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THE HISTORY AND PERFORMANCE OF VERTICAL WELL SOLUTION MINING OF NAHCOLITE ($NaHCO_3$) IN THE PICEANCE BASIN, NORTHWESTERN COLORADO, USA

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Abstract

American Soda, L.L.P. (American Soda), developed a solution mine plan for recovery of nahcolite from the vast resource in the Piceance Creek Basin using vertical wells and injection of high-temperature, pressurized water. The wellfield included 26 solution mining wells, which provided a nahcolite brine to the processing facility. The American Soda solution mining method utilizes dual, 7-inch casings cemented within a single, 19-inch borehole with 4½-inch casings being utilized as tubings within each 7-inch casing. The method injects 350°–420°F water to thermo-mechanically fracture the nahcolitic oil shale and dissolve the nahcolite. A nitrogen gas cap is maintained on the top of the solution mining cavity to limit vertical growth. The solution cavities have a productive height of approximately 500 ft. During the 3.75 years of commercial operation, American Soda mined approximately 2.6 millions tons of nahcolite with the wells producing between 75,000–150,000 tons each with cavern diameters of up to 200 ft.

Introduction

Vertical well solution mining of nahcolite on a commercial scale was initiated by American Soda in the fall of 2000. In the fall of 2004, after nearly 4 years of struggling economics, production from the American Soda project was curtailed and the solution mining facility placed on standby. Figure 1 shows the location of the American Soda project.

The American Soda project was piloted in the late 1990s with commercial production being initiated in late 2000. The solution mining process adopted for the American Soda project was pioneered by Shell Production and Exploration Company (Shell) as an outcome of an in situ oil shale experiment in the early 1970s.

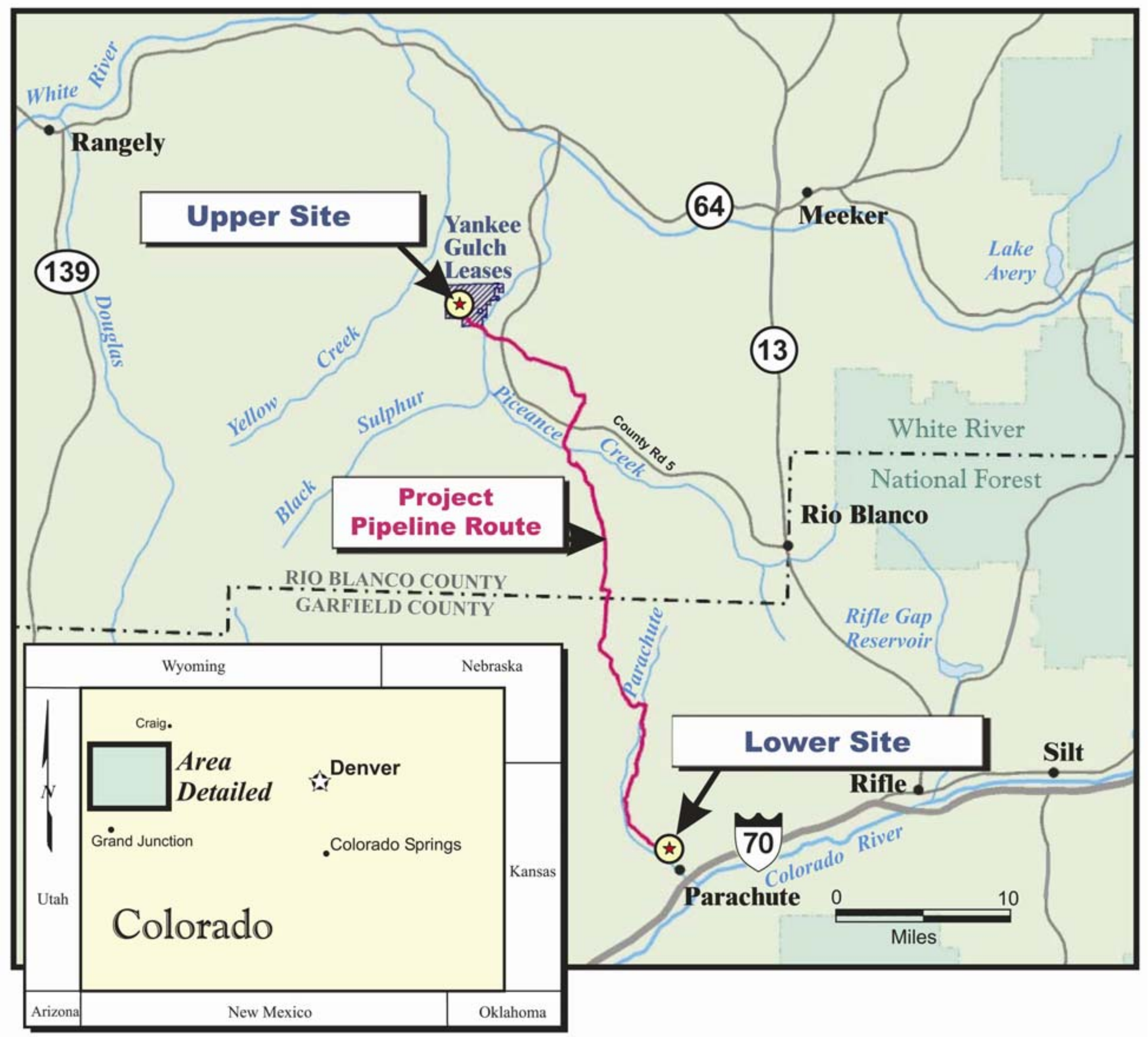

Figure 1. Location of the American Soda Project

Geological Setting

The Piceance Basin is well known for its vast reserves of oil shale, as well as mineral deposits of nahcolite ($NaHCO_3$) and dawsonite [$NaAl(CO_3)(OH)_2$]. Reserves of nahcolite within the basin have been estimated at 29 billion tons (Dyni 1974). The Piceance Basin is a broad, asymmetric, southeast-to-northwest structural and topographic basin located in northwestern Colorado, USA. The basin has an areal extent of approximately 7,225 square miles.

The Parachute Creek Member of the Green River Formation contains virtually all of the oil shale, nahcolite, and dawsonite resources in the Piceance Basin. The Parachute Creek Member is generally considered to comprise three distinct zones referred to as the Mahogany, Leached, and Saline Zones. Stratigraphic analyses of the Saline Zone have shown that various oil shale zones, along with nahcolite, dawsonite, and halite horizons, are laterally continuous over long distances. Figure 2 shows a north-south cross section through the American Soda Yankee Gulch Lease.

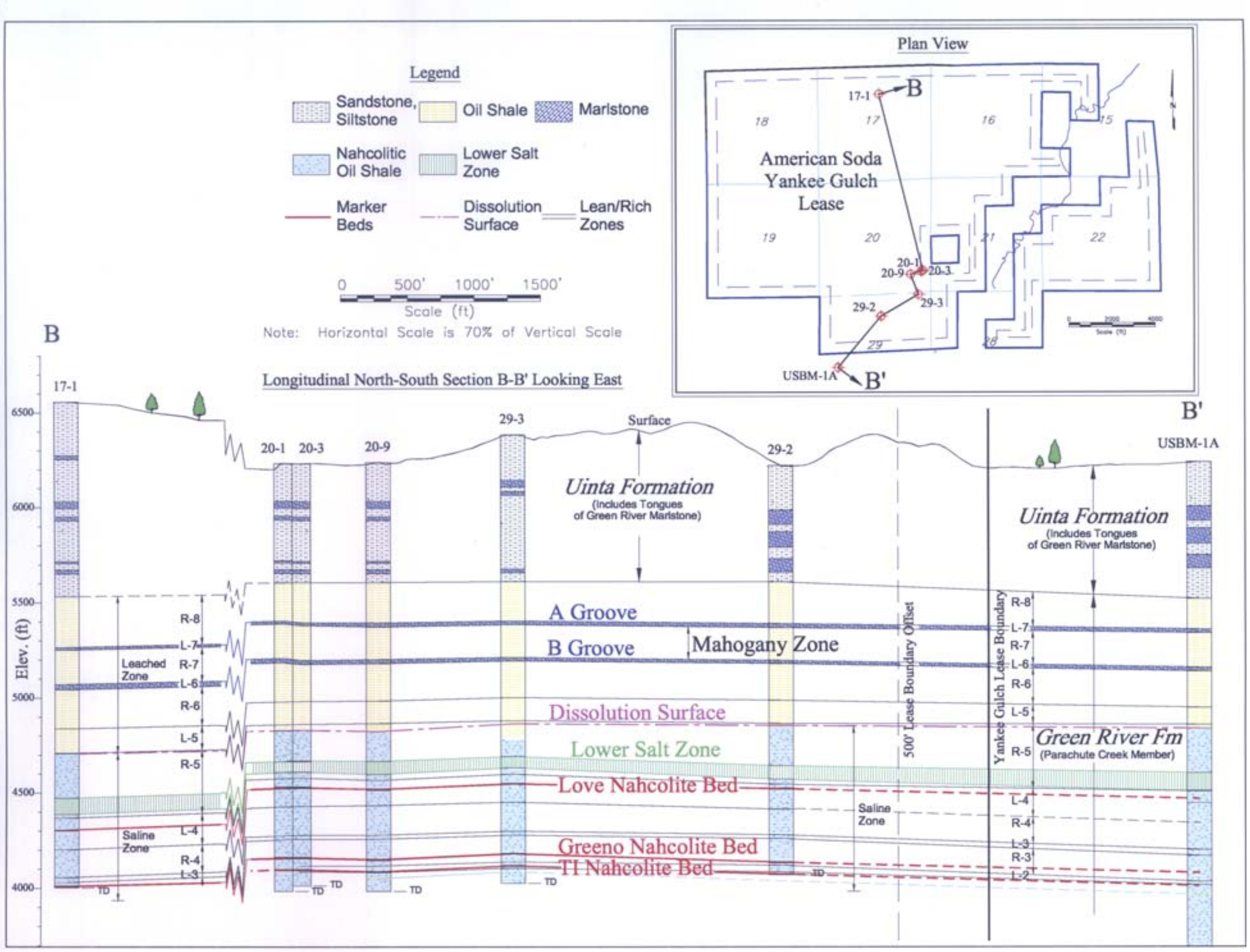

Figure 2. North-South Cross Section of Yankee Gulch Lease

The nahcolite mineralization occurs as disseminated nodules and thin beds within the Parachute Creek Saline Zone in the center of the basin with a mineralized thickness ranging from 200–1,000 ft. The average grade of the nahcolite mineralization ranges from 20%–24% nahcolite with dolomitic siltstones and kerogen comprising the remaining 76%–80% of the rock. The nahcolite mineralized zone is effectively impermeable. Figure 3 shows an oil shale core with large nahcolite nodules.

Shell Exploration and Production Company Pilot Test

From December 1970 through early 1972, Shell (Prats et al. 1977) piloted an oil shale recovery method that solution-mined nahcolite to create a rubblized oil shale that could be in situ retorted with high-pressure steam. The method was based upon the thermo-

Figure 3. Nahcolite Mineralization

mechanical fracturing of the oil shale and the solubility of nahcolite in high-temperature water.

One of the objectives of the Shell test work was to study the effect of simulated process environments on the spalling, rubbling, and disaggregating properties of the subsurface oil shale. Shell's test work was based on developing communication between the nahcolite nodules so they could be leached to establish an extensive oil shale interval of high permeability. Shell's test work focused on three mechanisms: stress release at open faces, thermally-induced stresses, and thermally-induced pressures (Prats et al. 1977).

The thermal-expansion coefficient of oil shale is large because of its kerogen content and is anisotropic because of its depositional nature. Upon heating, stresses are generated within confined oil shale often in the range of 50 to 100 psi per degree Fahrenheit rise in perfectly confined samples. The thermal stresses resulting from conduction heating in massive intervals help in creating fractures, especially near low-stress faces such as are present adjacent to a leached bed or a rubble zone (Prats et al. 1977).

Shell performed bench-scale tests by cementing a square-cut oil shale block, weighing approximately 200 pounds and assaying 25–27 gallons of hydrocarbons/ton cemented into a metal container. Hot water (300°–520°F) was circulated through the metal container for several weeks. These tests resulted in rubblization and fractures in the oil shale block. One test resulted in a 10% elongation parallel to the bedding planes. Another resulted in the average thickness of the block increasing by 12% (Prats et al. 1977).

Since nahcolite and kerogen tend to decompose upon heating to yield gaseous products, fluid pressures can increase significantly within the oil shale near a heated surface. This increase in internal fluid pressure occurs whenever the rate of increase of the gas volume, at a point within the oil shale, exceeds the rate at which it can flow outward through the matrix. Since this usually occurs near a free surface, it leads to spalling (Prats et al. 1977). This mechanism, sometimes referred to as the "popcorn effect," is particularly effective with isolated nodules, since nahcolite tends to decompose at relatively low temperatures (Papadopolous and Ueber 1972).

Shell operated the solution mining (leach) phase of the project for 44 days. During this time, 121,000 pounds of nahcolite was solution mined (Prats et al. 1977). Shell initiated steam injection for the in situ retort of oil shale in March 1971. The in situ retort test continued through December 1971. Shell produced at total of 420 bbls of oil during the in situ retort test (Prats et al. 1977). Shell was successful in the solution mining of nahcolite but encountered difficulty with the in situ retort of the oil shale.

American Soda, L.L.P., Project

Building on Shell's method, American Alkali, Inc., of Glenwood Springs, Colorado, and the Williams Companies of Tulsa, Oklahoma, formed a joined venture, American Soda, to construct a pilot solution mining facility and test the feasibility of solution mining nahcolite using high-temperature water in the fall of 1996.

Early studies included resource confirmation drilling, thermo-mechanical testing of the nahcolite core, and baseline hydrological and groundwater quality studies. The thermo-mechanical studies confirmed the reduction of strength of the nahcolite core at elevated temperatures and thermally-induced stresses resulting from the high-thermal expansion coefficient were sufficient to fracture the nahcolitic oil shale.

The American Soda pilot plant began operations in June 1997. By May 1998, results were encouraging enough to begin feasibility engineering of a full-scale sodium bicarbonate and sodium carbonate production facility.

In late summer of 1998, American Soda commissioned Kvaerner Metals to initiate the detailed design of a sodium carbonate and sodium bicarbonate production facility. Agapito Associates, Inc. (AAI), was commissioned to provide engineering support for the development of the commercial wellfield design and solution mining permitting efforts. These detailed design studies, complimented by the pilot testing results, formed the basis for the commercial decisions, the commercial mine plan for the Bureau of Land Management (BLM) [Steigers 1998], and Environmental Impact Statement (EIS0 [BLM 1999]. Detailed descriptions of the American Soda Project are contained in these documents: Yankee Gulch Sodium Minerals Project Commercial Mine Plan, the EIS prepared for the Environmental Protection Agency (EPA), and in a Mining Engineering article by M. P. Hardy, C. Yates, and K. Nielsen (Hardy et al. 2003).

The final engineering design was comprised of two facilities connected by 44 miles of dual, 12-inch insulated pipelines to produce 800,000 tons of sodium carbonate and 150,000 tons of sodium bicarbonate annually.

Figure 4. Upper Processing Facility

The Piceance facility, located at the sodium minerals lease site, 22 miles south-southwest of Meeker, Colorado, consists of the wellfield and upper processing plant. Figure 4 shows the processing facility, the injection water pipeline to the wellfield, and the production solution pipeline from the wellfield. The upper processing facility converts the sodium bicarbonate solution to sodium carbonate solution, produces liquid CO_2, concentrates the sodium carbonate solution through evaporation, and pumps the sodium carbonate solution to the Parachute, Colorado, facility. The sodium bicarbonate to sodium carbonate conversion process liberates CO_2 gas, which is utilized for the production of liquid CO_2. The ratio of production during the conversion process is one short ton of sodium bicarbonate equal to 0.63 short tons of sodium carbonate. United States patent number 6,609,761 (Ramey et al. 2000) fully describes the process.

The sodium bicarbonate to sodium carbonate conversion process is necessary due the temperature-solubility curve of sodium bicarbonate. A concentrated solution of sodium bicarbonate cannot hold sodium bicarbonate in solution as temperature losses are experienced in the 44-mile pipeline. Conversely, a concentrated solution of sodium carbonate can easily hold sodium carbonate in solution as temperature losses in the pipeline are experienced.

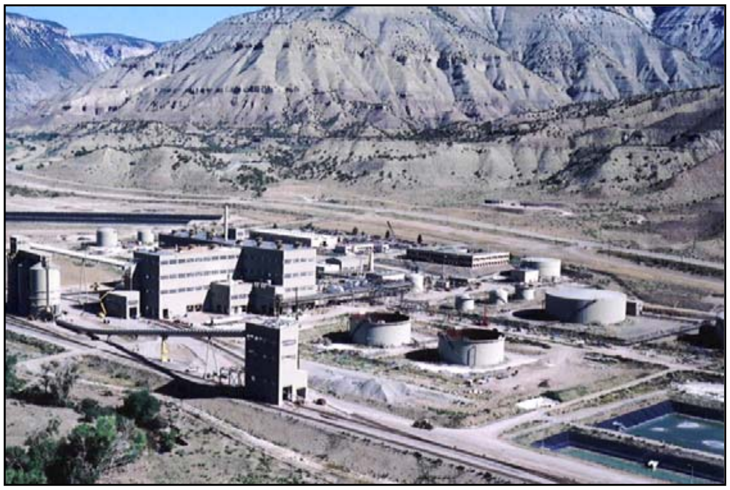

Figure 5. Parachute Facility

The Parachute facility (Figure 5), located 3 miles north of Parachute, Colorado, provides water for the solution mining operation, produces sodium carbonate by evaporation, and sodium bicarbonate by contacting a sodium carbonate solution with CO_2 to precipitate sodium bicarbonate. All administrative, sales, and shipping functions were performed from the Parachute facility.

The American Soda solution mining method utilizes dual, 7-inch casings cemented within a single, 19-inch borehole with a 4½-inch tubing within each 7-inch casing. The method utilizes 350°–420°F water to thermo-mechanically fracture the nahcolitic oil shale and dissolve the nahcolite into solution. A nitrogen gas cap is maintained on the top of the solution mining cavity to limit vertical growth. A minimum of a 150-ft crown pillar between the roof of each cavity and the dissolution surface is maintained to isolate the cavity from the overlying aquifers. The solution mining wells range in depth, between 2,200 and 2,600 ft, with the solution cavities having an average productive height of approximately 500–525 ft.

At start-up of the commercial operation, 26 solution mining wells were drilled and completed to provide nahcolite brine to the upper processing facility. The wells were spaced 600 ft apart with a single roll of wells placed on a 300-ft spacing. Future drilling was planned to fill in between the 600-ft spacing to recover approximately 40% of the nahcolite resource. Figure 6 shows a three-dimensional (3D) schematic of the wellfield and solution-mined caverns.

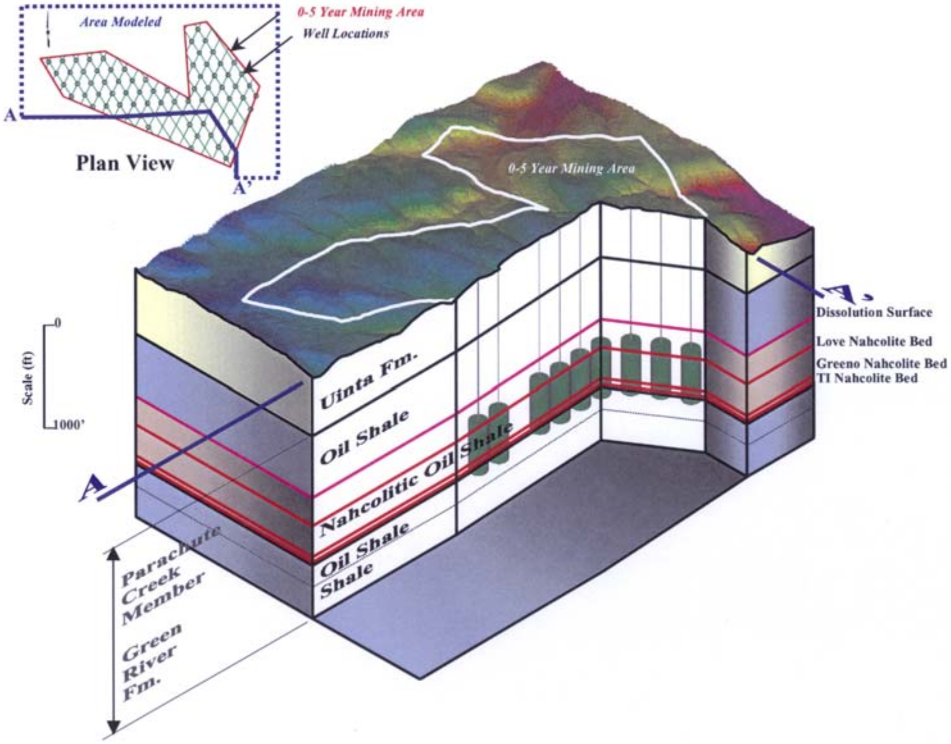

Figure 6. 3D Schematic of Wellfields and Solution-Mined Caverns

Each well was instrumented with measurements for temperature, pressure, flow for the injection fluid, the production fluid, and the nitrogen for the gas cap. The instrumentation connects to a centralized distributed control system (DCS). Each well was automated so that injection fluid flow and nitrogen gas flow could be controlled by the DCS. The data from the DSC was saved into a data historian database to provide data for production reports and performance trends. Figure 7 shows a typical American Soda wellhead and the instrumentation skid.

Figure 7. American Soda Wellhead and Instrumentation Skid

Construction of the Parachute facility was initiated in the spring of 1999. Shutdown of the pilot plant operation and construction of the Piceance facility were initiated in January 2000. Plant and pipeline commissioning and initial production for both facilities were accomplished in November 2000.

In the summer and fall of 2002, American Soda initiated the testing of solution mining of a smaller cavity height focusing on a higher grade section of nahcolite within the lower ore zone. These wells were referred to as "staged-production" wells. The concept was to produce the lower ore zone first, then to reposition the hot water injection position in the cavity and produce the upper ore zone. Two initial production wells were converted to staged-production wells and four wells were added as staged production wells on the second phase of drilling.

In September 2003, the Williams Companies bought the American Alkali, Inc., share of the project and announced the sale of American Soda to Solvay Chemicals, a division of Solvay America.

In April 2004, Solvay Chemicals announced the placement of the Piceance solution mining facility and the Parachute sodium carbonate production facility on standby due to high natural gas prices and continued depressed prices of sodium carbonate. Solvay also announced the continued production of sodium bicarbonate at the Parachute facility utilizing sodium carbonate from Solvay Chemical's Green River, Wyoming, operation.

The economics of the solution mining of nahcolite and converting the sodium bicarbonate brine to sodium carbonate brine is very sensitive to the price of energy. During feasibility studies, future natural gas prices were estimated to be \$1.80–\$2.00/mmbtu. In August 2004, natural gas prices in western Colorado were \$5.00–\$5.50/mmbtu. The solution mining cavities were on schedule to meet the designed tonnage goal of 180,000 short tons per well. The economics of production and permit limitations were the limiting factor to their size.

Solution Mining Well Performance

During the 3.75 years of commercial operation, American Soda mined in excess of 2.6 millions tons of nahcolite with the wells producing an average of 83,544 short tons each with an average cavity diameter of 130 ft. The average cavity diameter is the diameter of a right cylinder that contains the same volume within the formation as the nahcolite produced. Table 1 lists the tons of nahcolite produced from each well through May 2004 and the average diameter of the cavities (American Soda 2004).

Table 1. Well Production and Cavity Diameter

No.	Well	$NaHCO_3$ Production Tons through May 2004 (tons)	Average Cavity Diameter (ft)	Cavern Height	Drilling Phase
1	20-14	181,682	171.0	Full	Initial
2	29-24	176,604	204.5	Full	Initial
3	29-29	143,760	177.6	Full	Initial
4	20-30	131,643	170.6	Full	Initial
5	29-34	126,910	168.0	Full	Initial
6	29-23	123,651	168.1	Full	Initial
7	20-36	123,097	166.1	Full	Initial
8	28-21	117,551	168.9	Full	Initial
9	21-16	113,420	153.1	Full	Initial
10	20-32	113,160	157.9	Full	Initial
11	20-19	108,094	152.1	Full	Initial
12	29-26	98,810	149.8	Full	Initial
13	20-33	98,611	147.3	Full	Initial
14	29-28	97,857	143.9	Full	Initial
15	20-12	96,595	139.2	Full	Initial
16	20-74	94,820	212.4	Staged	Initial
17	20-31	90,615	140.2	Full	Initial
18	20-35	83,024	129.0	Full	Initial
19	29-27	81,775	132.3	Full	Initial
20	20-2	74,075	106.8	Full	Initial
21	29-20	70,039	191.0	Staged	Initial
22	21-15	65,833	104.6	Full	Initial
23	20-11	58,234	105.9	Full	Initial
24	29-68	46,658	133.2	Staged	2002
25	29-22	29,383	84.9	Full	Initial
26	28-17	18,200	66.5	Full	Initial
27	28-41	12,017	52.2	Full	Initial
28	20-3*	6,069	31.8	Full	Pilot
29	20-76	3,818	37.0	Staged	2002
30	29-53	2,000	30.8	Staged	2002
31	29-78	1,858	31.9	Staged	2002
	TOTAL	**2,589,863**			

*20-3 was a pilot well. No commercial production resulted from 20-3.

By assuming that the top ten wells operated 1,175 days of the 1,306 days available, the top ten wells averaged a production of 135,148 short tons of nahcolite, an average cavity diameter of 170.6 ft, and an average production rate of 114.8 short tons of nahcolite per day.

Conclusion

The Shell and American Soda projects illustrate the utilization of vertical wells and thermo-mechanical fracturing to solution mine nahcolite from an impermeable oil shale rock matrix. The method is dependent upon the physical characteristics of the matrix rock and contained minerals. The energy required for the mining and processing requires a low and stable cost of energy.

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