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Oil and Nitrate-Salt Coolant Trade-Offs with Crushed-Rock Heat Storage and CSP

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Abstract. The large-scale use of wind or solar results in collapse of electricity prices at times of large wind or solar production. Addition of heat storage to Concentrated Solar Power (CSP) plants enables (1) storing heat at times of high solar input, excess electricity production and low prices and (2) producing electricity when needed at times of high prices. We are developing a Crushed Rock Ultra-large Stored Heat (CRUSH) system with incremental capital cost goals of $2-4/kWh that enables hourly to multi-week storage with very large CSP systems. Heat is stored in crushed rock piles up to 40 meters high in an insulated building. Hot oil or nitrate salt is sprinkled on the rock, trickles through the rock, heats the rock and the resultant cold fluid is recovered by drain pans. Heat is recovered by sprinkling cold oil or salt on hot rock, trickling through the rock, and heating the fluid with oil or nitrate salt recovered by drain pans. There are different constraints for oil versus salt systems. Given the high-cost of heat-transfer oils, rock sizes and types are chosen to minimize residual oil in the crushed rock. Nitrate salts are less expensive; however, nitrate salts will interact with many rock types placing constraints on acceptable rock types. Rock impurities in the oil or nitrate salt can impose constraints on the CSP system and define fluid-system cleanup requirements.

Keywords: Crushed Rock, Nitrate Salt, Heat-Transfer Oil, Concentrated Solar Power

1. Introduction

Large-scale use of non-dispatchable solar without energy storage results in collapse of electricity prices and revenue when the sun is shining. This limits the economic use of solar to about 20% of total electricity demand. Larger-scale use requires energy storage to deliver electricity when the customer needs it. We are developing a Crushed Rock Ultra-large Stored Heat (CRUSH) system that couples to Concentrated Solar Power (CSP) systems, The CRUSH system capital cost goals are $2-4/kWh of heat with system sizes measured in 10s of gigawatt hours. The cost goal is less than one-fifth that of the commercial multi-gigawatt two-tank nitrate-salt storage systems currently deployed with nitrate-salt tower CSP systems. While CRUSH is less expensive than gigawatt-hour two-tank nitrate-salt systems, larger systems are required for very low costs because of how different systems scale with size. Our recent journal paper [1] provides a broad description of the system and multiple applications while this paper focuses on integration of CRUSH with CSP.

We first describe the generic CSP system and how low-cost storage improves CSP economics relative to solar photovoltaic (PV) systems. A description of CRUSH is provided. Last, we examine the technical challenges and solutions associated with oil-based or nitrate-based CRUSH systems directly coupled to CSP systems. The CRUSH system uses crushed rock for heat storage with heat-transfer oils or nitrate salts used for heat transfer in CRUSH and the CSP system. As a consequence, the CSP heat-transfer oil or nitrate salt contains rock impurities that can impact system behaviour. One could use heat exchangers to separate the fluid in the CSP system from the fluid in the CRUSH system but there are capital and efficiency penalties if this more conservative design strategy is used.

2. System Design

The largest heat storage systems today are the two-tank nitrate-salt systems [2-4] coupled to nitrate-salt tower CSP plants with heat storage capacities measured in gigawatt hours (GWh). CSP heat storage (1) provides constant power on partly cloudy days with highly variable solar input and (2) enables electricity production after dark. These systems operate with peak salt temperatures of 565°C. Lower-temperature oil-based CSP systems have peak temperatures of 400°C. Many oil-based systems use nitrate-salt heat storage with heat exchangers that transfer the heat from the CSP oil system to the nitrate-salt heat storage system. Nitrate salts are used for heat storage because of the high cost of heat transfer oils that makes it more economic to use heat exchangers and salt storage than directly store heat as hot and cold oil.

The generic system design shown in Figure 1 applies to all heat generating technologies. The same systems are proposed for coupling to existing light water nuclear reactors [5] and advanced nuclear reactors [6, 7] to enable variable electricity output while operating the nuclear plants in their most economic mode as base-load plants. These storage systems are also proposed as “batteries” for long-duration storage [8] where electricity is used to heat the nitrate salt at times of low electricity prices to provide power at times of high prices.

The CSP plant is not directly coupled to the power block. Instead, the CSP plant receives cold salt, heats the salt and sends the salt to a hot-salt storage tank. The power cycle takes hot salt and produces steam that produces electricity. If there is very low-price electricity, the power plant can buy electricity to heat more nitrate salt. If heat storage becomes depleted, a low-cost furnace burning natural gas or in the future hydrogen or biofuels can provide the additional necessary heat. This addresses seasonal variations in solar input. The system design assures high reliability. The power block with steam boilers and turbines may be sized to match peak electricity demand and may be several times the power output of the CSP plant.

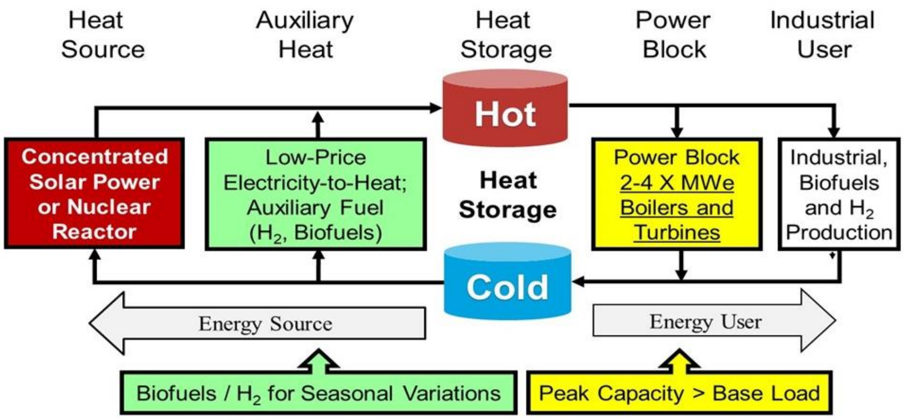

Figure 1. Heat Storage for Nuclear plants, CSP plants and Thermal Batteries for Variable Electricity Production and Industrial Heat.

Low-cost heat storage changes the relative economics of CSP versus PV with large-scale solar deployment. When solar PV is initially added to an electricity grid, it acts as a “fuel savings” technology [9-10] reducing the number of hours natural-gas-fired turbines operate. Added PV collapses the price of electricity at times of high solar input limiting the economic use of PV. Batteries can be added to provide electricity storage. The U.S. Energy Information Agency (EIA) shows decreases in battery capital costs [11] with time and a levelling off of capital costs for utility storage systems at about $500/kWh(e). This is the total system cost (battery, power conversion, land, buildings, engineering, etc.). EIA [12] has estimated the levelized cost of electricity for solar PV ($31.30/MWh), on-shore wind ($31.45/MWh) and battery storage ($121.86/MWh). Electricity from PV and batteries after dark is very expensive because battery storage costs are four times the cost of generating electricity. The system still requires gas turbines because batteries only provide storage for a few hours.

Today CSP with storage is more expensive than PV. However, as PV collapses electricity prices during the day, the economics change. To expand, PV requires storage but battery costs make larger use of PV uneconomic. The cheapest storage technology is the two-tank nitrate-salt storage system. Heat storage is efficient for CSP. For PV the electricity must be converted to heat and then back to electricity. Those two conversions reduce the round-trip efficiency of electricity to about 40%. Once PV collapses electricity prices when the sun is out, CSP can cost more than twice that of PV and becomes the economic form of added solar because it couples efficiently to heat storage.

For large systems using solar salts, the storage capital cost estimates [2-4] are $20-25/kWh of heat ($60-70/kWh(e)), far less than batteries or pumped hydro storage. The capital costs are associated with the tanks and salt—each contributing about an equal fraction of the capital costs. These storage costs are much less than batteries and enable daily but not weekly energy storage. Electricity demand decreases on weekends creating added low-price electricity. Very low-cost energy storage enables storing this energy for use during the weekday. CRUSH enables this type of long-duration storage.

3. Crushed-Rock Ultra-large Stored Heat (CRUSH) System

CRUSH is based on the experience with two-tank nitrate-salt storage tanks; but, replacing the use of nitrate salts for heat storage and the expensive tanks. CRUSH replaces these expensive components with (1) crushed rock for heat storage, (2) nitrate salt or oil to move heat to and from the crushed rock but not for heat storage and (3) an insulated building. A series of studies [1, 13-15] found solutions to the major technical challenges that has raised the Technology Readiness Level to 3. New features relative to other heat-storage systems include:

- Minimizing inventory of expensive oil or nitrate salt
- A liquid flow system that limits heat and exergy losses to conduction through insulation to the outside environment enabling long-term heat storage
- Building structure that replaces expensive tanks
- Start-up strategy for nitrate salt system where the salt melting point is significantly above initial rock temperature and
- Management of long-term build-up of impurities in the salt or oil.

CRUSH is shown in Fig. 2 where the sensible heat of crushed rock is used to store heat. The system can be built in large sizes, the crushed rock pile may be 20 to 40 meters high inside an insulated building like an aircraft hangar. A rock pile 20 m by 250 m by 250 m could store 100 GWh of heat. The use of an insulated building avoids the high costs associated with storage tanks. These features are shown in the upper left of Figure 2.

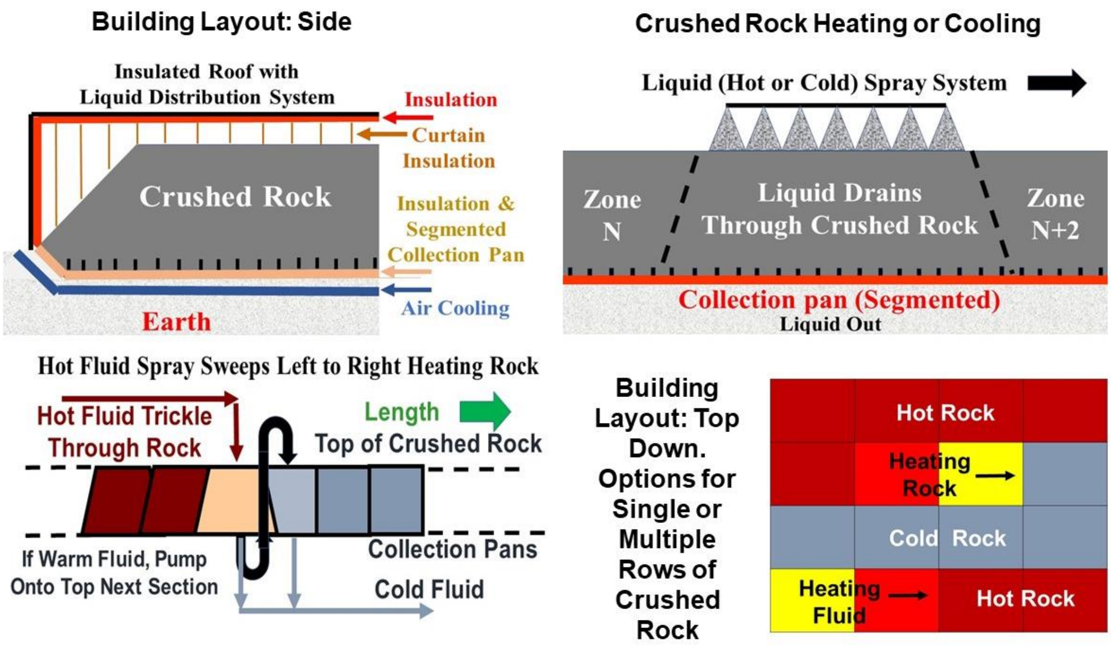

Figure 2. CRUSH Heat Storage System.

The heat transfer fluid can be heat-transfer oil (to 400°C) or nitrate salt (to ~600°C). Hot fluid from CSP or other high-temperature heat sources is sprayed onto the top of the rock, trickles downward by gravity to the drain pans below while transferring heat from liquid to crushed rock. If the fluid is not fully cooled when it reaches the drain pans, it is sprayed onto the next section of the rock and then returned to be reheated (Lower left). Rock is heated section-by-section (lower right). To recover heat from storage, cold fluid is sprayed on top of the hot crushed rock, trickles through the rock to be heated and sent to the power cycle. The fluid is used for heat transfer, not to store heat as is done in traditional heat storage systems

The crushed rock is contained inside a low-cost insulated building. The crushed rock pile has a flat top and sloped sides—there are no horizontal forces on the building sidewalls. This enables the use of a low-cost aircraft-hangar-type building with a low-cost steel structural at normal temperatures with the high-temperature insulation on the inside of the building. The heat losses are low because of the small surface-to-volume (stored heat capacity) ratio of this system relative to alternative heat-storage technologies

Figure 3 shows the sequential heating of two segments of adjacent crushed rock. There is no physical separation or insulation between adjacent sections of crushed rock. The scale and use of gravity-drain fluid for heat transfer minimizes heat transfer between adjacent hot and cold rock zones when there is no flowing fluid. With a cover gas in the voids between crushed rocks, heat transfer is slow. The width of each zone is the width of the drainage pans at the bottom. There may be 10 to 50+ zones with widths of 5 to 30 meters. The hot/cold interface between zones (interface zone) is physically small relative to the width of zones and expands in the downward direction with downward fluid trickle flow. This allows storage of hot and cold rock in the same building without insulated separators between hot and cold rock.

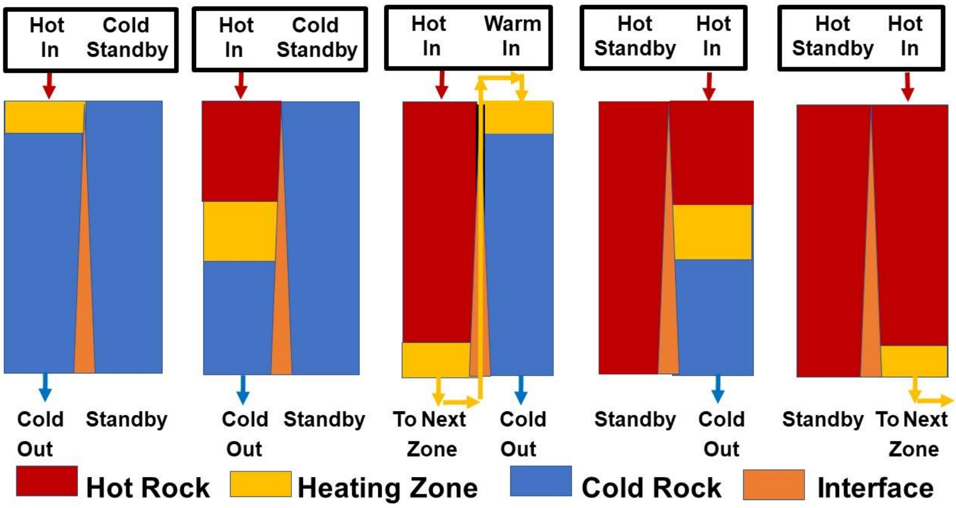

Figure. 3. Sequential Heating of Two Crushed Rock Zones (Not to Scale).

If hot fluid flow stops, heat conducts from hot rock to cold rock on the right or below to cool the hot rock. The yellow heating zone will expand in size. When hot fluid flow is restarted, it will reheat the partly cooled rock, flow to the bottom and the partly cooled fluid will be used to heat the next cold section of rock. If heating stops for weeks, the external surfaces of the rock pile will begin to cool as heat slowly flows through the insulation. Upon restarting of hot fluid flow, one can reheat (top off) each section of hot rock from left to right with partly cooled fluid exiting the bottom of each zone used to start heating the next zone of cold rock. The system is like an infinite-length column made up of many sections where this operational strategy eliminates exergy losses (inefficiencies) inside the system except for (1) heat losses through the external insulation and (2) the cost of pumping added fluid. This is unlike traditional two-tank or thermocline systems where there is no way to reheat the fluid to peak temperatures.

4. Coupling CSP to CRUSH

There are two ways to connect CRUSH and the CSP system. The first option is a heat exchanger between the CSP and CRUSH system with a clean nitrate salt or heat-transfer oil in the CSP system and a separate nitrate salt or heat-transfer oil associated with CRUSH. This avoids the complications of rock impurities from CRUSH in the CSP system but adds the capital cost and inefficiencies associated with the heat exchangers. The second option is to use the same fluid for both the CSP and CRUSH systems. This results in rock impurities in the salt or oil in the CSP system but reduces capital costs and exergy losses from heat exchangers. We discuss this second option herein.

The first requirement is to minimize CRUSH salt or oil inventory by selection of rock size and type. Because heat transfer oils cost more than nitrate salts, the requirements to minimize oil inventory are greater than for salt systems. This requirement sets the minimum rock size at several centimeters [16]. To minimize fluid inventory, the wetted surface area of the rock is minimized. As rock size decreases, the surface to volume (heat storage capacity) ratio of the rock goes up. Smaller rocks imply larger liquid holdup on rock surfaces. Second, surface tension holds liquids where individual rocks touch each other. Larger rocks have fewer contact points per unit volume of rock and thus lower residual liquid inventory. Last, rocks should be chosen with smooth surfaces (few cracks or pours) to minimize oil or nitrate salt remaining on the rock surface.

The maximum rock diameter will generally be less than 10 to 12 centimeters. Heat transfer is controlled by three factors: (1) flow of fluid downward by gravity through the crushed rock, (2) heat transfer from fluid to the rock surface and (2) heat transfer from the surface of the rock to the center of the rock. If we had meter diameter rocks, the rate of heat transfer between the rock surface and the center of the rock would be very slow and control rate of heat transfer. Crushed rock sizes up to 10 to 12 centimeters in size are acceptable before heat conduction from the surface to the center of the rock controls system heat-transfer rates.

The second requirement is for liquid coolant cleanup systems. The thermal expansion and contraction of the rock will generate fines. The fines will act as an abrasive to erode pumps and anywhere the liquid changes direction within the CSP system. There is a massive experience in filtering fines from crude oil at temperatures up to several hundred degrees in heavy oil and tar-sands processing facilities. Tests will determine if mechanical filters are used or centrifugal filters where centrifugal forces separate particles from the fluid. We are not aware of industrial experience in filtering high-temperature salts on a large scale.

The sand/fines filtering requirements are stricter for heat transfer oils than nitrate salts. If the fines were the same density as the oil or salt, they would flow with the oil or nitrate salt. However, if there is a density difference, when the fluid changes directions centrifugal forces will tend to separate the fines from the fluid and create abrasion. The densities of nitrate salts are similar to many types of rock. However, the density of the oils is below 1 gram/cm^3. The larger density difference between oil and rock fines will result in buildup of fines in the CSP system in areas of low flow and more erosion of equipment where high flow. However, the larger density difference between oil and solids improves centrifugal filter system performance.

There may also be a secondary coolant cleanup system to address longer-term coolant degradation. With the nitrate salt, there is the option to add fresh nitrate salt to the CRUSH system and sell degraded nitrate salt as fertilizer. There are commercial companies that purify heat transfer oils. During the first CRUSH startup, there will be significant water from the crushed rock that will be removed as steam from the off-gas system.

The third requirement is for mechanical and chemical compatibility—separate from the above requirements for relatively smooth surfaces to minimize fluid holdup on rock surfaces. The mechanical requirements are to withstand thermal cycling and avoid rock breakup into smaller pieces. A wide variety of rocks are compatible with hot oil; however, only a small subset is compatible with nitrate salts because of (1) higher temperatures, (2) oxidation by nitrate salts and (3) dissolution of some rock species into salt. Igneous rocks are the most mechanically stable rocks with moderate chemical performance and metamorphic rocks are the most chemically stable rocks with moderate mechanical performance. Other than the outlier of taconite, sedimentary rocks are typically neither chemically nor mechanically stable. Of the 26 different rock types that were evaluated [15], six rock recommendations are made based on good mechanical and chemical response: basalt, peridotite, taconite, quartzite, quartzitic sandstone and serpentinite. Testing is required in all cases to assure compatibility.

The forth requirement is to rethink CSP. With large-scale solar, storage costs drive system design—not the CSP system. The incremental capital cost of CRUSH heat storage in dollars per kilowatt-hour decreases rapidly as the storage capacity increases—primarily because of lower building costs. The cost of the power block decreases rapidly with increased electric generating capacity. The operating crew for a 100 MWe power block is about the same as a 500 MWe plant. Recent studies [14] have explored alternative CSP systems coupled to CRUSH with average power outputs up to 1000 MWe as shown in Fig. 4. Multiple CSP farms pump hot oil or salt to a central storage and power block. There is massive experience in pumping hot oil many kilometers associated with the recovery of heavy oils. The design challenge is to minimize oil inventory in the transfer systems because of the high cost of heat transfer oils. The challenge with nitrate salt is the lack of experience in pipeline transfer of hot salts over several kilometres. The heat losses with such pipelines are relatively low [17].

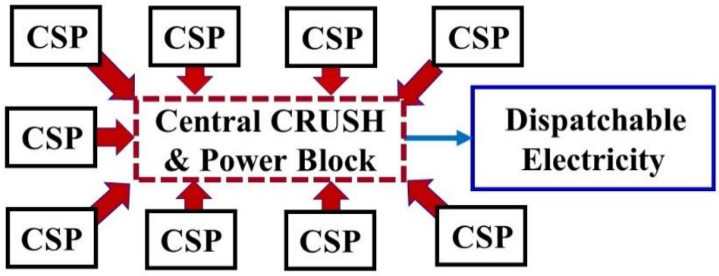

Figure. 4. Multiple CSP Farms Sending Heat to Central Storage via Pipeline.

The other question is whether low-cost storage changes the preferred tower CSP system design. There is ongoing work to develop CSP systems with direct volumetric adsorption of light in nitrate salt [18] where mirrors focus light onto liquid nitrate salt with direct adsorption of the light. In these systems, the salt builds up impurities from air over time; thus, the expectation that such systems can more easily couple to CRUSH that also has impurities in the salt from the crushed rock.

5. Conclusions

With large-scale solar deployment, energy storage drives system design because of electricity price collapse and thus revenue collapse at times of high solar input. CRUSH is the lowest cost storage option because it uses the lowest-cost materials—but at an early stage of development (TRL=3). The largest challenge with oil systems is minimizing the inventory of expensive heat-transfer oil. The largest challenge with nitrate systems is assuring chemical compatibility with rock and CSP systems.

Data availability statement

Data available on request and in papers listed below

Author Contributions

CF originated the CRUSH storage system and wrote the paper.

Competing interests

The author declares no competing interests.

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