Empire District Electric Company and BSC Holding, Inc.

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Compressed Air Energy Storage (CAES) Project Study and Bulkhead Test

Final Report

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INTRODUCTION

HISTORY AND STATUS OF COMPRESSED AIR ENERGY STORAGE

Municipal compressed air energy systems were installed in several cities (Dresden, Paris, and Buenos Aires) in the early 19th century. These systems were used to deliver power to industry and to homes. By 1896, the Paris system had 3,000 hp (2.24 MW) of generation distributed at 80 psi in 30 miles of air pipes for use in lighting as well as heavy industry. This compressed air energy was the main source of energy delivered to homes at that time.

There are currently two operating CAES plants in the world. A 290-MW hybrid (compressed air and gas-fired combustion turbine) plant was commissioned in Huntorf, Germany in 1978, and a 110-MW hybrid plant commenced operation near McIntosh, Alabama in 1991. See Appendix N - Photo of Huntorf, Germany CAES Plant and Appendix O - Photo of McIntosh, Alabama CAES Plant. Both systems use off-peak energy for the air compression, and both use salt caverns for compressed air storage and combustion turbines for power generation. The McIntosh, Alabama plant made improvements to the Huntorf, Germany design by incorporating a recuperator (air-to-air heat exchanger) to preheat air from the cavern with waste heat from the turbines. Since overcoming some start-up issues, the plant has functioned with over 95 percent reliability.

Despite its success from a technological standpoint, CAES was not deployed in other installations during the 1980s and 1990s for a number of reasons:

1. Utilities developed a strong portfolio of base-load (coal and nuclear) plants in the decades of the 60s, 70s, and 80s. The resulting relatively cheap power and excess generating margin precluded the need for energy storage and recovery.

2. The 1990s saw a boom in combustion turbine-based power plant construction. This put pressure on turbine suppliers, expanding equipment lead times and raising costs dramatically. Major turbine manufacturers had sold out production capacity and had not been willing to invest in the development of CAES turbines.

Current, known US CAES plant projects are:

1. Iowa Stored Energy Park (ISEP) (West of Des Moines):
    a. Storage: Geologic aquifer.
    b. Hybrid power (wind/gas-compressed air).
    c. Capacity of 75 to 100 MW.
    d. Status: Under study and consideration. Not believed to be under construction.
2. Norton, Ohio:
    a. Capacity of 2,700 MW.
    b. Storage: Limestone mine.
    c. Status: Started in 2001, but there is no indication that construction has commenced.
3. Public Service Enterprise Group (PSEG) (New Jersey):
    a. Storage: Limestone cavern.
    b. Status: Announced in August, 2008 that PSEG would be investing $20 million over the next three years into developing underground compressed-air storage systems for wind turbines.

A similar energy storage technology using a different medium is pumped storage hydroelectric, or pumped hydro. These systems incorporate two water storage reservoirs at different elevations, with pumps and hydro turbine/generators between them. Water is pumped from the lower reservoir to the upper reservoir during low power demand (i.e., lower cost) periods and drawn down through penstocks to the turbine/generators during higher power demand periods; much like hydro plants below dammed reservoirs. There are an estimated 300 pumped hydro plants world-wide, with 90 GW of capacity. Typical electrical recovery efficiency is approximately 70 percent; however, water loss due to evaporation can have an effect on efficiency. A famous (perhaps infamous) local example is the Ameren Taum Sauk pumped hydro plant in southeastern Missouri. Built in 1963, this 225-MW facility is the largest pure pumped hydro plant in North America. It suffered a breach of its upper reservoir in December 2005 and is currently being re-built.

REASONS FOR THIS STUDY AND TEST

Empire District Electric Company (Electric Utility), BSC Holding, Inc. (Lyons Salt Mine Owner and Operator), and Sega Inc. (Design Engineer), have entered into an agreement to investigate the feasibility and benefits of building a CAES plant at the Lyons Salt Mine near Lyons, Kansas. A Viability/Feasibility study was conducted by Sega for the purpose of establishing the plant design basis and probable operating parameters, as well as calculating the expected plant performance and estimated installed cost. This is a "budgetary" study, intended to be utilized by the three parties to decide whether or not to proceed with a more detailed CAES plant design and evaluation phase, and eventual CAES plant installation.

Empire receives electric generation from two separate wind farms in Kansas via Power Purchase Agreements (PPAs). The Elk River wind farm, a 150-MW plant in southeast Kansas, and the Meridian Way wind farm in north central Kansas of which Empire receives a 105-MW share, compose Empire's 255 MW of wind PPAs. Empire owns non-wind electricity generating assets totaling 1,255 MW. Since wind energy is not dispatchable, i.e., not available to dispatch to Empire's electricity consumers on demand, and since wind energy can enter and leave Empire's balancing area at unpredictable times and at high rates, Empire is seeking a means to better utilize their wind energy commitment without causing upsets and inefficiencies in their electric system. A CAES plant has the potential to meet these needs.

BSC owns the Lyons Salt Mine near Lyons, Kansas. This salt mine was originally opened in 1917, and has been a productive salt mine for the past 90 years. As a result, an extensive network of mined space is available for alternative uses, such as a compressed air reservoir. BSC is interested in putting this mined space to secondary use as they pursue salt mining operations in other areas.

STANDARD COMPONENTS, UNIQUE PROCESS

The proposed plant will be based on a CAES plant design which does not rely on a natural gas-fueled combustion turbine. This will be unique, since the only other two CAES plants are "hybrids", requiring fuel firing to generate electricity. The Lyons CAES plant will store the heat generated in the compression process in thermal storage tanks, and recover this heat as part of the air expansion process. Despite this key difference, the components and fundamental technologies to be incorporated are proven.

Underground natural gas storage is common around the world and actively used in the state of Kansas, including gas storage fields very near the Lyons mine. According to the Energy Information Administration (EIA) there is approximately 4-trillion ft^3 of working gas storage in the US. Natural gas storage is typically at very high pressure, some in excess of 4,000 psi. Most underground gas storage occurs in naturally porous rock layers, not mined cavities. However, the design/technology used to inject and withdraw the compressed gas can be used for this CAES project. The air compressors and expander/generators which were studied are those supplied by Atlas Copco and are "catalogue" equipment.

The CAES plant would require isolating a portion of the mined area using massive concrete bulkheads. To seal the concrete cold joints, as well as the concrete-to-salt interface, perforated tubes would be installed at these junctures. A proprietary rubberized grout would then be injected into the tubes under pressure. The CAES plant is expected to be designed to operate at a maximum air storage pressure of 850 psig, the design pressure. This design pressure was selected to match standard equipment capability. The isolated compressed air storage area would then be initially pressurized from atmospheric pressure to the design pressure. When demanded, stored compressed air energy would be withdrawn and expanded through expansion turbines, driving electric generators to convert the stored energy back into electricity. For efficiency purposes, a compressed air storage pressure of 650 psig has been established as the lower limit. Therefore, the compressed air reservoir would operate between a design pressure of 850 psig and 650 psig.

A full-scale, reinforced concrete test bulkhead was installed in the mine, isolating a salt cavity with the dimensions of 25-ft wide, 17-1/2-ft high, and 4-ft deep, or 1,750-ft^3 of volume. This critical sealing device/system was based upon similar designs used in mine applications and was tested successfully as part of this study.

MINE BULKHEAD TEST

The as-installed bulkhead is constructed of concrete, strengthened with No. 8 reinforcing bars placed vertically and horizontally. The bulkhead concrete was placed in six separate lifts, using a concrete pump and vibrated to reduce voids. The completed bulkhead is approximately 25-ft wide, 17.5-ft high, and 16-ft in depth, not including the beveled perimeter which extends approximately 34-inches (at the deepest point), into the salt formation to transfer the pressure load laterally into the salt walls.

To seal the bulkhead periphery at the salt wall interface, and to seal the concrete placement (cold) joints, a rubberized grout system was used. Sovereign Hydro from Perth, Australia provided this system design. Three perforated steel tubes with a diameter of 2 inches were placed in rows, 12 inches on center, at approximately the mid-point of the bulkhead depth or thickness at the cold joints and around the perimeter. The perforated tubes were protected from concrete infiltration by wrapping them with cardboard. The grout was injected under pressure into these tubes after the concrete had reached adequate strength (determined by breaking concrete cylinders which were filled at the time of placement). Approximately 300 gallons of rubberized material was injected into the bulkhead sealing tubes. This volume matches the quantity of sealing material calculated prior to the installation. The pressurized grout penetrates the protective cardboard and fills gaps and voids in its vicinity. The "raw" rubberized material can then be "cured" by injecting an activator. However, since brine also serves to activate or harden the rubber, a limited amount of activator was injected. Any brine leakage during the hydrostatic test would contact the rubber, activating it and sealing the leak. This was experienced during the initial pressurization with brine.

A manway (24-inch diameter carbon steel pipe), was installed horizontally through the concrete bulkhead at a height above the mine floor of approximately 5 ft. A 600-pound class flange was welded to the bulkhead face end of this pipe. A 3-inch thick carbon steel blank plate was gasketed and bolted to this flange. The plate has two 1-1/2-inch pipe connections penetrating it. Each pipe is equipped with either a 450-pound class ball valve or gate valve.

One pipe is routed through the manway and then vertically up through the pressure cavity to the high point of the cavity to vent trapped air during the brine filling operation. The other pipe terminates on the opposite side of the blanking plate. These pipes were used to fill the cavity with saturated brine solution and air, vent the cavity, and test pressure in the cavity. For clarity, the pipe which vents the top of the pressure cavity will be referred to as the "vent pipe", and the other pipe will be referred to as the "fill pipe".

The pressure cavity (behind the concrete bulkhead) is an irregular rectangular shape, excavated into a salt wall, with dimensions of approximately 25-ft wide, 17.5-ft high, and 4-ft deep. This results in a volume of approximately 1,750 ft^3, or approximately 13,500 gallons.

See Appendix I - Bulkhead Test Data and Photos for the bulkhead test protocol, a schematic of the test arrangement and instrument, and photographs of the test equipment.

A hydrostatic test of the test area, bulkhead design and construction, and rubberized grout was completed on Saturday, February 7, 2009. The test chamber had been previously filled with brine solution, however, due to the shape and nature of the test chamber, approximately 20 ft^3 of air remained in the test chamber, thus providing an additional air test of the entire system. It was known that approximately 20 ft^3 of air at atmospheric pressure remained in the cavern because an approximate 60 additional gallons of brine was pumped into the test chamber while approximately no gain in pressure was noted.

All test equipment and personnel were in a remote location out of direct exposure to the bulkhead and test chamber. A Rice EL-2 boiler hydro pump was used to pump additional brine solution into the cavern. This pump is powered by a small air compressor. Standard air hoses were used to transfer the compressed air to the pump. A 3,000-psi hydraulic hose was used to transfer the brine solution from the pump to the test chamber. Two 1,500-psi water-filled gauges were used to read the pressure on both the boiler hydro pumps as well as the inlet on the test chamber, see Appendix I - Bulkhead Test Data and Photos for Test Layout Sketch and overall test equipment layout.

1. Arrived at bulkhead face at 7:30 a.m. and observed 50 psi of residual pressure from the previous test.
2. Reconfigured testing header for remote sensor. Set up Rice EL-2 test pump.
3. From 10 a.m. to 10:40 a.m. injected 40 gallons of brine into the bulkhead cavity raising the pressure to 100 psi.
4. From 10:45 a.m. to 11:20 a.m. injected an additional 20 gallons of brine raising the pressure to 100 psi.
5. Reconfigured injection system to use water and the boiler hydro pump from Empire's State Line plant. Set up pump, remote monitor, and water supply system out of direct exposure to the bulkhead.
6. From 12:30 p.m. to 2 p.m. slowly injected about 10 gallons of water. This raised the pressure to 390 psi. Visually inspected bulkhead face for leaks. None observed.
7. Coordinated with the mine staff and cleared all personnel from the area. Slowly raised the pressure to 800 psi by injecting about 5 gallons of water between 2:30 p.m. and 2:50 p.m. Observed bulkhead face with a mirror. No audible noises were heard.
8. At 3 p.m. raised pressure to 1,220 psi. Held pressure until 3:20 p.m. Released water through pump bleed off to reduce pressure to 850 psi.
9. At 4 p.m. observed pressure still at 850 psi. Left mine.
10. Returned to mine on February 8, 2009 at 7:45 a.m. and observed that the pressure was still 850 psi. No bleed off.
11. Reduced pressure to 400 psi through pump bleed-off valve. Inspected bulkhead face for leaks or deformations. None were observed.
12. Reduced pressure to 14 psi by opening valve in the test header assembly and spraying about 120 gallons into "F" drift.
13. Demobilized equipment and left mine at 11 a.m.

The bulkhead and the salt walls exterior of the bulkhead were monitored during the pressurization test for movements. The survey results indicate that the bulkhead maximum movement outward under the pressurization was slightly over 3/4 inch. This outward movement is as expected since the bulkhead is designed to wedge itself against the salt walls and movement is required for the force transfer between the bulkhead and the salt to occur. The salt walls exterior of the bulkhead was also monitored for movement during the pressurization of the bulkhead. The maximum movement in the salt wall was slightly over 3/4 inch horizontally inward and slightly over 1/2 inch vertically upward. The expected movement of the salt walls was unknown, but it was expected that the walls would move slightly inward during the pressurization. The results observed do not appear to be excessive because they are equal to or less than the movement observed in the bulkhead.