Technical Feasibility of Compressed-Air Energy Storage in an Aquifer Storage Vessel
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Abstract
Air has never been stored in a natural aquifer structure for use as a commercial energy storage system. CAES in aquifer storage media is problematic in constraint of air storage pressure around the hydrostatic pressure of the aquifer, limitations on well productivity, the potential for oxygen depletion, and the potential of water production with the air. Mitigation of these issues is dependent on the selection of an anticline structure at the proper depth within a highly permeable porous media. The presence of a caprock above the air storage zone is also a key factor.

The U.S. Department of Energy and EPRI has conducted an air injection field experiment at the Pittsfield structure in Illinois in 1982. A test volume of air was injected into an aquifer to create a bubble. The air was then cycled in and out of the aquifer. The results of this research were published by EPRI. Limited research was conducted on chemical reactions between air and aquifer fluids during this program. The Iowa Stored Energy Project (ISEP) engaged The Hydrodynamics Group, LLC through a U.S. Department of Energy grant, supported by Sandia National Laboratories, to research the technical feasibility of CAES in the Dallas Center Iowa aquifer structure. The results of this research indicate that 1) a suitable geological structure in the Mt. Simon formation exist at Dallas Center, 2) air bubble develop in stages will be necessary to displace the water out of the work gas air bubble, and 3) that the Dallas Center air storage vessel could support one to two 135 MWe CAES power plant. A geological field exploratory drilling a testing program is essential to verify the results of our research.

Geologic Framework of Iowa

The Mid-continent Rift System (the rift) trends through central Iowa (Figure 1). The rift forms a structural low that extends from the southwestern portion of Lake Superior to central Oklahoma. The rift was formed by a period of stretching of the continental crust by an underlying spreading center approximately 1.1 billion years ago. The rift formed a large trough that contains over 30,000 feet of sedimentary fill in places. In Iowa, the rift is covered by approximately 1,200 to 5,500 feet of younger rocks and glacial soils (Anderson, Witske, and Bunker, 1997). A large up thrown block in the center of the rift forms the Iowa Horst where compressional forces about 1 billion years ago pushed a large block of rock upward over 30,000 feet.

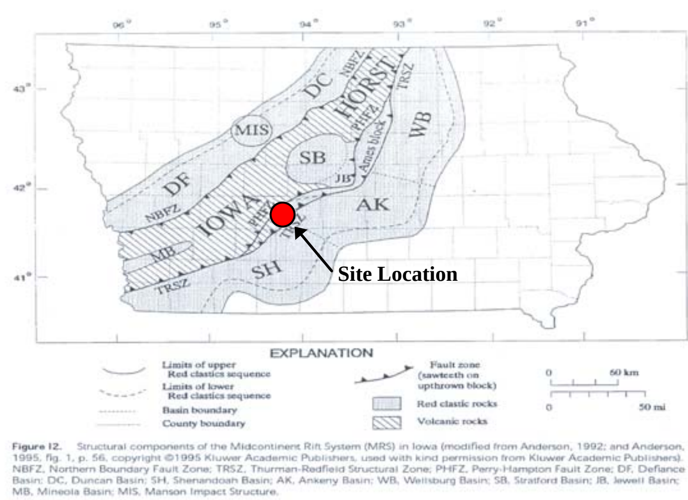

Figure 1. Structural Setting of the Iowa Horst and the Thurman-Redfield Structural Zone.

The Dallas Center Structure lies above the Thurman-Redfield Structural Zone (TRSZ) (Figure 1) along the southeastern edge of the Iowa Horst. Structural movement of up to 400 feet has been detected in the Silurian age and older strata of the TRSZ (Anderson, Witske, and Bunker, 1997). Younger strata show less displacement.

Figure 2 presents the stratigraphic column of Iowa. Several sandstone units are known to be very permeable and serve as excellent gas storage reservoirs. Most notable in the Dallas Center area are the Cambrian Mount Simon Sandstone and the Ordovician St. Peter Sandstone. The geologic deformation caused by the tectonic activity along the TRSZ and Iowa Horst has folded the strata and created several dome structures that are suitable for storing gas.

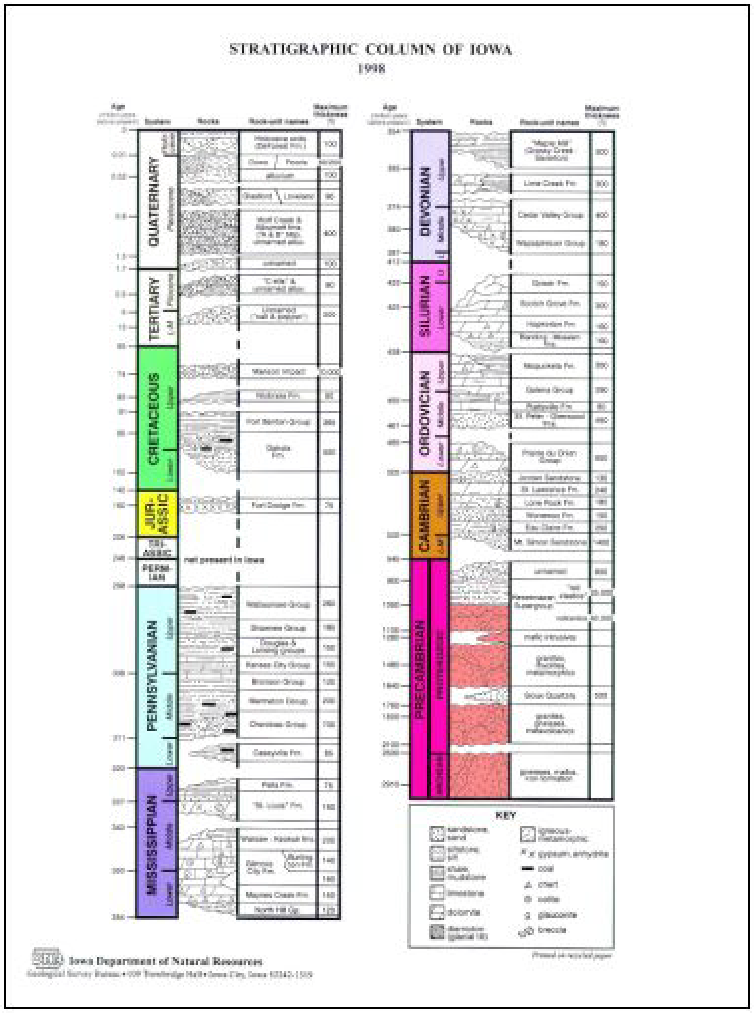

Figure 2. Stratigraphic Column of Iowa (from Iowa Department of Natural Resources)

Dallas Center Structure

The Iowa DNR with *Hydrodynamics* created a three-dimensional top of St. Peter subsurface map for both the Redfield and Dallas Center structures to show their spatial relationship (Figure 3). The tops of the Redfield St. Peter and Mt. Simon structures are approximately 500 feet in elevation above the same structures at Dallas Center. The Redfield structure is faulted and the faulting appears to be associated with the deeper Precambrian faults. Displacement on the Redfield faults ranges from approximately 20 feet on the crest of the structure to over 100 feet on the east flank. The deeper Precambrian faults flank both the east and west perimeters of the Dallas Center structures, but appear to not bisect the structures. This fact was confirmed with Bay Geophysical 2006 Dallas Center geophysical survey (Hydrodynamics, 2006).

A subsurface elevation map drawn on the top of the Mt. Simon formation at Dallas Center was drafted from an interpretation of Bay Geophysical reflection survey and from driller logs and some geophysical logs of well within the bounds of the structure (Figure 4). The map was created using the SURFER contouring program.

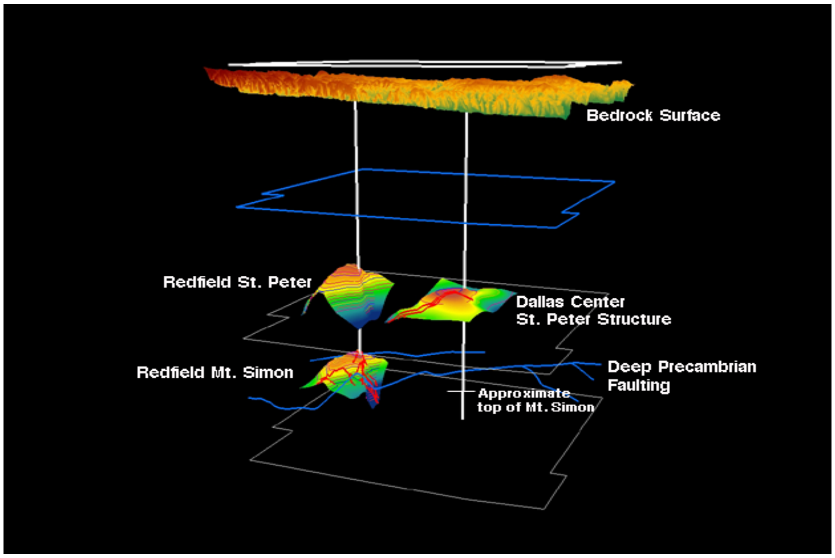

Figure 3. Three-dimensional Projection of Redfield St. Peter and Mt. Simon and Dallas Center St. Peter Structures (DNR, 2006).

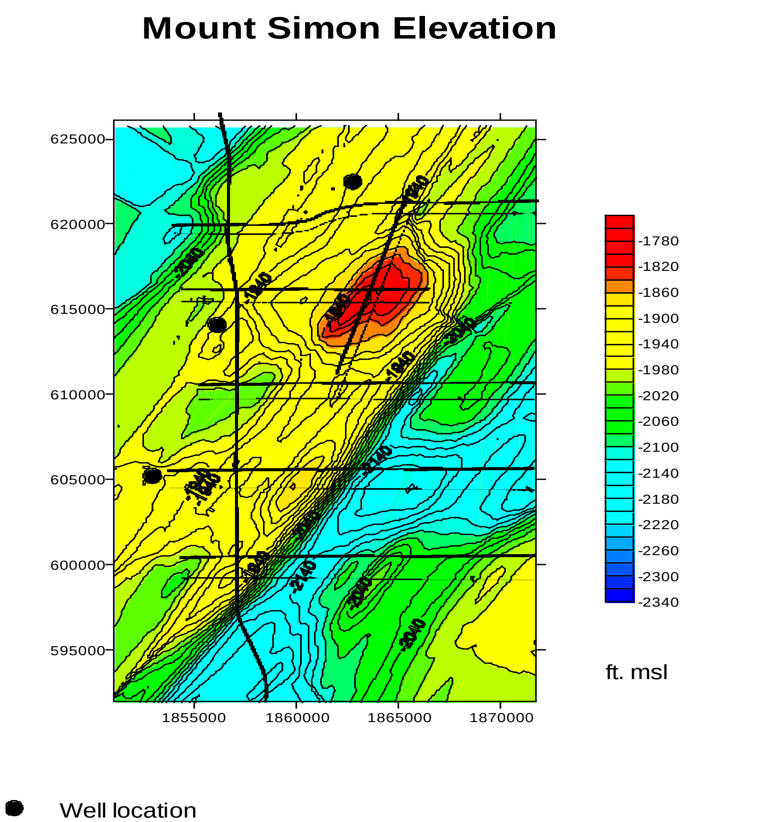

Figure 4. Contour Map of the Mount Simon Surface Elevation.

Dallas Center Stratigraphy-Air Storage Interval

An effective CAES storage vessel requires the presence of a permeable reservoir that is confined with a relatively impermeable caprock. The St. Peter and Mt. Simon Formations are the primary permeable sand formations in the Dallas Center area. Specifically, these two Formations are currently being used as natural gas storage host rock at the adjacent Redfield structure. Both of these Formations are present at depth within the Dallas Center structure. The Mt. Simon Formation is the selected air storage zone for the Dallas Center CAES facility. The Mt. Simon has an adequate thickness, aerial distribution, pore space, and permeability to operate as an air storage vessel. The Mt. Simon is at depth with a hydrostatic pressure that is suitable for air storage. Operations at the Redfield gas storage field show that the Mt. Simon gas storage zone was divided into four units labeled A, B, C, and D. as illustrated for Well A in Figure 5. This division of the Mt. Simon is based on porosity and permeability zones defined by Acoustic geophysical logs, core analysis, and operation experience. It is also based on North Natural Gas operational experience of the Redfield gas field.

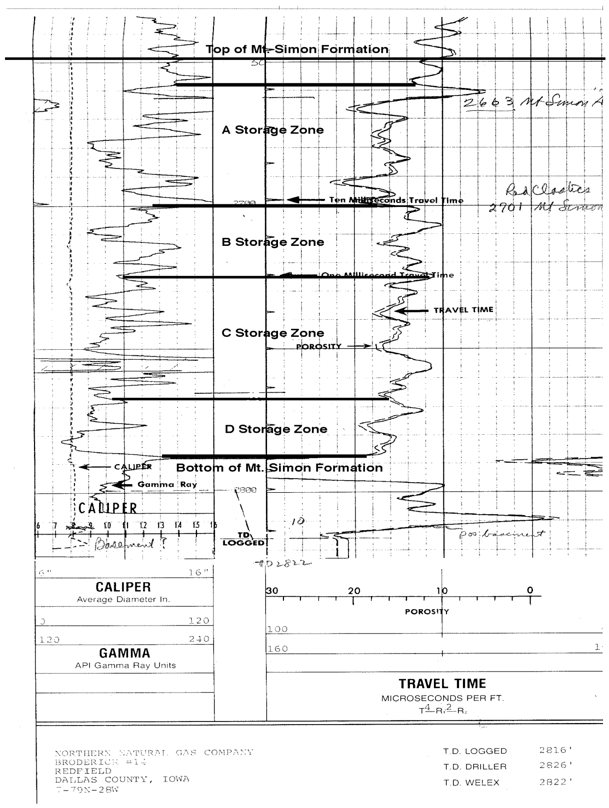

Figure 5. Acoustic Log for Redfield Well A Showing Key Storage Zone Intervals (Broderick #14 Well).

CAES Design Criteria

The design and operation of an underground air storage system is based first on the concept of multiple barriers to airflow, and second on reservoir engineering hydraulic principles. An additional principle is that air pressures must not compromise the stability or integrity of the vessel. Thus, the goals of any air storage vessel selection and characterization study are to confirm the stability of the vessel at anticipated air storage pressures, and to determine the potential for air migration from the vessel. CAES technology requires the matching of operating reservoir pressure and air flow rate constraints of the air storage vessel to pressure and air flow requirements of traditional turbo-generator equipment. For purposes of this analysis a 135 MWe Dresser-Rand CAES turbo-machine was selected that requires a minimum air pressure of 830 psi and a mass flow rate of 400#/sec or 464 MMscf/day. The key elements of an air storage facility are a geological containment structure, an air storage cavity or reservoir, a system of injection and withdrawal wells, and surface compression.

CAES Feasibility Analysis

The technical feasibility of developing the Dallas Center aquifer structure as a CAES air storage vessel was analyzed using the TOUGH+H2OG simulator code (Pruess, et al, 1996). The study consisted of two components. Our approach was to first use the Redfield natural gas storage field as an analog reservoir to represent the Dallas Center aquifer storage vessel. In this task we developed a numerical model to match historical gas injection/withdrawal volumes and pressures of the Redfield Mt. Simon storage zone for a sixty-year period. This match aimed to provide a level of validation of the geological model, of the storage capacity and of the current conditions of the Redfield. The second component was to convert the Redfield model to match geological and reservoir conditions at the Dallas Center structure for air storage. The model was used to simulate the creation of an air bubble in the aquifer storage vessel, and then to evaluation the system performance during weekly cycles during air injection and withdrawal.

<u>Redfield Gas Storage Model</u>: The Redfield Mt. Simon gas storage operation was modeling using the TOUGH+H2OG Code. Our Redfield 3D Model grid was composed of 246,400 grid blocks with 62 layers. The history-matching process involved inverse modeling that sought to determine the system parameters by adjusting to minimizing the deviations between the measured field data and the simulation predictions. Figure 6 show the comparison between predicted and observed pressures in Well C, respectively over a period beginning on May 21, 1986. The agreement between predictions and observations is very good.

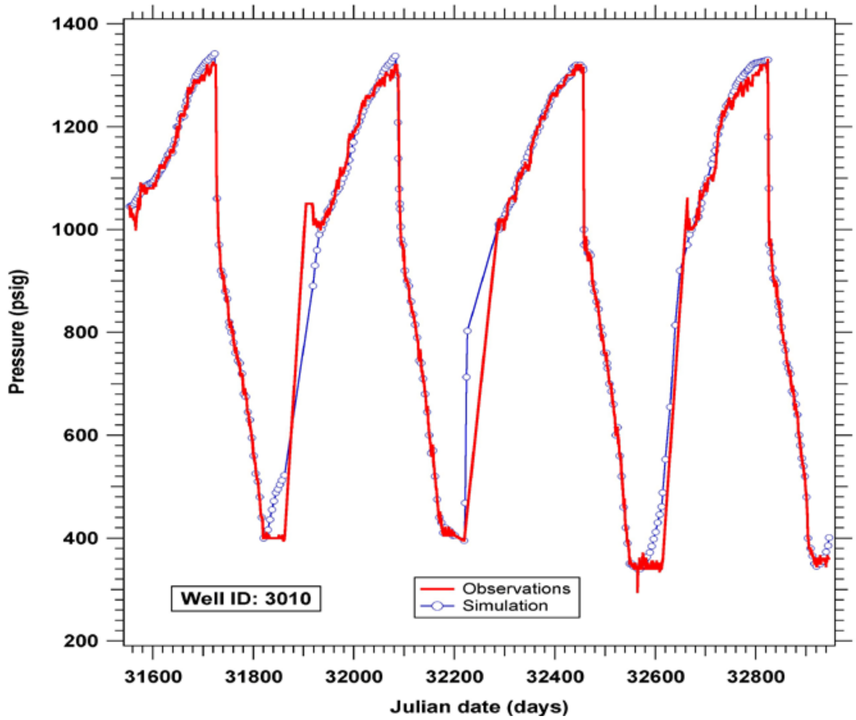

Figure 6. Redfield Study: Comparison of Observed and History-matched Pressures at the Well C. Note that the origin of time at t = 31553 days starting at May 21, 1986).

<u>Dallas Center CAES Feasibility Model Analysis:</u> The Dallas Center Mt. Simon formation structure is assumed to be very similar to the Redfield Mt. Simon gas storage facility. Based on this assumption, a numerical model of the Dallas Center Mt. Simon structure was developed using our Redfield gas field simulation. Initially the model defined the geometry of the Mt. Simon structure. A 3D Cartesian grid was used to describing the reservoir geometry, conditions and properties composed of about 128,000 cells in (r,z). The total dome height was limited to 31 m. A flat upper confining layer (overburden) for R > 1130 m (i.e., the R corresponding to the maximum dome height, with R measured from the center well), and constant-condition boundaries were assumed at R = 5000 m. The model reflected the difference in reservoir properties for the A, B, C, and D zones within the Mt. Simon. The strata above the dome were considered to be a trap (caprock), thus no-flow boundaries. The CAES feasibility simulation involved the definition of a well injection/withdrawal pattern, the simulation of development of the required air bubble, and finally the simulation of commercial CAES air pressure/flow rate cycles. A radial pattern of 13 wells with a 150-meter spacing was used for this study. We developed a strategy for the initial air injection phase. This strategy prevents pressure from rising to unacceptably high levels, while ensuring a wide region of high air saturation that can provide the minimum required mass flow rate during air withdrawal without encumbering the process with large water flow rates. The initial air injection strategy involves four stages (Figure 7).

Figure 8 shows the evolution of maximum pressure in the dome during the weekly cycle when two CAES compressor units are in operation. The most important observation is that the maximum pressure remains modest, significantly below the safe pressure of 2090 psia, and quite close to the hydrostatic pressure at this location. Because there is a net air withdrawal during the first 4 days of the operation cycle, the minimum pressures decrease at the end of each of each day. However, the deficit is replenished during the last period during the weekend.

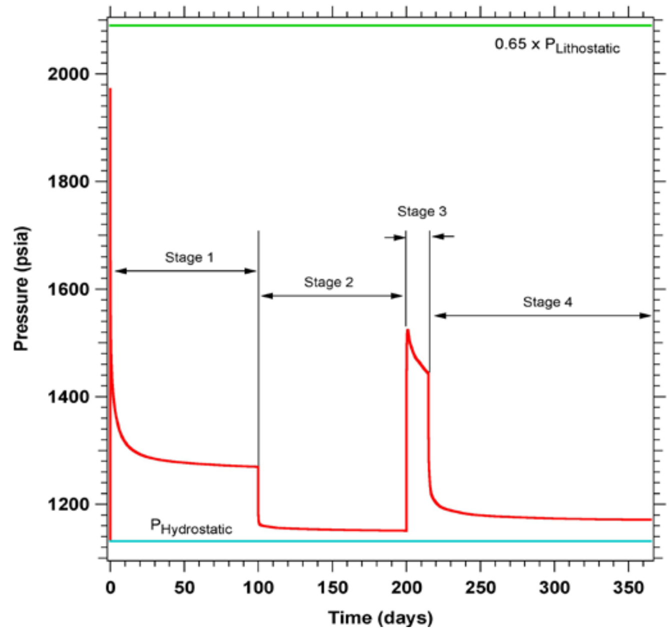

Figure 7. Evolution of Maximum Pressure in the Reservoir During the Initial Air Injection Stage (Bubble Build-up).

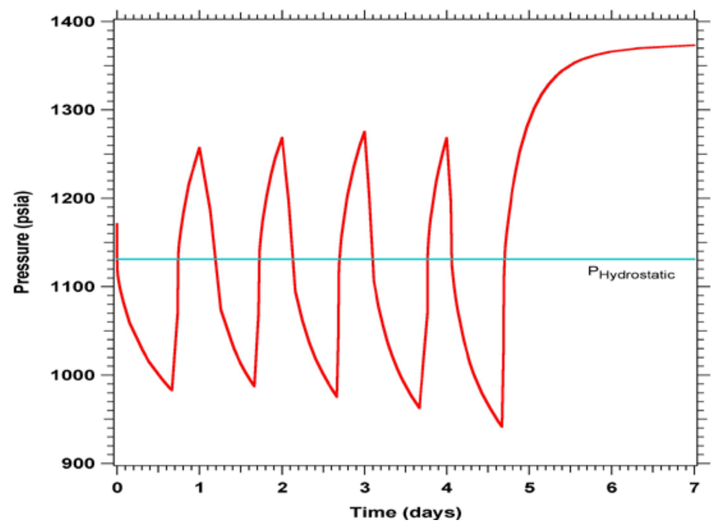

Figure 8. Pressure Evolution During the Weekly Production Cycle for Two Operating CAES Units.

The results of this research indicate that 1) a suitable geological structure in the Mt. Simon formation exist at Dallas Center, 2) air bubble develop in stages will be necessary to displace the water out of the work gas air bubble, and 3) that the Dallas Center air storage vessel could support one to two 135 MWe CAES power plant. A geological field exploratory drilling a testing program is essential to verify the results of our research.

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