100-GWH CRUSHED ROCK ULTRA-LARGE STORED HEAT (CRUSH) SYSTEM: DESIGN DESCRIPTION, ASSOCIATED TECHNOLOGIES AND CURRENT STATUS

Charles Forsberg
Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA, 02139, cforsber@mit.edu

INTRODUCTION

We are developing a 100-GWh Crushed Rock Ultra-Large Stored Heat (CRUSH) system to enable nuclear, concentrated solar power (CSP) and other heat-generating systems to operate at full capacity with variable electricity to the grid [1-4]. There is also the option of buying electricity at times of very low prices, converting the electricity to stored heat and using the heat to produce peak electricity—a thermal battery. The commercial goal is a CRUSH capital cost of $2-4/kWh—a factor of 5 to 10 less than existing heat storage technologies and 50 times less than battery storage. Achieving this cost goal [5, 6] would fundamentally change the role of storage in power systems. The capability of a 100-GWh heat storage system is about equal to the Tennessee Valley Authority Raccoon Mountain hydroelectric facility that provides 1600 MW(e) of electricity for 22 hours. The scale and low cost of CRUSH enables hourly to weekly storage of heat for dispatchable electricity from nuclear and Concentrated Solar power (CSP) plants operating at full capacity.

This is a third generation heat storage system. Existing CSP plants store heat as hot oil or hot salt with separate tanks for hot and cold storage. Second generation systems in the laboratory [7-8] are developing thermocline single-tank systems with hot fluid on top of cold fluid in a tank filled with crushed rock. Crushed rock is used to minimize the inventory and cost of the coolant. The single tank reduces tank costs.

POWER SYTEM

A schematic of the power system [2] with CRUSH is shown in Fig. 1 on the left. The heat source can be (1) a nuclear plant, (2) a CSP plant or (3) low-price electricity that is converted to heat. The nuclear or CSP plant operates at full capacity. The power block is sized to meet peak demand with variable electricity output. Heat can be delivered to the power block or industrial customers. The time-averaged heat input is measured in gigawatts. If heat storage is depleted, there is the option to use a furnace to provide hot fluid to CRUSH to provide assured electric generating capacity.

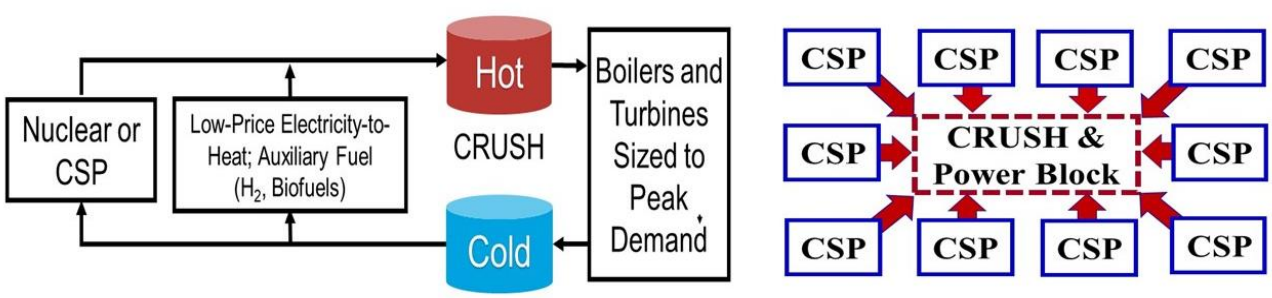

Figure 1. Power System with CRUSH (left) and CSP Design with CRUSH

Heat is transferred from nuclear or CSP systems using heat transfer oils or nitrate salts—the same fluids used in existing CSP systems. Heat transfer oils are used at temperatures up to 400°C while nitrate salts are used in systems up to ~600°C. Hot oil would be used with light-water reactors and lower temperature CSP systems. Nitrate salts would be used with higher-temperature advanced reactors and solar power towers. If the primary heat input is low-price electricity, nitrate salt is used because the higher heat storage temperatures imply more efficient conversion of heat to electricity. The CRUSH design characteristics that enable very low costs do not scale down to small heat storage capacities of a few GWhs. For CSP systems [1], this implies that 10 or more CSP farms would transport hot oil or hot nitrate salt to a central heat storage and power block facility (Fig. 1, right) via insulted pipeline. To match this scale of heat storage, the set of solar farms would cover more than 100 square miles.

CRUSH SYSTEM DESIGN

The CRUSH system is shown in Fig. 2. Sensible heat is stored in crushed rock 20 meters deep with horizontal dimensions of 250 meters by 250 meters. Crushed rock is the lowest cost heat storage material. Heat is added to the crushed rock by spraying the hot heat-transfer fluid from the nuclear plant, CSP plant or heat-from-low-price-electricity over the crushed rock section by section (Fig. 2, top). Each section is nominally 25 m by 25 m with the area depending upon the maximum design rate of heat input. Fluid flows by gravity through the crushed rock to the drain pan below that section of rock. The cold heat transfer fluid is collected in the bottom collection pans to be reheated. If the nitrate salt or heat transfer oil is not fully cooled by the time it reaches the collection pan, the warm fluid is pumped onto the top of the next section of crushed rock to preheat the crushed rock (top right). A wave of hot oil or nitrate salt heats the crushed rock from left to right as shown in Fig. 2, lower left. This system has many similarities to heap-pile leaching of low-grade copper ores [10, 11] that is responsible for about 20% of global copper production. In heap-pile leaching a leach solution is sprayed over low-grade copper ore, drains through the pile by gravity and is collected by drain pans below the pile.

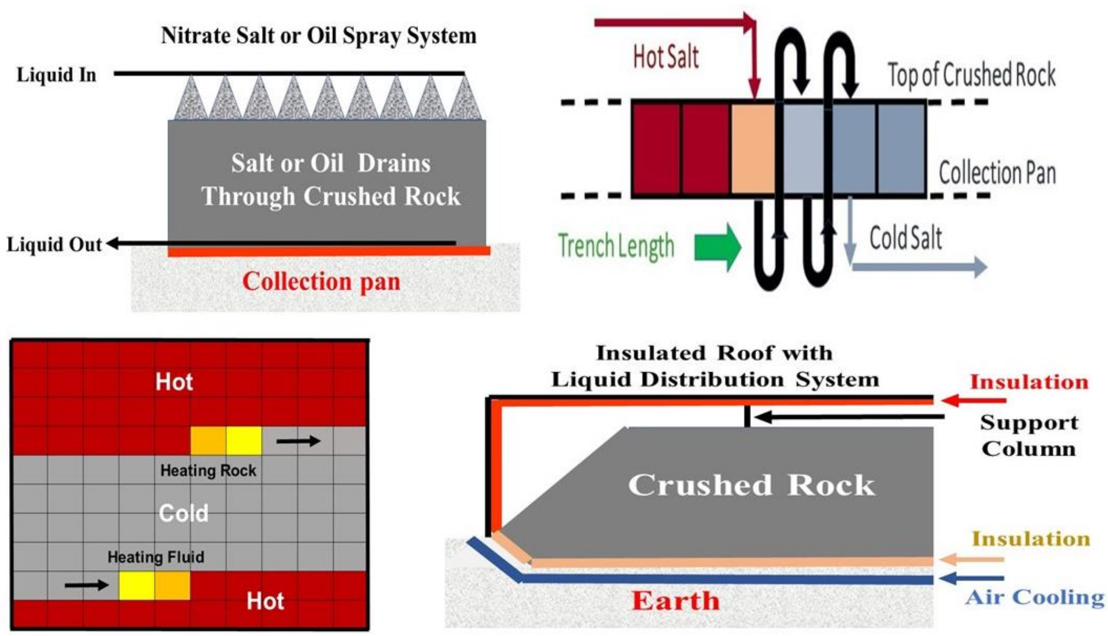

Fig. 2. CRUSH SYSTEM

Heat is recovered by spraying cold heat-transfer fluid over hot crushed rock and collecting the hot oil or nitrate salt at the bottom. There is a rock heating wave followed by a second wave to recover heat (Fig. 2, lower left). There are segmented collection pans under the crushed rock. When either wave reaches the end of the insulated structure, it starts over at the other end of the system. The design minimizes the inventory and cost of the heat transfer fluid that is expensive relative to the crushed rock. For a 100-GWh system, the crushed-rock bed is in the form of square that is about 250 meters on a side. If we heat a 25 by 25 meter zone at a time, the storage system would be divided into 100 zones each with its own drain pan.

Figure 3 shows in more detail the sequential heating of two segments of adjacent crushed rock. Figure 4 shows in more detail heat recovery from the hot crushed rock. In the real system the crushed rock zone is 20 meters high and the width of each segment may be 25 meters; that is, the figures are not to scale. The scale and use of gravity-drain oil or nitrate salt for heat transfer minimizes heat transfer between adjacent hot and cold rock zones. Crushed rock thermal conductivity is low because pieces of the crushed rock only touch at a few locations and the inert gas is a good insulator. This allows storage of hot and cold rock in the same container without insulated separators between the hot and cold rock. This is in contrast to heat storage systems with tanks of oil or liquid salts filled with crushed rock to reduce the inventory of expensive oil or salt. In those systems natural circulation of liquid oil or nitrate salt results in a rock pile with efficient heat transfer from hot to cold zones.

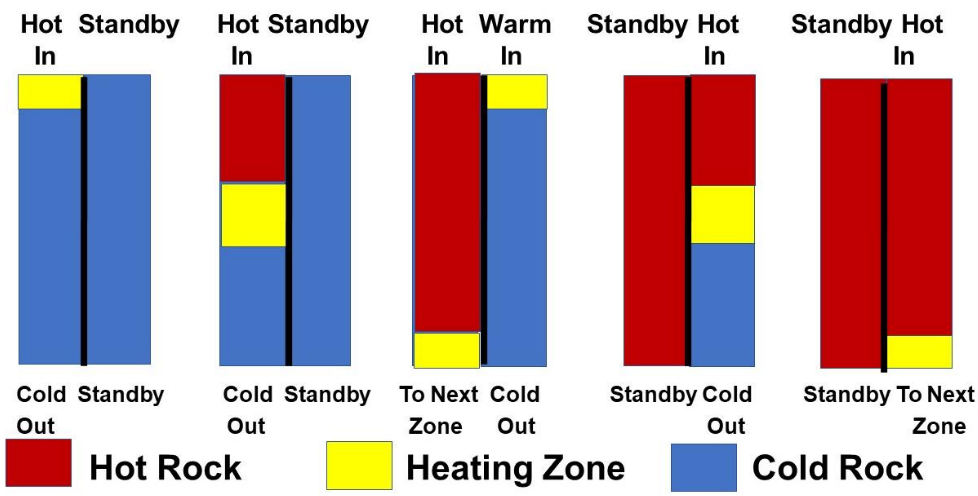

Fig. 3. Sequential Heating of Two Crushed Rock Zones (Nominal height 20 m and width 25m)

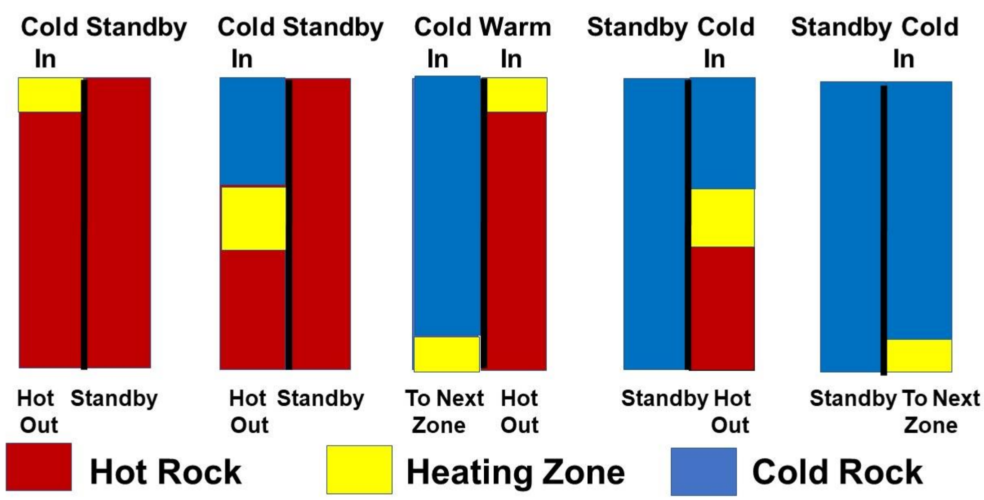

Fig. 4. Sequential Heat Recovery from Two Crushed Rock Zones (Nominal height 20 m and width 25m)

The tank cost [9] in a traditional nitrate-salt CSP system with a GWh of heat storage is almost half the total cost of the heat storage system. The capital cost of these heat storage systems is $20-30/kWh of heat storage. CRUSH container costs are minimized by three strategies. First, the large system minimizes the surface area (insulation and structure) per unit volume of heat capacity (crushed rock). The height is determined by experience with heap-pile leaching of copper ores. Increasing dimensions in the horizontal directions reduces container wall costs per unit of heat stored. Second, the crushed rock edges are sloped rock (Fig. 2, lower right). This enables free expansion and contraction of the rock with temperature and avoids the high cost of container walls to hold in the crushed rock with added forces generated by temperature cycling of the rock. The gravity drain of fluid implies there is no fluid hydrostatic pressure on the side walls—the only requirements are that the walls be gas tight and well insulated. However, the slope of the sides of the rock pile implies a large system so that only a small fraction of the pile is slope. The building side walls and ceiling in design are similar to a very-large aircraft hangar with highly-insulated interior walls and ceilings and an air-tight membrane.

A separate challenge is the insulated foundation structure that includes drain pans. The traditional foundation structure for two-tank heat storage is shown in Fig. 4 on the left. In a two tank system there is a hot and cold tank—neither of which sees large changes in temperature after initial startup. The fluid is in a steel tank both to contain the fluid and provide a clean container for the fluid. The bottom of the foundation is cooled by natural circulation of air to prevent structural damage of the foundation. Addressing thermal expansion and contraction has been a major design challenge.

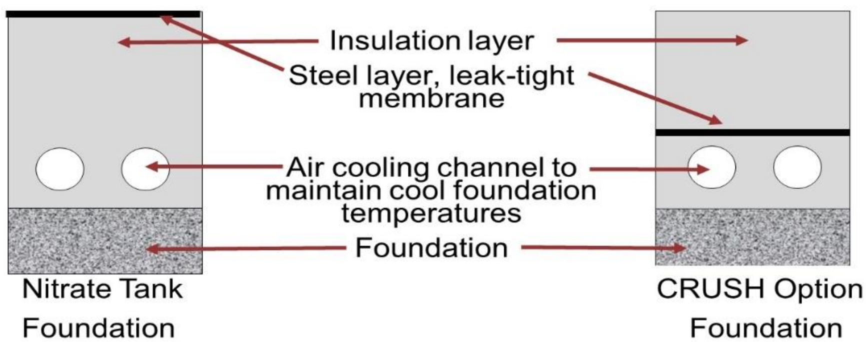

Fig. 5. Foundation Options

In the CRUSH system, the foundation sees multiple cycles of hot and cold oil or salt. One option to address this is shown in Fig. 5 on the right. The foundation and steel membrane are kept near room temperature by air-cooling channels. The insulation is between the steel membrane and the crushed rock that is heated and cooled with oil or nitrate salt. The insulation may be firebrick or potentially some mixture of sand and other components. The liquid flows across the top of the insulation to the drains. There may be a few centimeters of residual oil or nitrate salt depending upon drain elevation. There will be some infiltration of oil or salt into the insulation. If it is salt, the freeze point of the salt will be inside the insulation. The thermal expansion and contraction stresses are in the insulation—not the steel container. This assures foundation integrity.

There are two important auxiliary systems. Thermal expansion and contraction of the rock will generate fines; thus, the liquid systems require on-line filters to remove these fines. Second, CRUSH requires an off-gas system. The heat-transfer oil system will have a nitrogen atmosphere to minimize oil degradation. The nitrate system will have an air or oxygen enriched system to minimize salt degradation. The container is at atmospheric pressure; thus, an off-gas system is required to avoid local air pollution as atmospheric air pressure changes and the container breaths in and out. There are multiple industrial systems to avoid air pollution when atmospheric tanks breathe in and out with changes in atmospheric pressure.

There are alternative design options. Alternative lower-cost coolants include higher-temperature chloride salts and sulfur; but, there is little experience with these coolants. There is the option of a kilometer-long narrow CRUSH design where the building is one heating zone wide. This allows draining of the heat transfer fluid to the outside walls with simplified foundation and ceiling structure—including the option of a Quonset-type building and no internal building supports that go through the crushed rock.

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