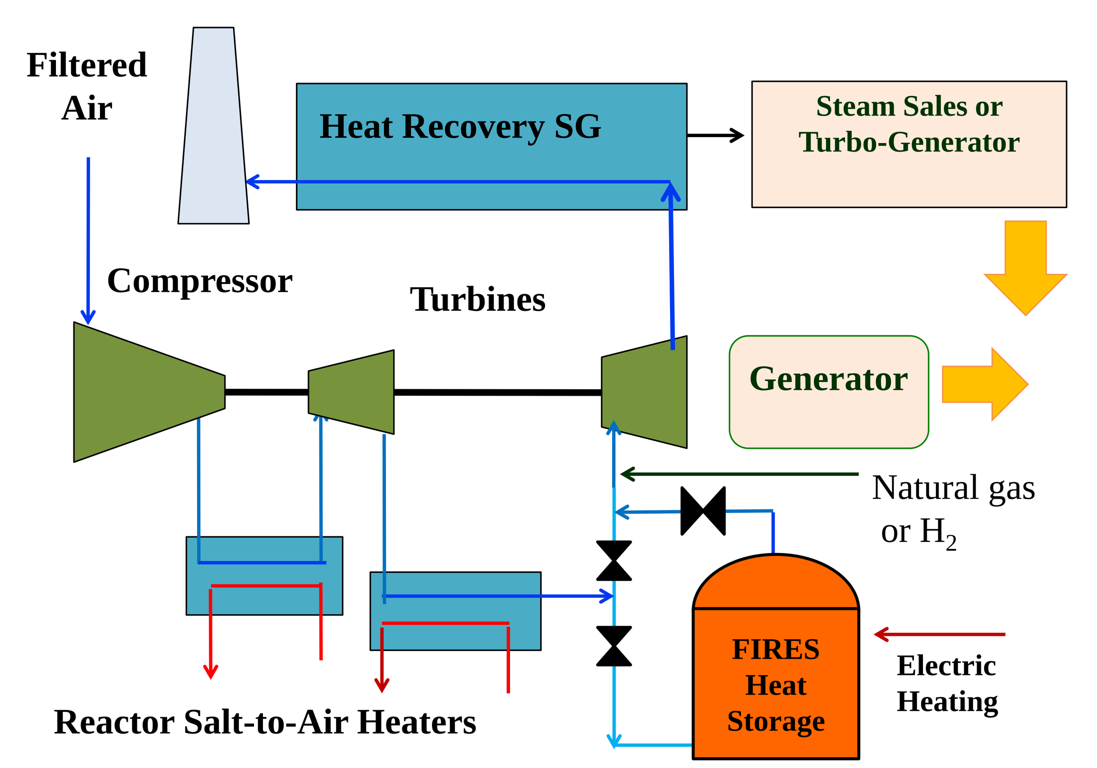
- Store low-price electricity in the form of heat
- Assured peak electricity if storage is depleted
- Solution: Heat storage coupled to combined cycle gas turbine
  - Burn natural gas, biofuels or H_2 if storage depleted
  - Turbine inlet temperature ~1600ºC for heat from storage

Combined Cycle Gas Turbine

~60% Heat to Electricity Efficiency

Nuclear Air-Brayton Combined Cycle (NACC)

- Add FIRES heat to NACC for peaking electricity production
- Charge FIRES with nuclear electricity during low demand
- **Roundtrip Electrical Efficiency ~70%**
- **Load following with constant reactor output**



Power cycle of fluoride salt-cooled high temperature reactor (FHR)

Strategic FIRES Goals

- Storage: Heat firebrick up to 1800ºC. Firebrick stores ~1 MWh/m³ with 1000ºC range. $1-2/kWh incremental storage cost
- Charge: direct resistance heating through conductive firebrick, or with integrated heaters. Design geometry for desired charge rate
- Discharge: blow cool air through system. Design air channel dimensions and variable flow system for desired output rate
- **Design Space: 100-1000s MWh, 10-100s MW_e and MW_t**
- **Comparison: Order of magnitude cheaper than batteries, and more deployable than hydro or compressed air storage**

Same Technology for High-Temperature Heat to Industry and Other Users

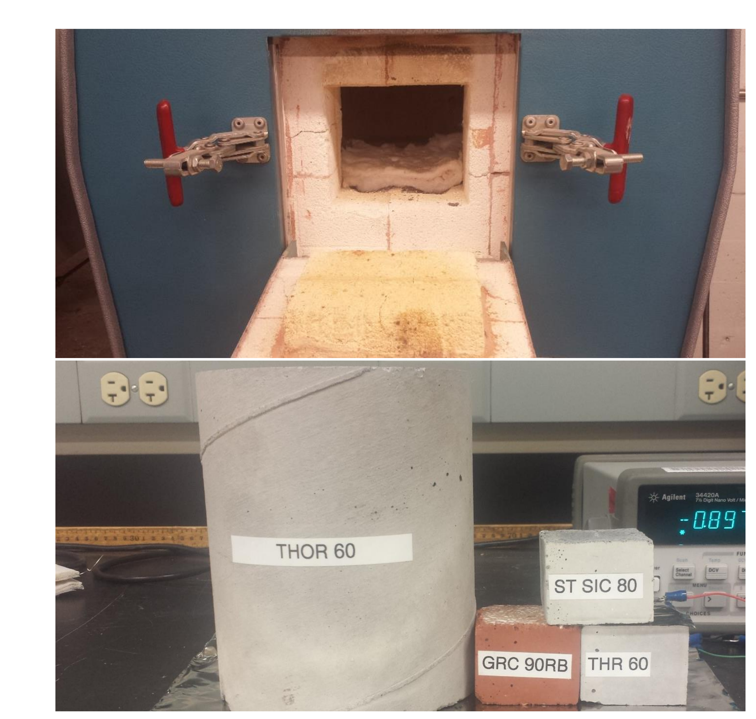
The Potential Economics

- Gas turbine assures peak power capability, no added cost for heat-to-electricity system; No backup gas turbine
- Use same electrical system (grid connection, transformers, switchgear) to buy or sell electricity
- Potentially low-cost resistance heaters (see below)
- Low-cost storage because of large hot-to-cold temperature swing
- Better economics than other options
  - Lower capital costs
  - High heat-to-electricity efficiency

The Challenge: Low-Cost Reliable High-temperature Resistance Heaters

Experiments on Electrically Conductive Firebrick

- Direct resistance heating (DRH) of firebrick promising alternative to existing heaters:
  - Higher peak temperature
  - Improved reliability
  - Lower cost
- **Electrical resistance testing underway**
- **New technology heaters**



Conclusions

- **A low-carbon energy grid demands energy storage**
- **FIRES prevents electricity price collapse by converting cheap electricity to high-temperature heat for the industrial heating sector or to produce peak electricity**
- **Large-scale deployment of FIRES can set a minimum wholesale price of electricity near that of natural gas**
- **Reliable performance and profitable economics**

Added Information:

- ***Electricity Journal*, July 2017,** https://doi.org/10.1016/j.tej.2017.06.009
- **and *Applied Energy*, May 2019,** https://doi.org/10.1016/j.apenergy.2019.03.100

Work supported through: (1) the INL National Universities Consortium (NUC) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517; and (2) Exelon Corporation.

For more information: dcstack@mit.edu, cforsber@mit.edu

LATENT HEAT THERMAL ENERGY STORAGE SYSTEM

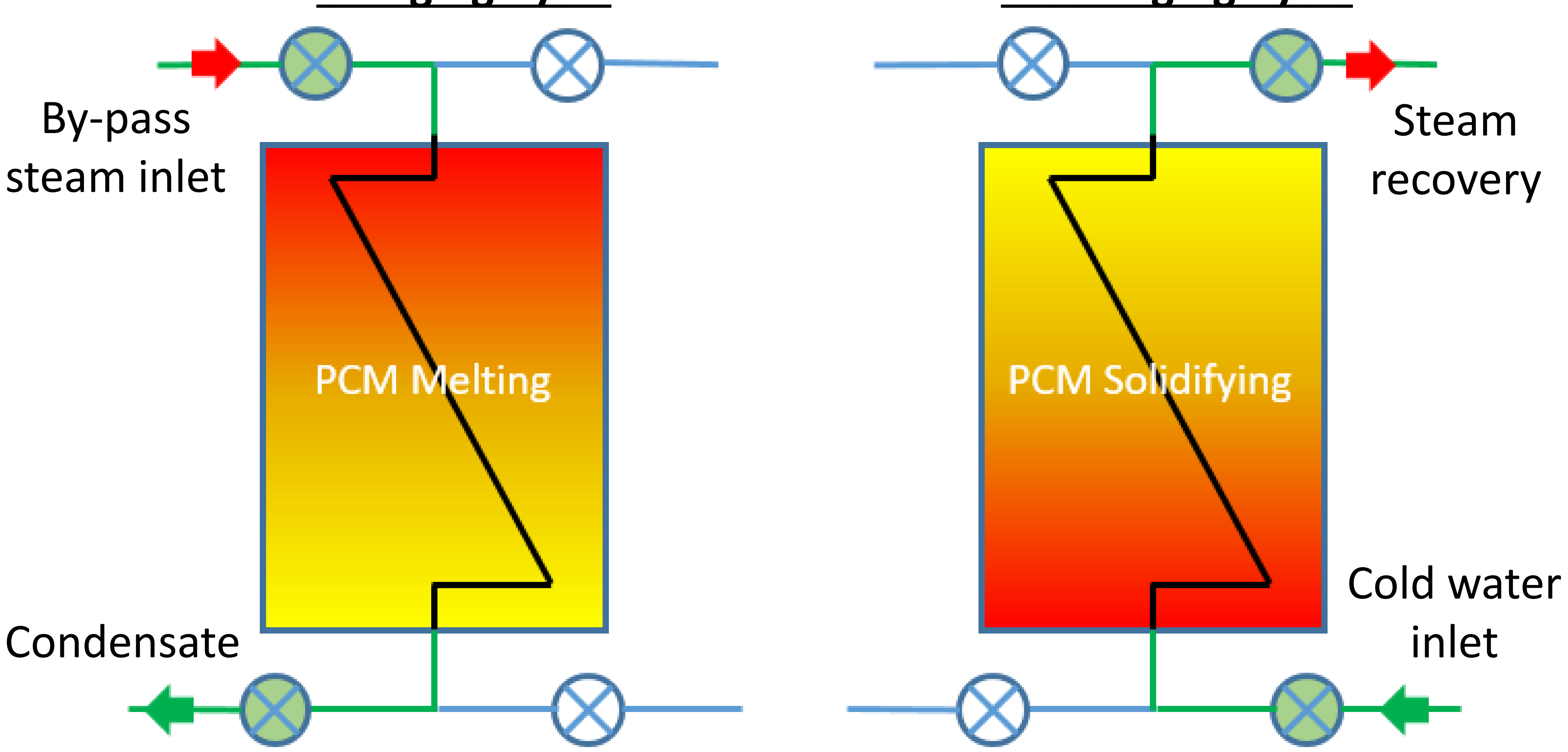
Amey Shigrekar (UI), Piyush Sabharwall (INL), Richard Christensen (UI), and Matt Memmott (BYU)

Background

The Nuclear-Renewable Hybrid Energy System (N-RHES) is an integrated facility comprised of a nuclear reactor, renewable energy sources, and industrial processes that can simultaneously address the need for grid flexibility, greenhouse gas emission reductions, and optimal use of investment capital. In order to make the N-RHES technology more attractive, it is herein proposed to couple the N-RHES with a latent heat thermal energy storage (LHS). Excess heat not demanded by the grid for electricity production can be allocated to the LHS, and therefore be used later when there is high demand or low renewable energy contribution.

Overview

LHS systems employ phase change materials (PCMs), thereby utilizing the large amount of heat that can be stored during the phase change process. Given the characteristics of latent heat, high energy density storage systems can be produced that operate at isothermal conditions.



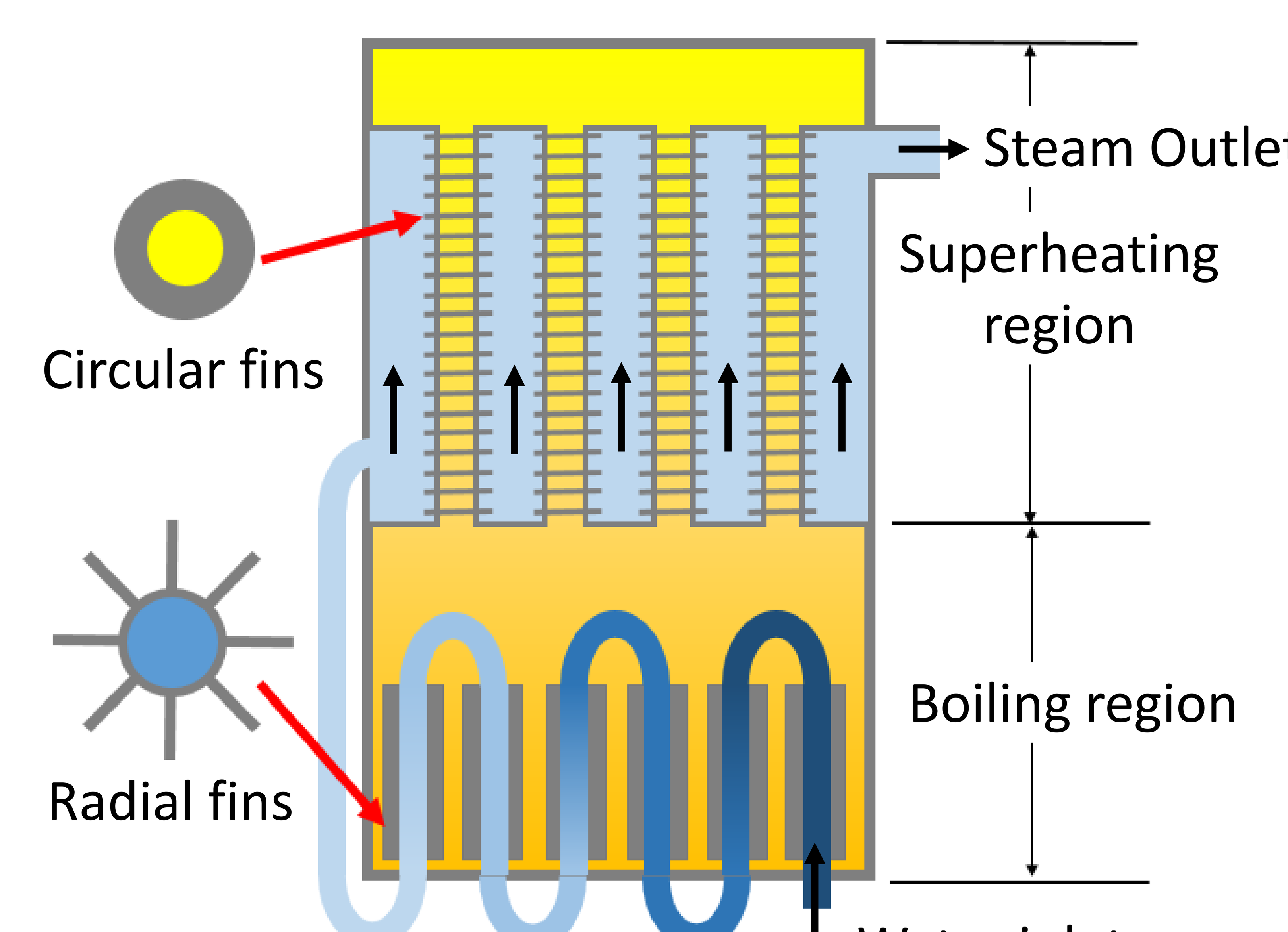
Working principle of an LHS – charging and discharging

Objective

- ❖ Develop a math- & physics-based analytical model for the LHS in Modelica, to be integrated with on-going N-RHES modeling efforts.
- ❖ Validate the analytical model using numerical and experimental results.
- ❖ Optimize the integrated model using RAVEN for economic benefit and sensitivity analysis.

Methodology

A 2-D analytical model for the LHS is currently being developed with steam as the heat transfer fluid and $NaNO_3$-KNO_3 salt mixture as the heat storage medium. For preliminary analysis, the model assumes pure conduction heat transfer in the PCM during melting and solidification. The effects of convection will be taken into account by utilizing an empirically developed effective thermal conductivity, based on the materials used and the geometry of the LHS. The results from the numerical and experimental studies will be used to improve the accuracy of the analytical model.



Potential design concept for an LHS

Solid–Liquid Phase Change Materials for High-Temperature Nuclear Reactor Heat Storage

W. N. Mann*, S. Landsberger, M. E. Webber
Walker Department of Mechanical Engineering, Cockrell School of Engineering, The University of Texas at Austin, *nealmann@utexas.edu

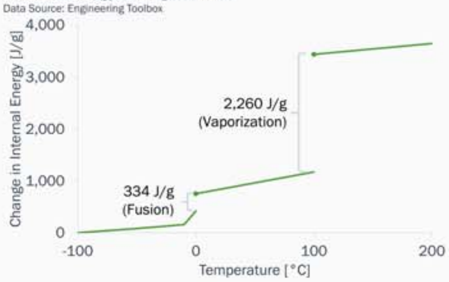
Objective

Find promising solid–liquid phase change materials (PCMs) for high-temperature nuclear reactor heat storage.

Background

- Latent heat: energy absorbed or released at constant temperature during a phase change
  - Solid–liquid
  - Liquid–gas
- Solid–liquid avoids pressure vessels
- Melting (solid–liquid) generally stores less energy per mass [J/g] than evaporating (liquid–gas)

Internal Energy Change, Water
Data Source: Engineering Toolbox

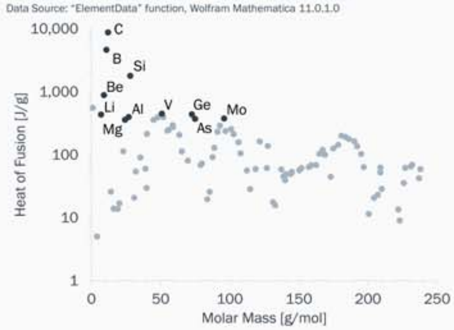


Methods

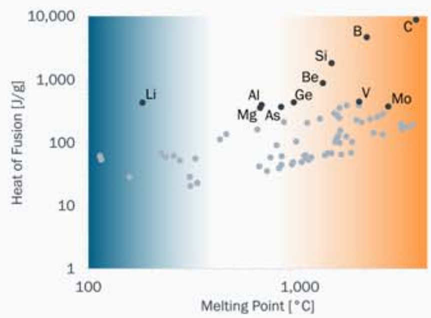
- Three selection criteria: melting point, heat of fusion, safety hazards
- Melting point in the range of expected HTFs: sH_2O, sCO_2, Na, He, et c.
  - 374–850 °C
- High heat of fusion
  - >375 J/g
- Evaluated basic safety hazards
  - GHS physical and health hazards, NFPA 704 codes
- Best candidate chosen from a cluster of related elements/compounds with similar properties

Results

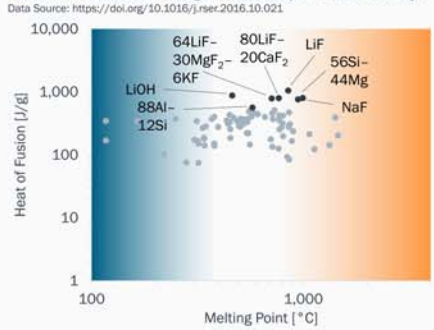
Heat of Fusion vs. Molar Mass, Pure Elements
Data Source: "ElementData" function, Wolfram Mathematica 11.0.1.0



Heat of Fusion vs. Melting Point, Pure Elements
Data Source: "ElementData" function, Wolfram Mathematica 11.0.1.0



Heat of Fusion vs. Melting Point, Compounds and Alloys
Data Source: https://doi.org/10.1016/j.rser.2016.10.021



Safety Hazards of PCM Components (NFPA 704, GHS)
Data Sources: Alfa Aesar, MilliporeSigma, PubChem; Image Source: Wikimedia Commons

	Health (NFPA)	Health (GHS)		Flammability	Instability	Physical (GHS)	Special Hazards
Al	0			0	0		N/A
CaF_2	2			0	0		N/A
KF	2–3			0	0–1		N/A
LiF	2–4			0	0–1		N/A
LiOH	3			0–1	0–1		N/A
Mg	0–2			4	2		~~W~~
MgF_2	2			0	0		N/A
NaF	2			0	0–1		N/A
Si	0–1			0–2	0		N/A

Conclusions

- 88Al–12Si eutectic is a good compromise: melts 576 °C, heat of fusion 560 J/g, low hazards
- Eutectic mixtures of LiF, CaF_2, MgF_2: higher melting temperatures & heats of fusion, but more hazardous

Future Work

- Identify compatible containment and heat exchanger materials
- Complete simplified storage system component model
- Incorporate materials costs to estimate and minimize system cost for different temperature ranges

Acknowledgments & Disclaimers

The authors acknowledge support from the U.S. Department of Energy, Office of Nuclear Energy (Nuclear Energy University Program, project 14-6950).

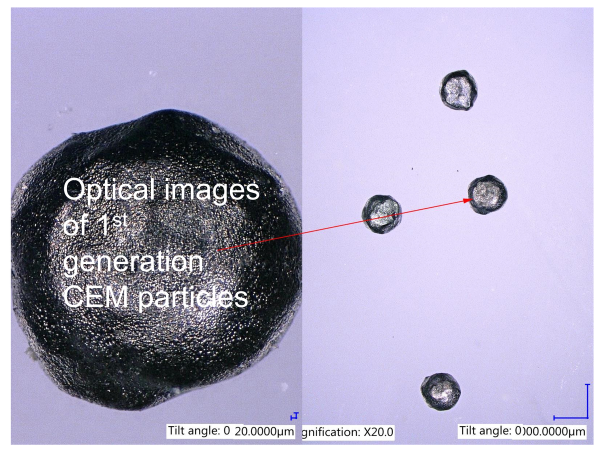
This material is based in part on work supported under an Integrated University Program Graduate Fellowship.

Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Department of Energy, Office of Nuclear Energy.

The University of Texas at Austin
Walker Department of Mechanical Engineering
Cockrell School of Engineering

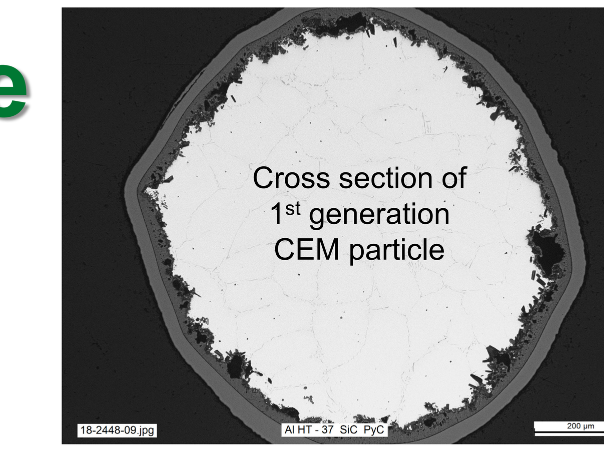
Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors Workshop

23–24 July, 2019
Idaho Falls, ID
Sponsors: MIT, INL, Exelon



Ceramic Encapsulated Metal Phase Change Material for Tunable, High Temperature Thermal Energy Storage

JW McMurray, BC Jolly, SS Raiman, AT Schumacher, KM Cooley, and E Lara-Curzio



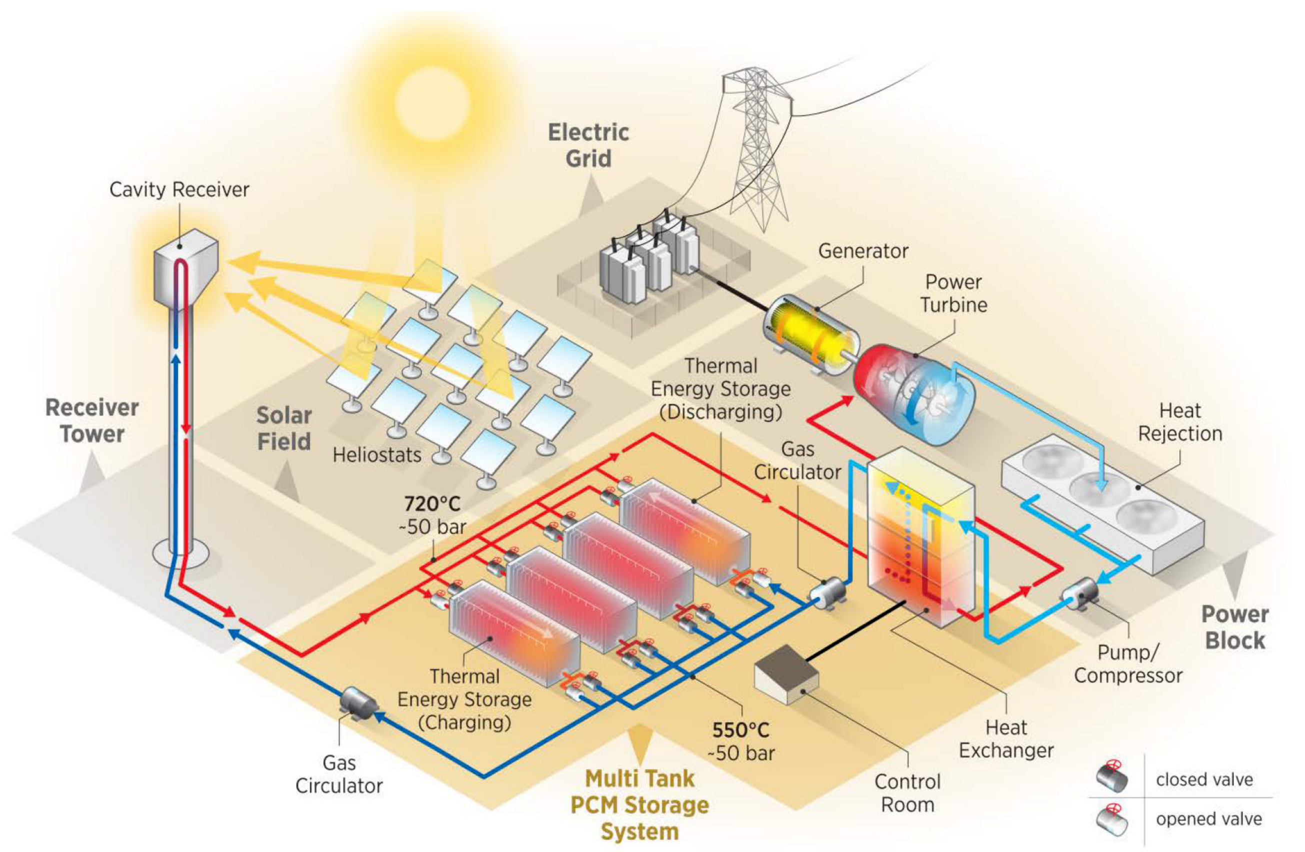
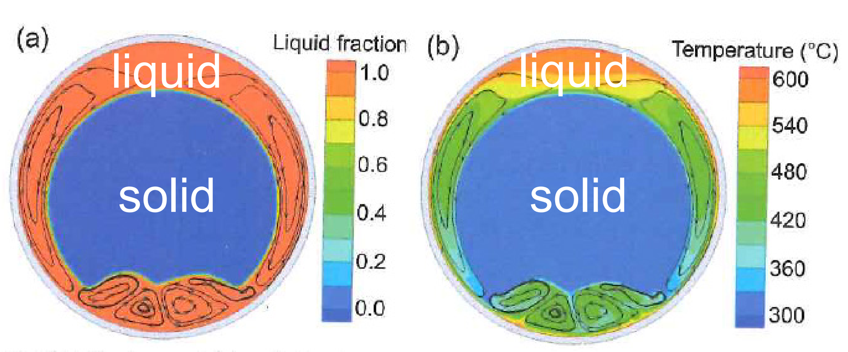


Image from Mehos et al., Concentrating Solar Power Gen3 Demonstration Roadmap, NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)), (2017)



Results of a simulation of a charging event in a Tube and Shell heat exchanger from Blanco and Ramirez Santigosa in *Advances in Concentrating Solar Thermal Research and Technology*, Elsevier, Amsterdam (2017)

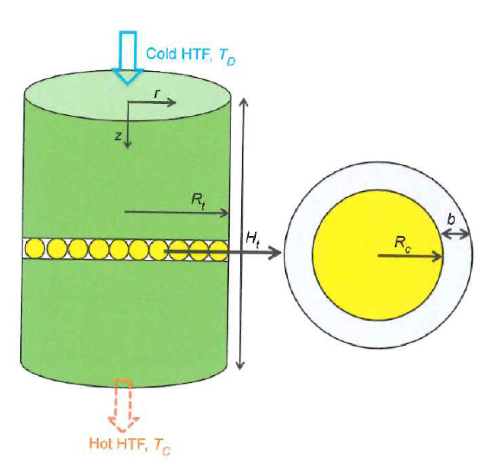
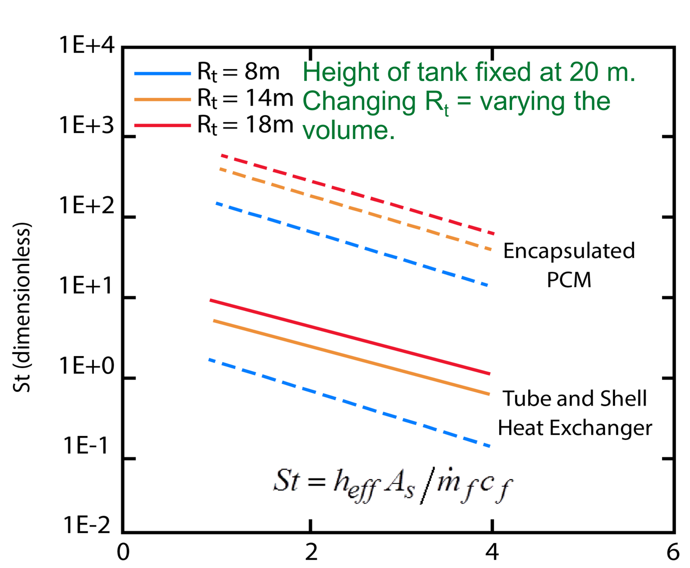


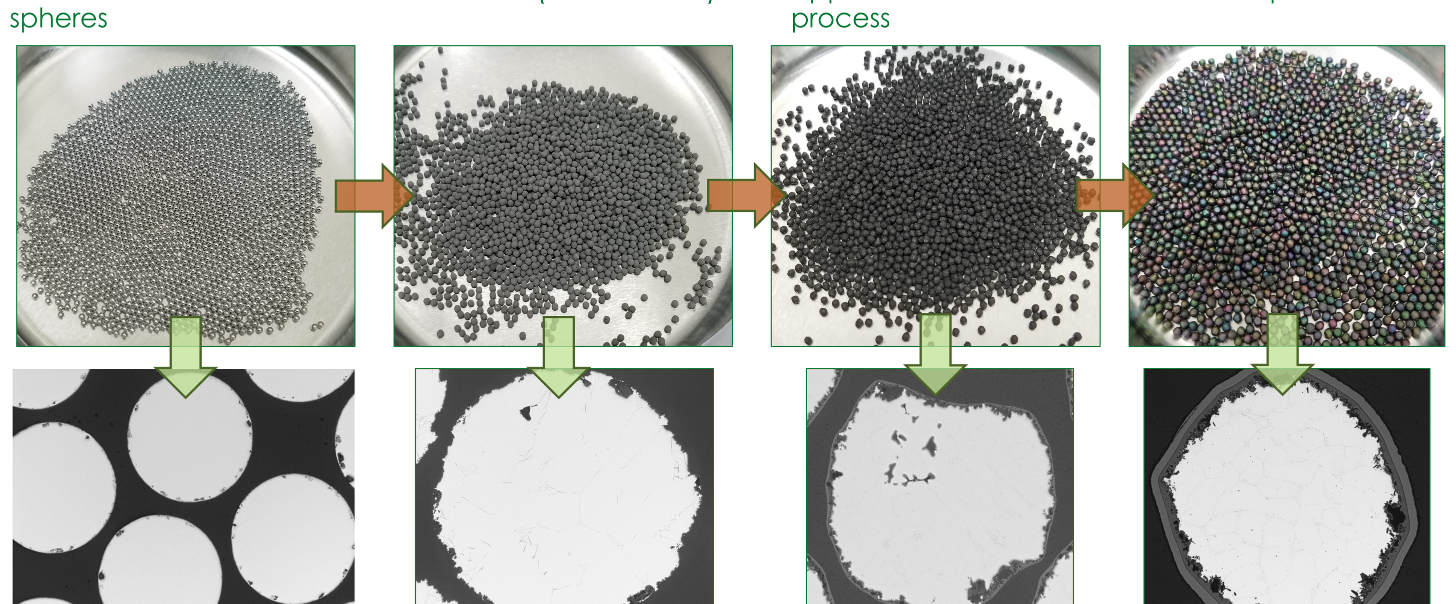
Image from Blanco and Ramirez Santigosa in *Advances in Concentrating Solar Thermal Research and Technology* Elsevier,, Amsterdam *(2017)*

Comparison of the radius for the tubes against the radius of the particles for the same volume of PCM at various tank volumes



$$St = h_{eff} A_s / \dot{m} \, c_f$$

ORNL has developed a process for encapsulating liquid metal in ceramic coatings



Optical cross sections of, as received, oxidized, carbon coated, and SiC coated Al spheres

Background

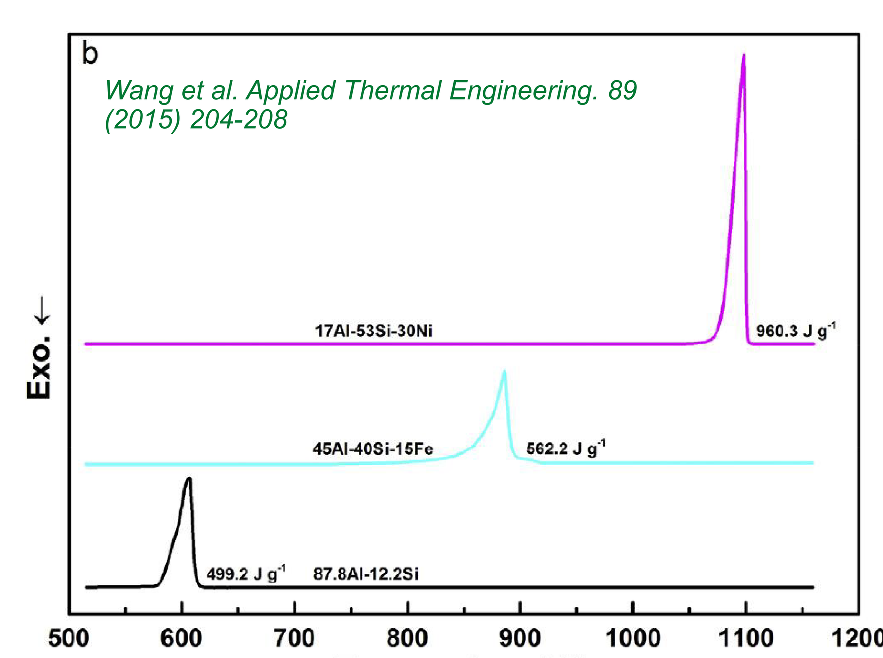
- Thermal Energy Storage (TES) is a broad based technology
  - TES improves efficiency and economics of fossil fuel, nuclear, and CSP plants
- TES makes renewables compatible with the grid
- Thermal energy storage is less expensive than other types of storage
  - Battery, pumped hydro, etc. \$340/kWh
  - Al as a PCM is \$12/kWh

Encapsulated Phase Change Materials are the future of Thermal Energy Storage

- In a tube and shell heat exchanger you get hot/cold spots
- It takes time for natural convection to complete the melting
- The Stanton number (*St*) is the ratio of the overall heat transfer to the heat carrying capacity of the heat transfer fluid. The higher the better
- Encapsulated phase change materials show orders of magnitude increases in heat transfer

Encapsulating a Phase Change Material requires overcoming a technological challenge: How do you coat a liquid?

- The process uses aluminum (Al) as the base metal because Al:
  - is abundant and inexpensive
  - has a high melting point ~660°C
  - has a high heat of fusion
  - has good heat transfer properties
  - **forms an oxide layer upon heating that fully encapsulates the melt**
- The Al can be alloyed to further reduce cost and tune the melting point and energy density



Key to the process is the oxidation characteristics of aluminum

- Oxidation allows the Al to be taken to full volume as a liquid
- Voids (14.5 vol %) form in the Al to accommodate volume expansion upon melting.
- Repeated melting/freezing cycles for storing/releasing thermal energy can be accomplished without cracking open the encapsulating layers

Silicon Carbide (SiC) is deposited as the outer coating layer using a Chemical Vapor Deposition (CVD) process

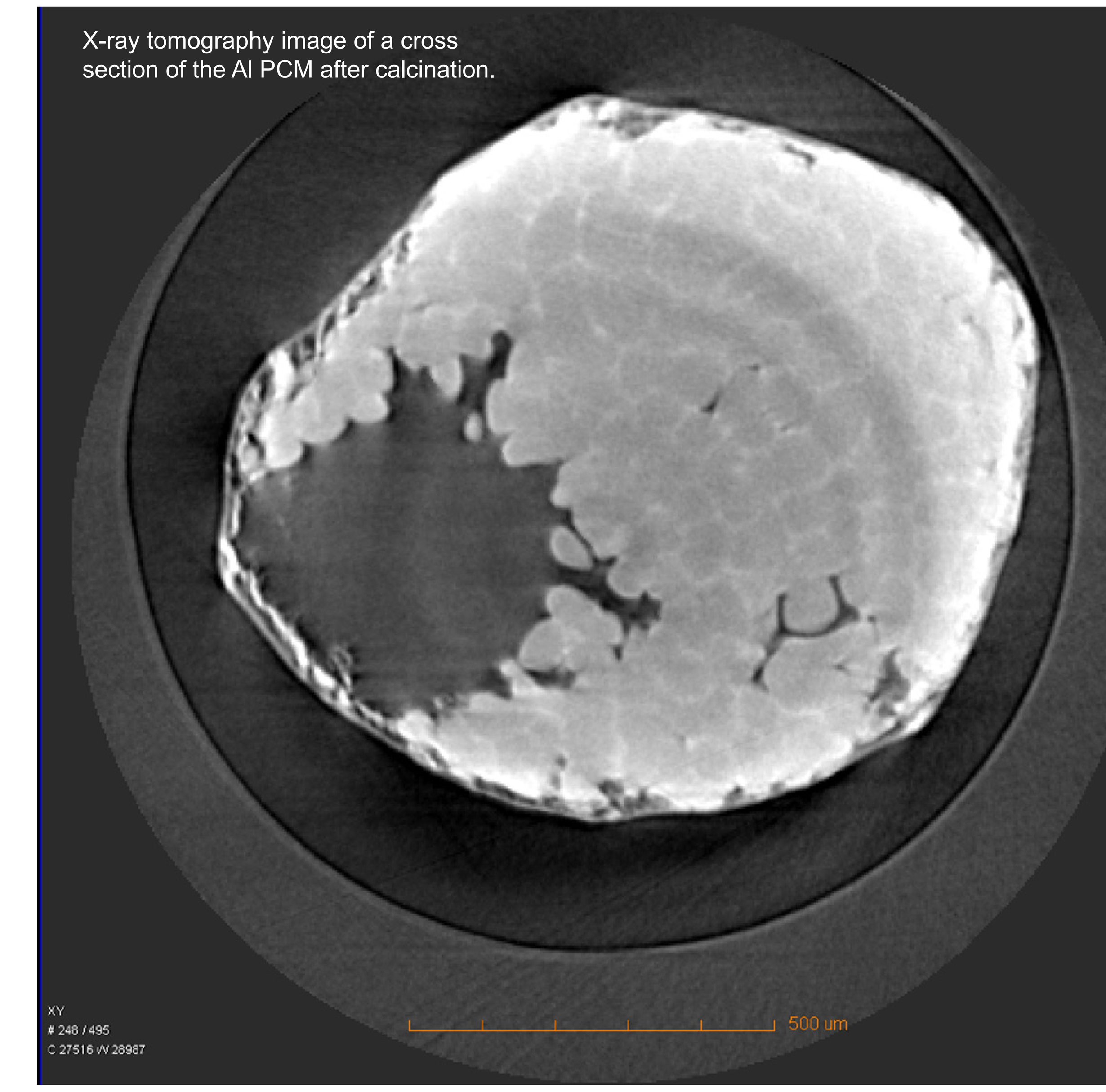
- A pyrocarbon (PyC) diffusion layer is first deposited to avoid halogen attack from the SiC precursor on the oxide layer
- SiC is chemically compatible with most, if not all heat transfer fluids (HTFs) including:
  - molten salts
  - supercritical CO_2
  - air
  - steam
- SiC has good strength and heat transport properties

Challenges

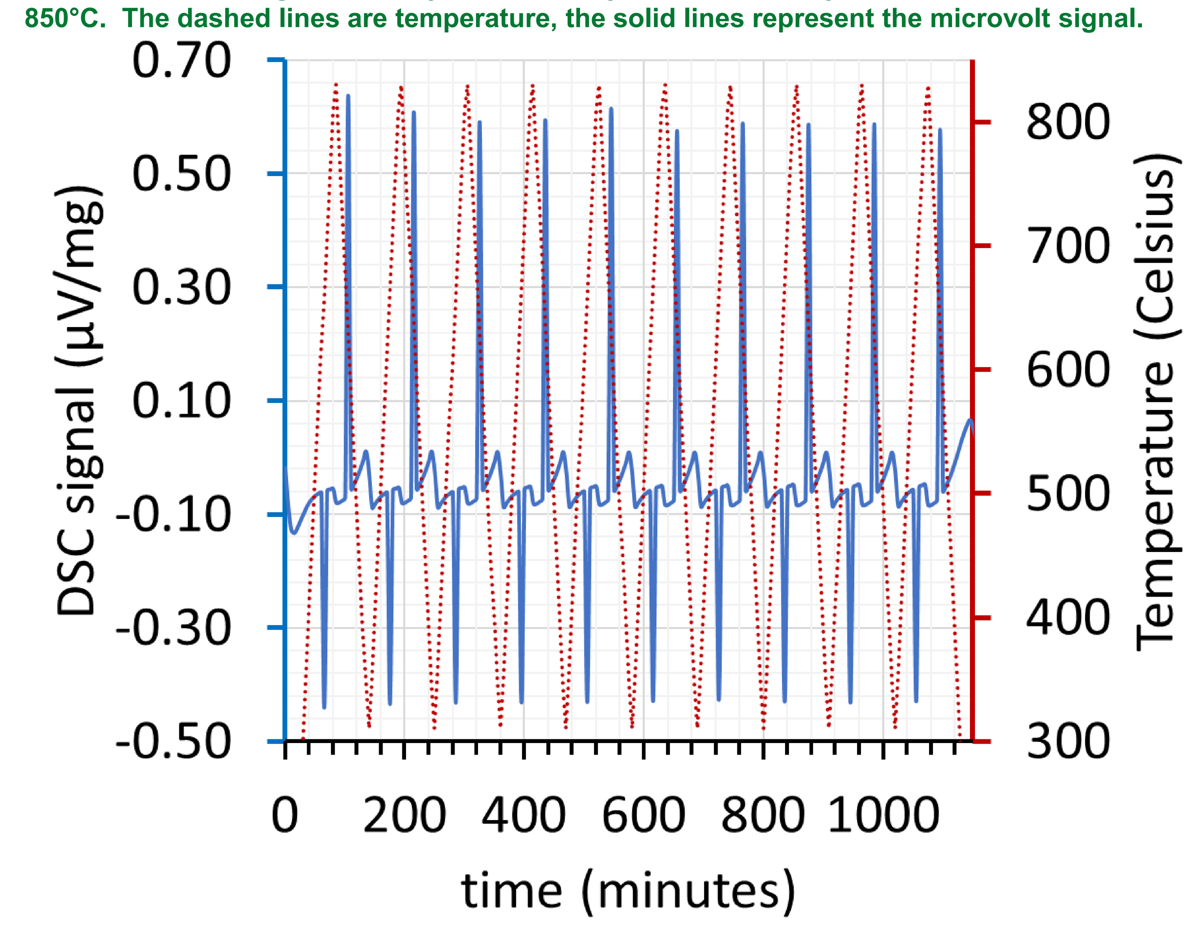
- CVD SiC coating is expensive
- Eliminating SiC cracking due to thermal expansion mismatch between SiC and PyC upon cooling

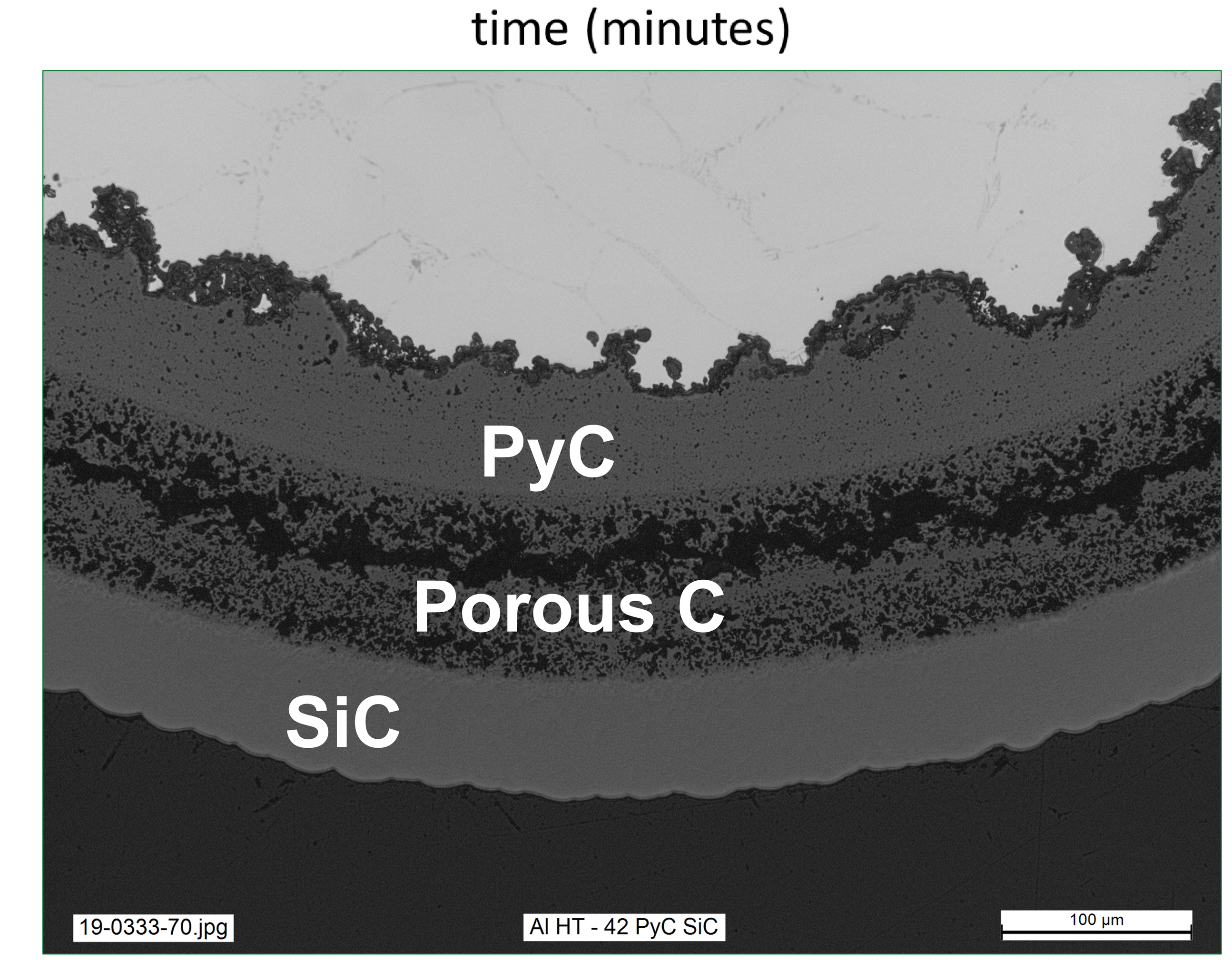
Future work

- Optimizing layer properties for mitigating SiC cracking
- Validating CVD SiC corrosion resistance to HTFs
- Demonstrating the process with engineered alloys for higher/lower melting points and greater energy density
- Developing more economical processing routes for the outer SiC coating layer



Differential scanning calorimetry results for PyC coated CEM cycled 10 times from 300 to 850°C. The dashed lines are temperature, the solid lines represent the microvolt signal.





Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy.

Experimental Investigation and Analysis of $Ca(OH)_2/CaO$ Chemical Heat Pump for Thermal Energy Storage

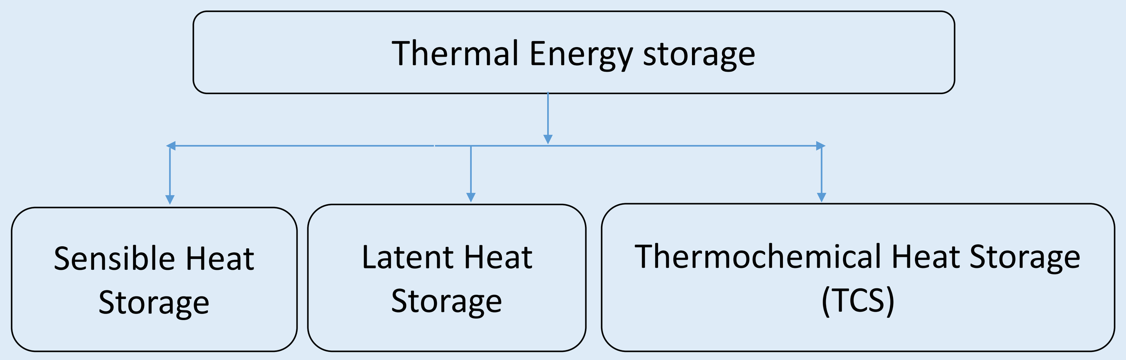
Aman Gupta,* Paul D. Armatis,‡ Piyush Sabharwall,† Vivek Utgikar* and Brian M. Fronk‡

*Department of Chemical and Materials Engineering, University of Idaho, Moscow, ID 83844, vutgikar@uidaho.edu, gupt2851@vandals.uidaho.edu

†Idaho National Laboratory, Idaho Falls, ID 83415, piyush.sabharwall@inl.gov

‡School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR 97331, brian.fronk@oregonstate.edu, armatisp@oregonstate.edu

INTRODUCTION



- ❑ Chemical Heat Pumps (CHPs) are the systems that uses reversible chemical reaction to change temperature levels of thermal energy, stored in chemical substances.
- ❑ Advantages of CHPs over other Mechanical Heat Pumps are high storage capacity, long term storage of both reactant and product, lower heat loss and energy upgradation for low temperature heat.
- ❑ A TCS method based on the reversible decomposition reaction of $Ca(OH)_2$ has attracted wide attention due to potential temperature amplification which can be achieved through Chemical Heat Pump.

$Ca(OH)_2(s) + \Delta\hat{H}_r \leftrightharpoons CaO(s) + H_2O(g)$ $\Delta\hat{H}_r = 104.4$ kJ mol^{-1}

OBJECTIVE

- ❑ Develop and demonstrate temperature amplification capabilities of a chemical heat pump (CHP) system for thermal energy storage
- ❑ Validate the theoretical model and system parameter with obtained data for scale-up and design

METHODOLOGY

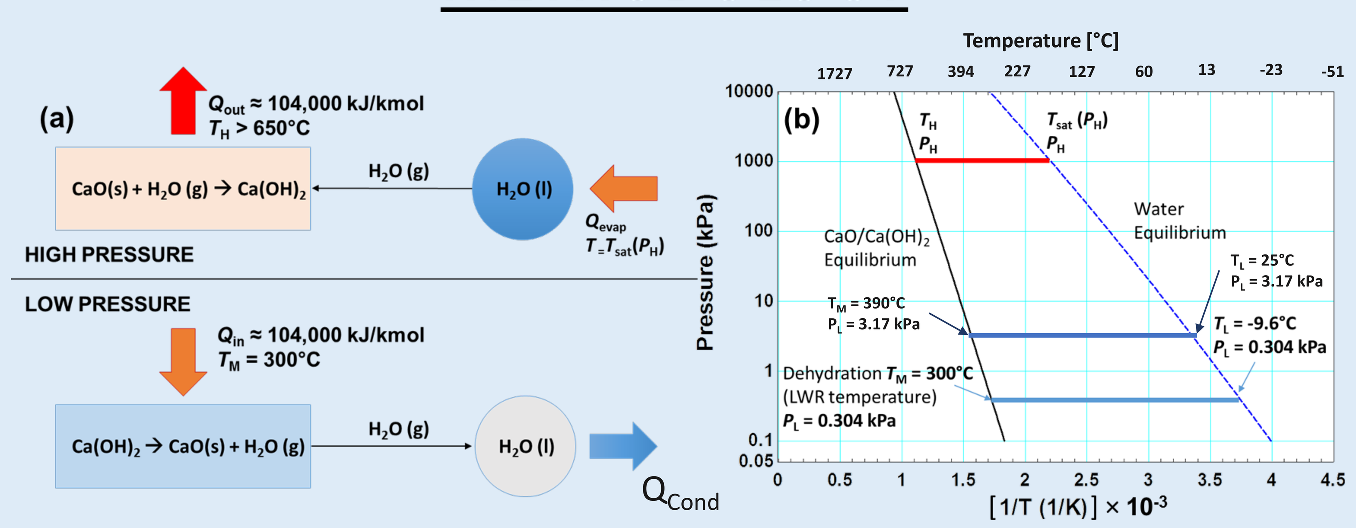


Figure 1 : (a) Schematics of component of CHP systems and (b) Heat pump cycle on Clausius-Clapeyron diagram showing equilibrium of $CaO/Ca(OH)_2$ and $H_2O_{(L)}/H_2O_{(G)}$

- ❑ A TCS-CHP coupled with a nuclear reactor in an integrated nuclear renewable energy system (INRES) can increase the efficiency of the system by letting the reactor operate at its maximum thermal capacity, diverting the excess thermal energy to TCS during periods of low electrical demand.
- ❑ Cycling of water between the hydration/dehydration reaction is accomplished by means of a condensation-evaporation cycle as shown in Fig. 1. Alternately, this transfer can be accomplished by an absorption-desorption cycle, typically as in the lithium bromide refrigeration cycle.

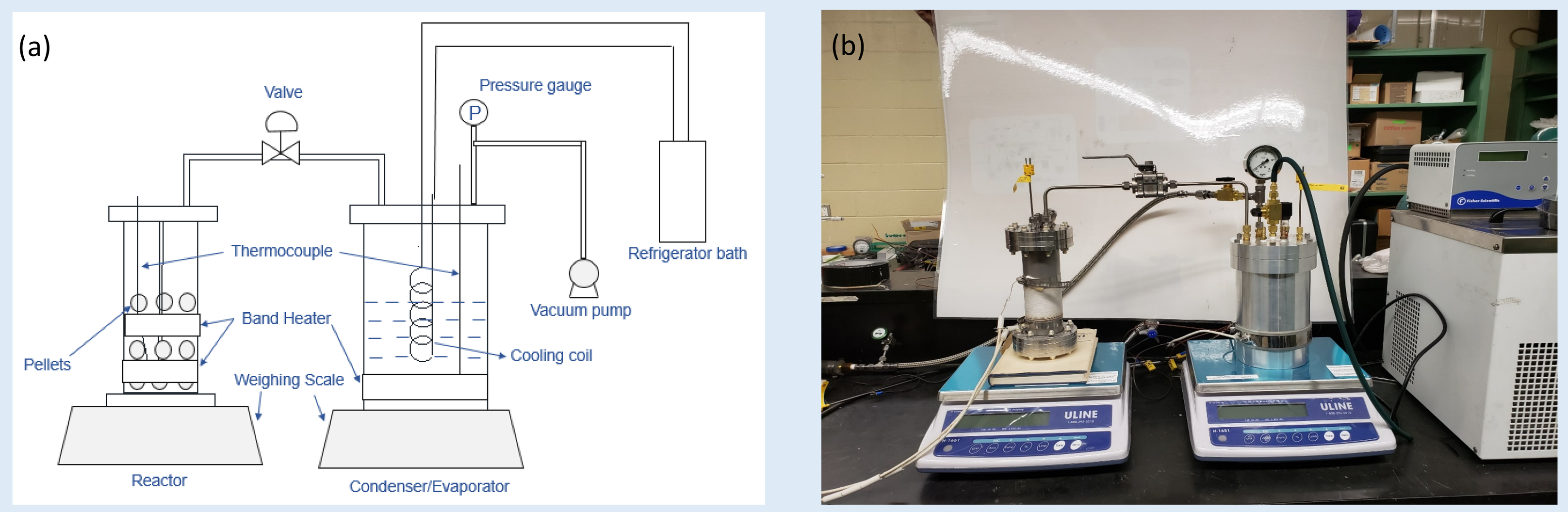


Figure 2 : (a) Schematic of experimental setup and (b) Laboratory scale experimental setup (Reactor Dimensions : ID – 2.5" and Height – 9"; Condenser/Evaporator Dimensions : ID – 4.4" and Height – 8")

- ❑ Dehydration process : Energy storage step (endothermic reaction)

$Ca(OH)_2(s) + \Delta\hat{H}_r \leftrightharpoons CaO(s) + H_2O(g)$

  - Charging pellets
  - Vacuuming the system
  - Water injection in condenser
  - Starting cooling water flow
  - Heating the reactor
  - Monitoring the temperatures and mass transferred

- ❑ Hydration process : Energy discharge step (exothermic reaction)

$CaO(s) + H_2O(g) \leftrightharpoons Ca(OH)_2(s) + \Delta\hat{H}_r$

  - Vacuuming the system
  - Water injection in evaporator
  - Heating both the reactor and condenser
  - Monitoring the temperatures and mass transferred

RESULTS AND DISCUSSIONS

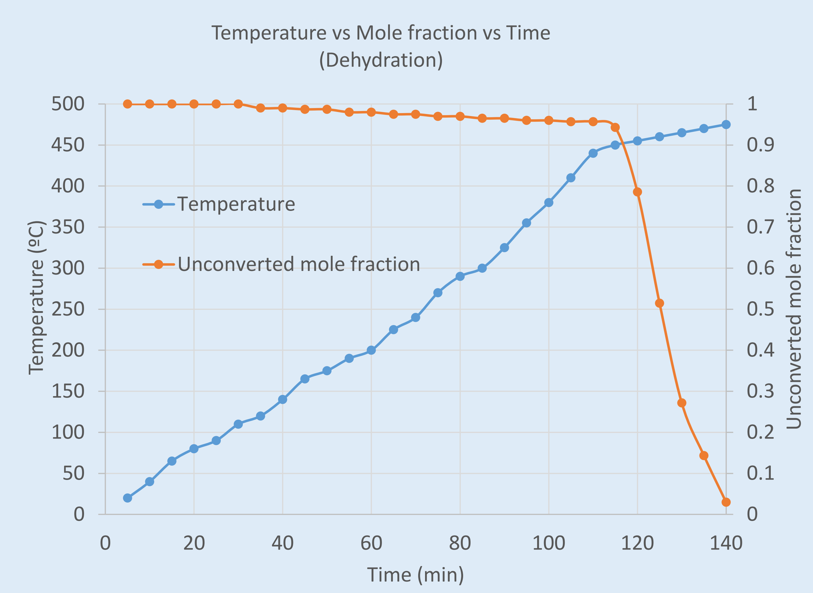


Figure 3 : Temperatures and unconverted mole fraction during dehydration reaction P=3.17kPa

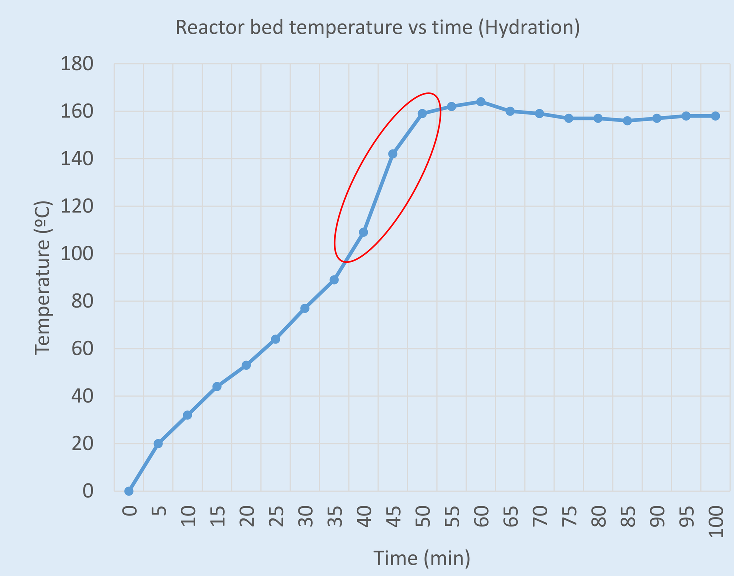


Figure 4 : Temperature profile during hydration process

- ❑ During dehydration process, when temperature of the reaction bed is higher than 350°C, dehydration reaction takes place. When the temperature reaches up to 400°C, dehydration reaction progresses rapidly. After 150 min, unconverted mole fraction decreased to about 0.03 and the dehydration reaction was nearly completed as seen from Fig 3.
- ❑ Hydration reaction progresses rapidly causing a temperature rise, and then the extent of reaction was limited at operating condition as shown in Fig 4. Under high pressures, the temperature can be further boosted to higher values as per Clausius-Clapeyron diagram in Fig. 1.

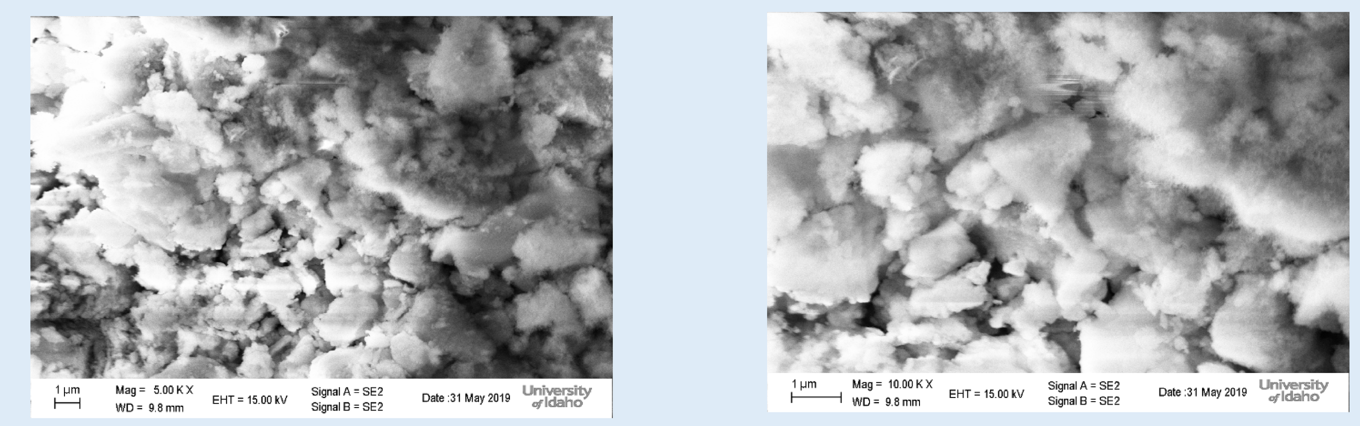


Figure 5 :SEM images before the reaction

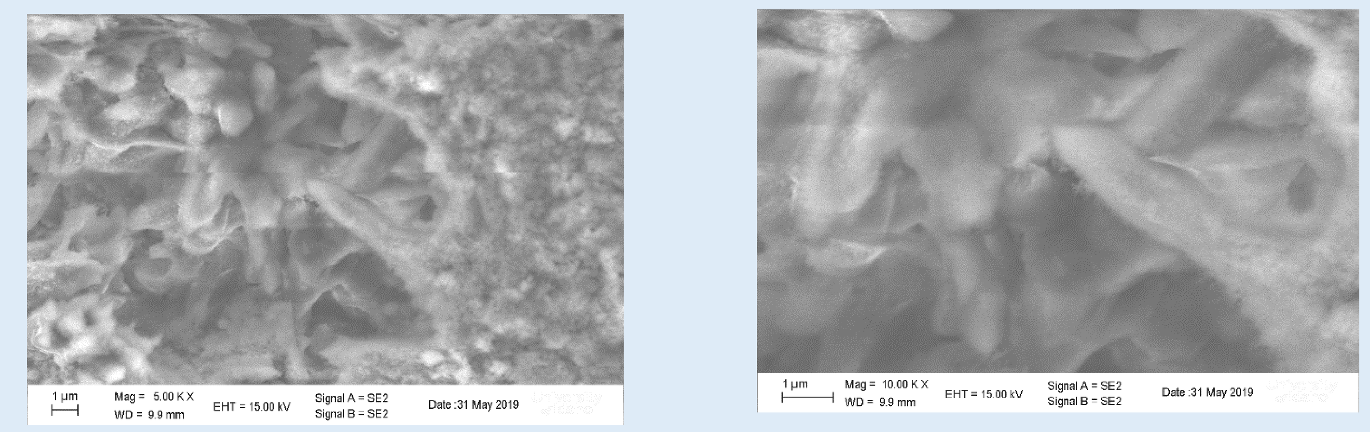


Figure 6 :SEM images after one complete reaction cycle

- ❑ SEM images shown in Figs. 5 and 6 show how the structural morphology changes after one complete cycle. Some decrease in area after one complete cycle was observed.

CONCLUSIONS AND OBSERVATIONS

- ❑ The dehydration reaction was successfully performed and during the process the reactor temperature increased gradually until the onset of the reaction and after that it changes relatively slowly.
- ❑ The hydration process showed a positive result as reactor temperature increased due to exothermic reaction could be observed during the process. Temperature rise can be higher at higher pressures.
- ❑ SEM images after one complete cycle showed that there were some changes in the structure and morphology of the particles.

FUTURE WORK

- ❑ Experimental investigation of performance change for repeated dehydration/hydration cycles
- ❑ Validation of experimental data with theoretical analysis

ACKNOWLEDGEMENTS

This research is supported by the funding received from DOE Nuclear Energy University Program (NEUP).

Nuclear Energy Thermal Energy Upgrade with a Chemical-Absorption Heat Pump

School of Mechanical, Industrial, and Manufacturing Engineering

Paul D. Armatis*, Aman Gupta‡, Piyush Sabharwall†, Vivek Utgikar‡, and Brian M. Fronk*

* School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR 97331, brian.fronk@oregonstate.edu

†Idaho National Laboratory, Idaho Falls, ID 83415, piyush.sabharwall@inl.gov

‡Department of Chemical and Materials Engineering, University of Idaho, Moscow, ID 83844, vutgikar@uidaho.edu

Introduction

In the integrated nuclear-renewable energy systems (INRES) concept (Fig 1), nuclear power is coupled with industrial thermal processes, renewable energy sources, and energy storage, to promote grid flexibility and stability.

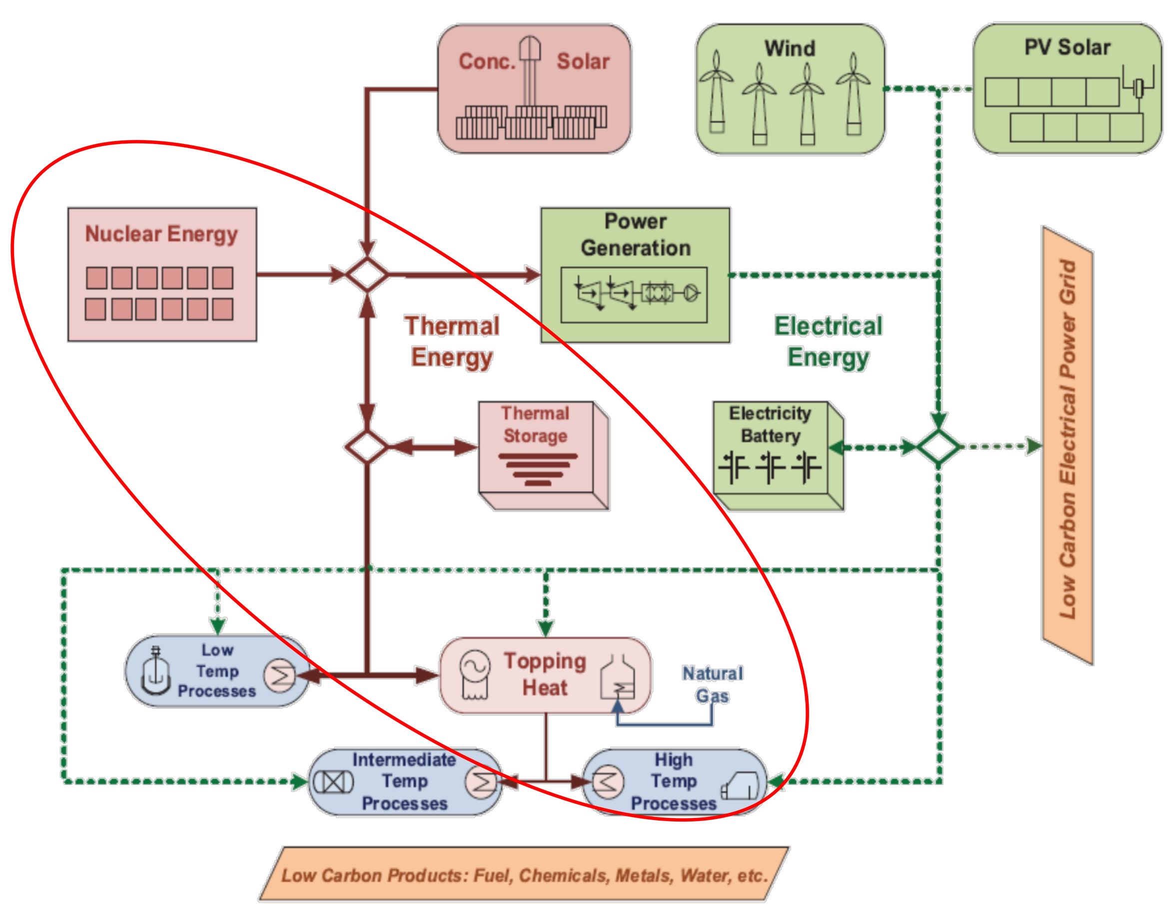


Fig 1: Example of Integrated Nuclear-Renewable Energy System
Bragg-Sitton *et al.* (2016) INL/EXT-16-38165

Heat from a conventional light water reactor (LWR) can be coupled with high-value industrial thermal processes and used when grid demand is low and/or renewable energy is plentiful. However, many industrial thermal processes require heat at temperatures higher than a LWR can provide requiring thermoamplification.

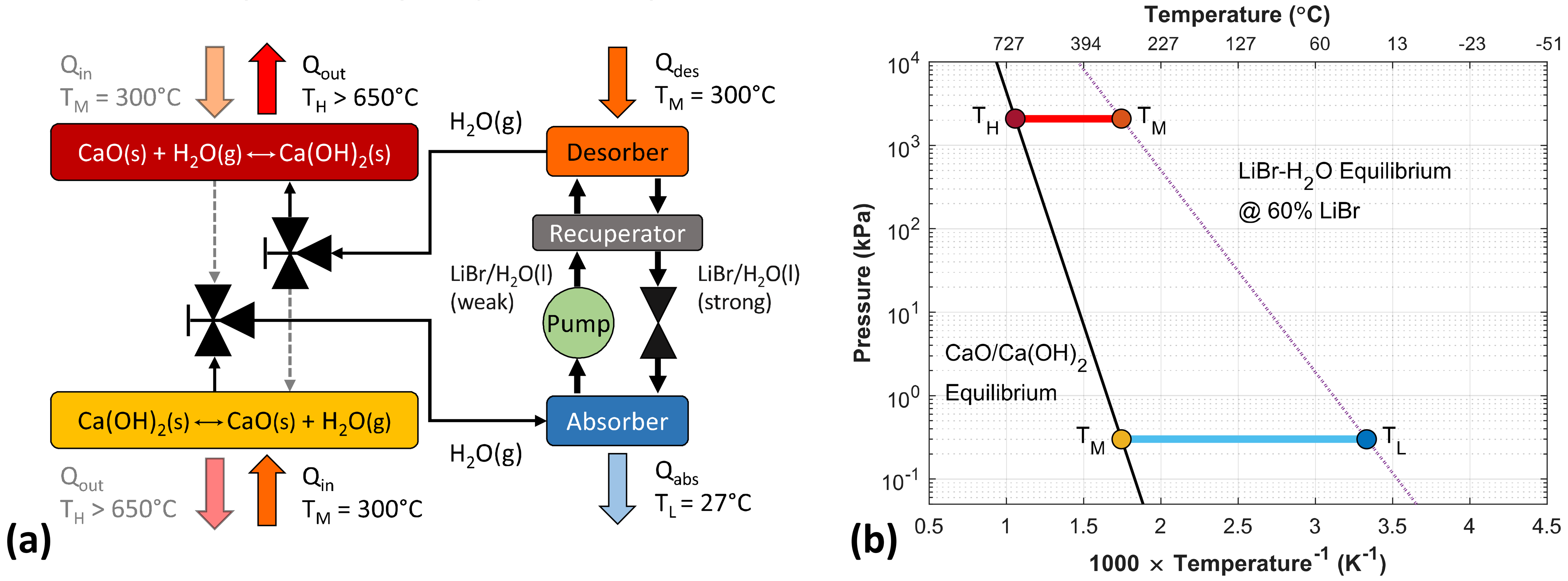


Fig 2: (a) Chemical-absorption heat pump schematic and (b) Clausius-Clapeyron diagram

Proposed System: Thermoamplifier

Thermoamplification is the process of increasing the temperature or quality of heat. Chemical heat pumps (CHPs) are capable of large temperature lifts >300 °C which are required for many high temperature processes. In Fig 2, a CHP is augmented by an absorption heat pump (AbHP) to provide a primarily thermal pathway for thermoamplification which increases the exergetic efficiency by avoiding the use of a compressor or rejecting heat at sub ambient temperatures.

Model Results and Discussion

A state point model was developed in *Engineering Equation Solver* to evaluate the performance of the system compared to conventional process heating as well as changes in performance under different operating conditions. The exergetic efficiency (Eq 1) was compared between conventional processes heating with LWR power in Fig 3a and the chemical-absorption heat pump in Fig 3b.

$$\eta_{II} = \frac{\text{Exergy Delivered}}{\text{Exergy Supplied}} = \frac{\left(1-\frac{T_0}{T_H}\right)\dot{Q}_H}{\sum_{j=1}\left(1-\frac{T_0}{T_{j,in}}\right)\dot{Q}_{j,in} + \sum \dot{W}_{in}} \quad \text{Eq 1}$$

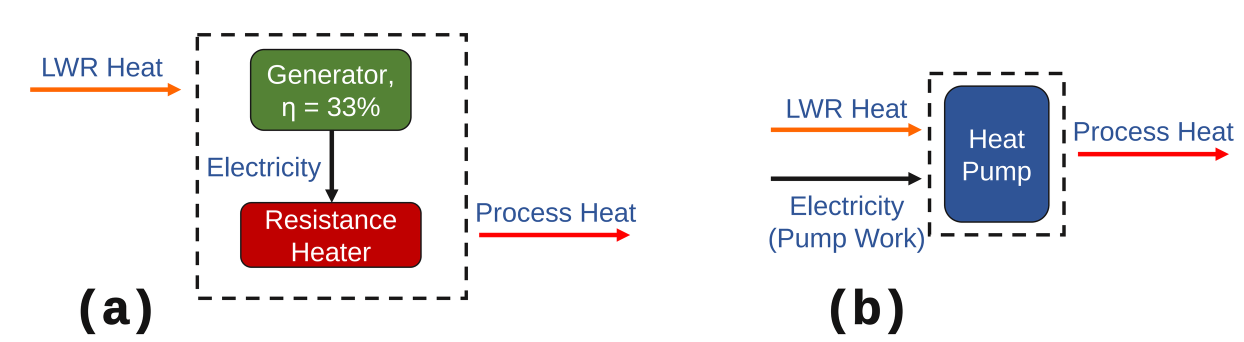


Fig 3: (a) Conventional and (b) thermal processes heating schematics

The exergetic efficiency increased from <50% with the conventional system to >85% with the chemical-absorption heat pump.

In another study, the process heat temperature and LiBr-H_2O concentration was calculated for various pressure drop values between the chemical bed and the absorber shown on the bottom right of Fig 2a. As the pressure drop increases, the process heat temperature lowers while the LiBr-H_2O concentrations increase.

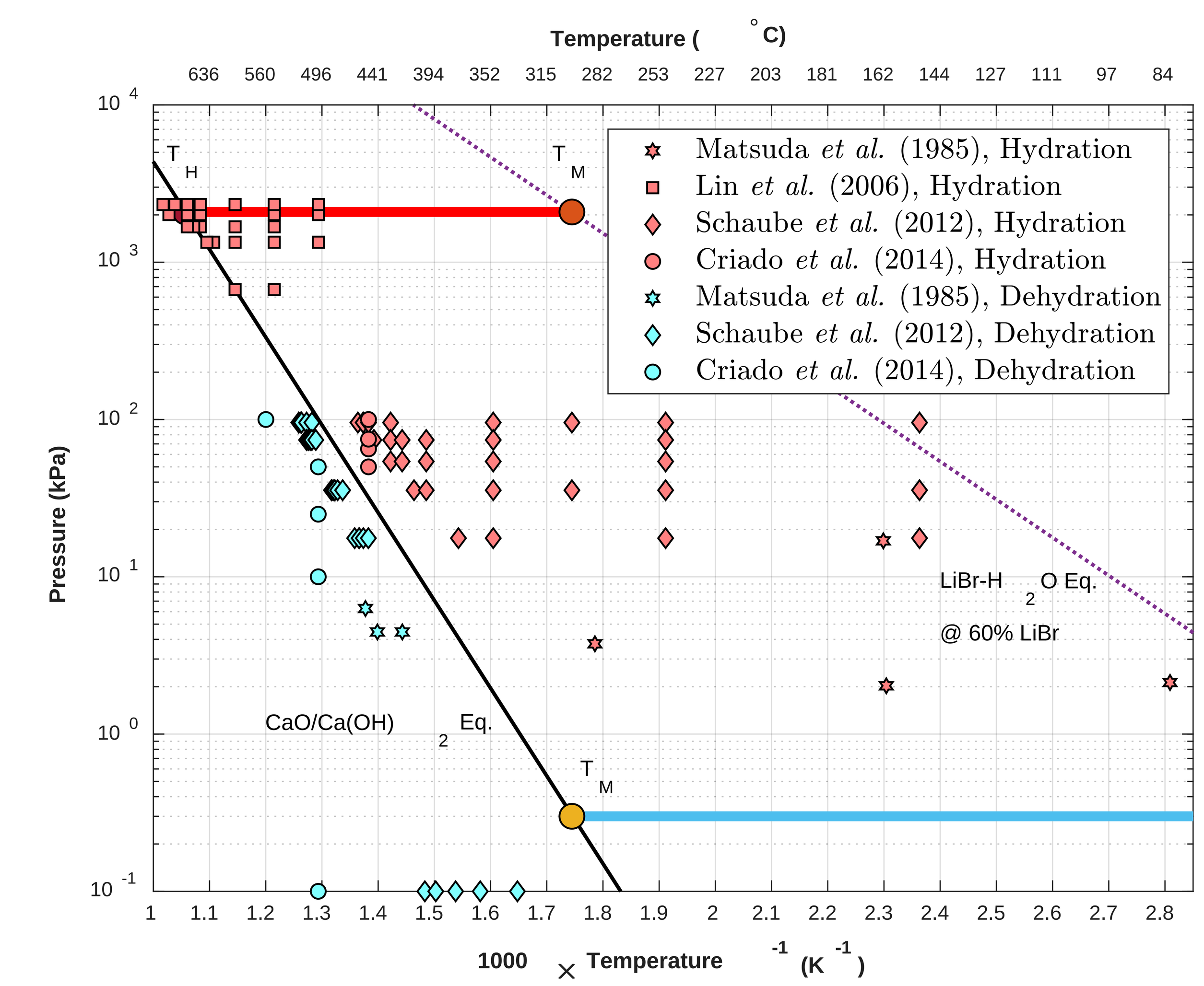


Fig 4: States CaO/Ca(OH)$_2$ reaction rate data was obtained in the literature

Conclusions and Future Work

- This chemical-absorption heat pump systems enables the upgrade of LWR heat though a primarily thermal pathway, significantly increasing the exergetic efficiency
- Operational variables such as pressure can significantly impact the performance of the system
- System dynamics will have to included in the model since the system is inherently unsteady
- Appropriate chemical reaction rate equations will have to be used in future modeling efforts (Fig 4) to accurately capture the effect of system dynamics on performance

Acknowledgement

This research is being performed with funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Program

Oregon State University · University of Idaho · Idaho National Laboratory · NEUP Nuclear Energy University Program · U.S. Department of Energy

WELCOME

Heat Storage for Gen IV Reactors for Variable Electricity from Base-Load Reactors

Exelon®