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**YANKEE GULCH NAHCOLITE
COAL FUELS U.S. ENERGY NEEDS
MINE ROOF TRUSS SUPPORTS
AUTOMATING UNDERGROUND VENTILATION**



Solution mining of nahcolite at American Soda's Yankee Gulch Project

The Yankee Gulch sodium minerals project (YGP) is a solution mining project operated by American Soda. The mine operates on a federal lease administered by the U.S. Bureau of Land Management (BLM). Commercial operations began in November 2000.

In 1964, Irv Nielsen discovered nahcolite mineralization where the YGP pilot plant is now located near the Piceance Creek in Rio Blanco County, Colorado (Nielsen, 1969). Development of the project accelerated after Williams Corp., of Tulsa, OK, joined with American Alkali in 1996 to form American Soda. Pilot testing by American Soda led to commercial permitting, plant design, construction and startup. Figure 1 shows the location of the Yankee Gulch leases and the location of the upper and lower plant sites.

Geologic setting and resource

The geologic setting of the nahcolite resource of the Piceance Basin is documented by Beard et al. (1974), Dyni (1974), and Cole et al. (1982). The nahcolite is co-mingled with oil shale. Colorado has a large oil shale resource that has been extensively studied because of its potential to supply oil to the nation.

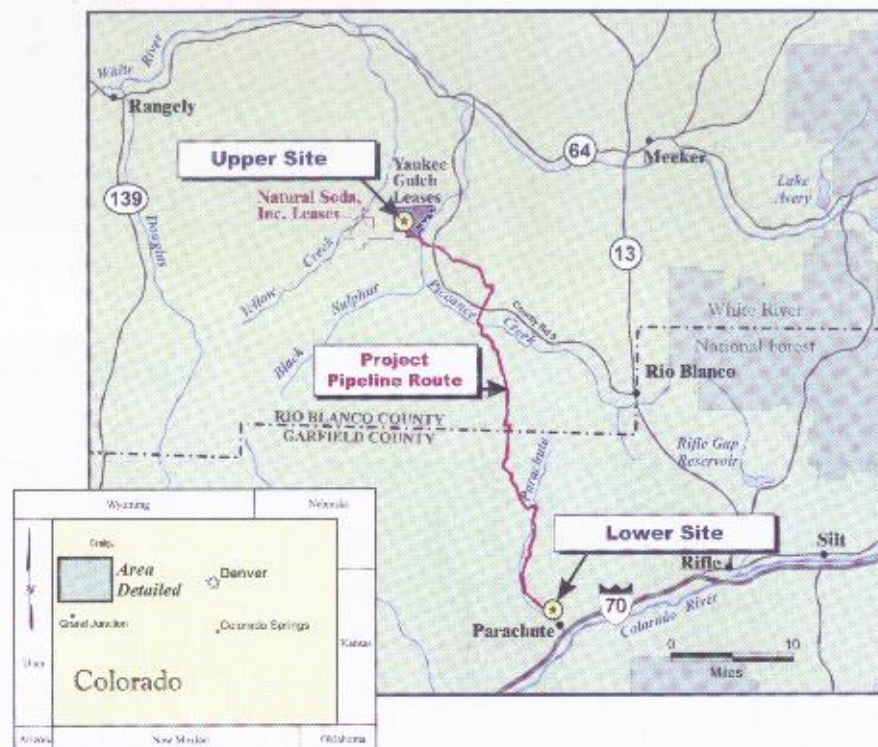
Adjacent to the federal leases held by American Soda is another nahcolite producer, White River Nahcolite Minerals was recently acquired by AmerAlia and is now known as Natural Soda. It solution mines nahcolite from the Boise Bed. The Boise Bed is a high-grade nahcolite (<80 percent) bed that is not present in core holes drilled in the Yankee Gulch lease. Natural Soda solution mines from horizontal holes (Day, 1994) that are directionally drilled along the bottom of the Boise Bed. Liquor is injected into the holes at less than 121° C (250° F).

Natural Soda's leases were drilled in the early 1980s by MultiMinerals to confirm the nahcolite and oil shale resources. On the Yankee Gulch leases, two holes were cored in the 1960s and 1970s and an additional six holes were cored in 1997. Additional holes that were drilled for resource, gas or hydrology characterization surround the leases and confirm resource continuity.

The nahcolite resource in the center of the Piceance Basin is present in beds of high-grade crystalline nah-

FIG. 1

Site map of the Yankee Gulch sodium minerals project. The lower plant site is located at a former oil shale upgrade facility. The pipeline between the upper and lower plants is about 71 km (44 miles) long.



colite. It is also present as disseminated nahcolite in oil shales of the Saline Zone of the Parachute Creek Member, Green River Formation. Its thickness ranges up to 330 m (1,000 ft). Figure 2 shows the isopach map of the Saline Zone below the Dissolution Surface at the American Soda lease. The Saline Zone contains the nahcolitic oil shale from which American Soda solution mines nahcolite.

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FIG. 2

Isopach map of the Saline Zone with core hole locations.

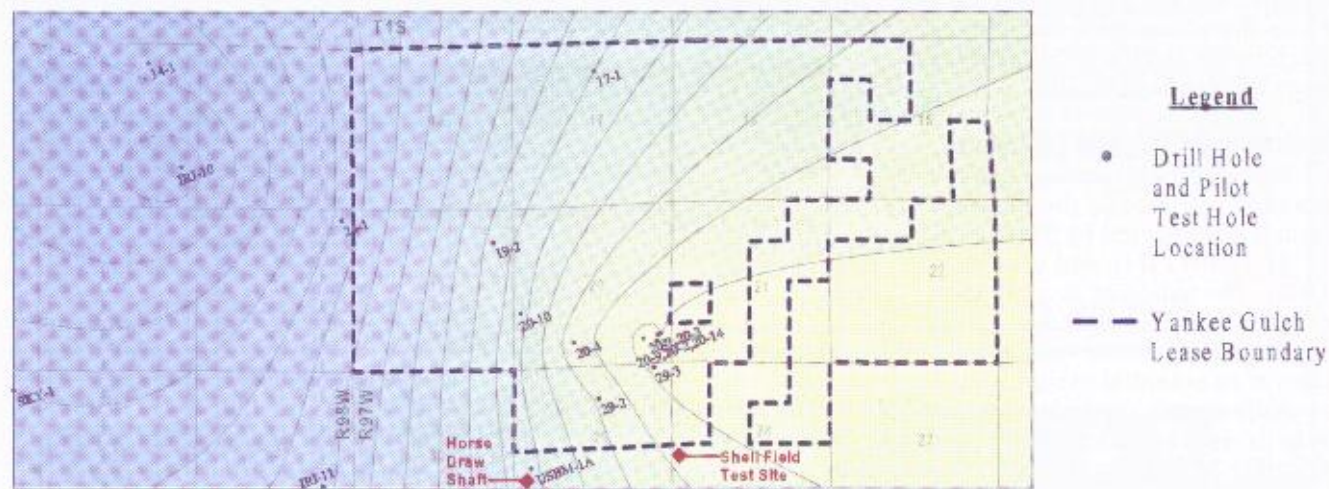
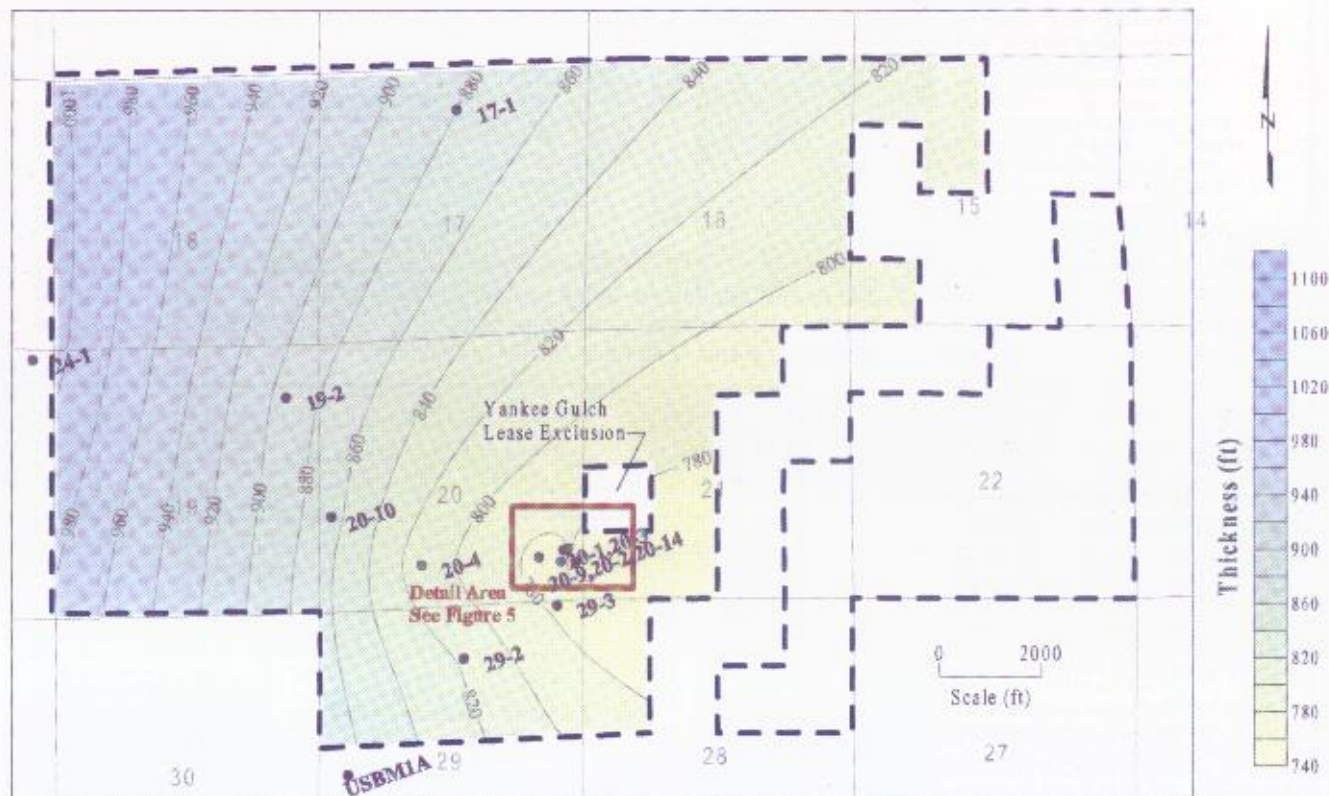


Figure 3 shows a north-south cross section through the Yankee Gulch lease with general stratigraphy. Individual beds of high-grade nahcolite (<80 percent) are present, with thicknesses of up to 9 m (30 ft) in the Lower Salt Zone east of the Yankee Gulch lease. In some parts of the Yankee Gulch lease, halite is present in the lower salt beds. The nahcolite is leached and brecciation has occurred above the Dissolution Surface. The brecciation above the Dissolution Surface is presumably a result of collapse and consolidation of the oil shales following leaching of the nahcolite (Gulliver, 1985). Over the full column of the Saline Zone in the center of the basin, the average nahcolite grade ranges from 20 percent to 30 percent.

Solution mining at the YGP uses vertical wells and

solution mines strata below the Lower Salt Bed or 45 to 60 m (150 to 200 ft) below the Dissolution Surface. The Lower Salt Bed is halite rich in portions of the American Soda lease. In other portions, it is rich in nahcolite and devoid of halite. The target zone for solution mining at American Soda has a thickness of 150 to 200 m (500 to 650 ft) with 23 percent nahcolite and less than 1 percent halite.

The north-south cross section, shown in Figure 3, traverses the lease area and includes data from seven holes. Core hole Nielsen 20-1 is the nahcolite discovery well located on the Yankee Gulch lease. The figure shows the Lower Salt Zone, the stratification of the rich and lean oil shale beds, and the Love, Greeno and T1 nahcolite beds. The Upper Salt Bed and the Boise Bed

are not evident in this cross section. The richest oil shale in the area is in the Mahogany Zone between the A and B Groove beds (Fig. 3) some 120 to 150 m (400 to 500 ft) above the Dissolution Surface. The Mahogany Zone can average more than 120 L/t (35 gal/st) oil content. The oil shale contains kerogen that when retorted will yield more than 120 L/t (35 gal/st). Individual thin beds of oil shale can yield more than 206 L/t (60 gal/st). In the Saline Zone below the Dissolution Surface, the oil yield from the oil shale is below 85 L/t (25 gal/st), again with thin layers higher than 85 L/t (25 gal/st).

The nahcolite-rich oil shale in the Saline Zone below the Dissolution Surface is generally devoid of open joints or fractures and faults. The nahcolite-rich oil shale is impermeable and can maintain high fluid pressures with minimal bleed off. Above the Dissolution Surface, the oil shales are fractured and brecciated and are water bearing. The ground water quality is below Under-ground Source of Drinking Water (USDW) standards. Total dissolved solids (tds) higher than 10,000 can be potable at higher stratigraphic elevations.

The nahcolite resource estimate for the Yankee Gulch lease is based on the two original core holes, the six core holes completed in 1997 and surrounding core holes for stratigraphic continuity. The total resource is about 1.7 Gt (1.9 billion st). The nahcolite reserve esti-

mated within a 380-m (1,250-ft) radius from assayed cored holes is about 227 Mt (250 million st). This estimate also factored in the mine height, well spacing, surface topography, possible archeological site, and geologic and hydrologic anomalies.

Solution mining concept

The solution mining concept proposed by American Soda was based on field tests conducted by Shell Oil in the early 1970s and reported in Prats et al. (1977). Shell undertook field testing of a concept to recover oil by injecting high-temperature steam into the nahcolite-rich oil shale below the Dissolution Surface in the Saline Zone near the southeast corner of the Yankee Gulch lease. As part of that field test, Shell injected steam at 149° C (300° F) in a vertical well and produced significant quantities of nahcolite. Shell Oil then increased the steam temperature to 315° C (600° F) in an attempt to produce oil. The oil production did not meet the company's expectations, so the field test was abandoned.

American Soda proposed to inject pressurized water at high temperatures sufficient to fracture the rock and to produce high-concentration sodium bicarbonate liquor. The high-temperature injection fluid was needed for two reasons. The first was to fracture the oil shale and provide access for the fluid to contact the dissemi-

FIG. 3

North-south cross section through the American Soda Lease.

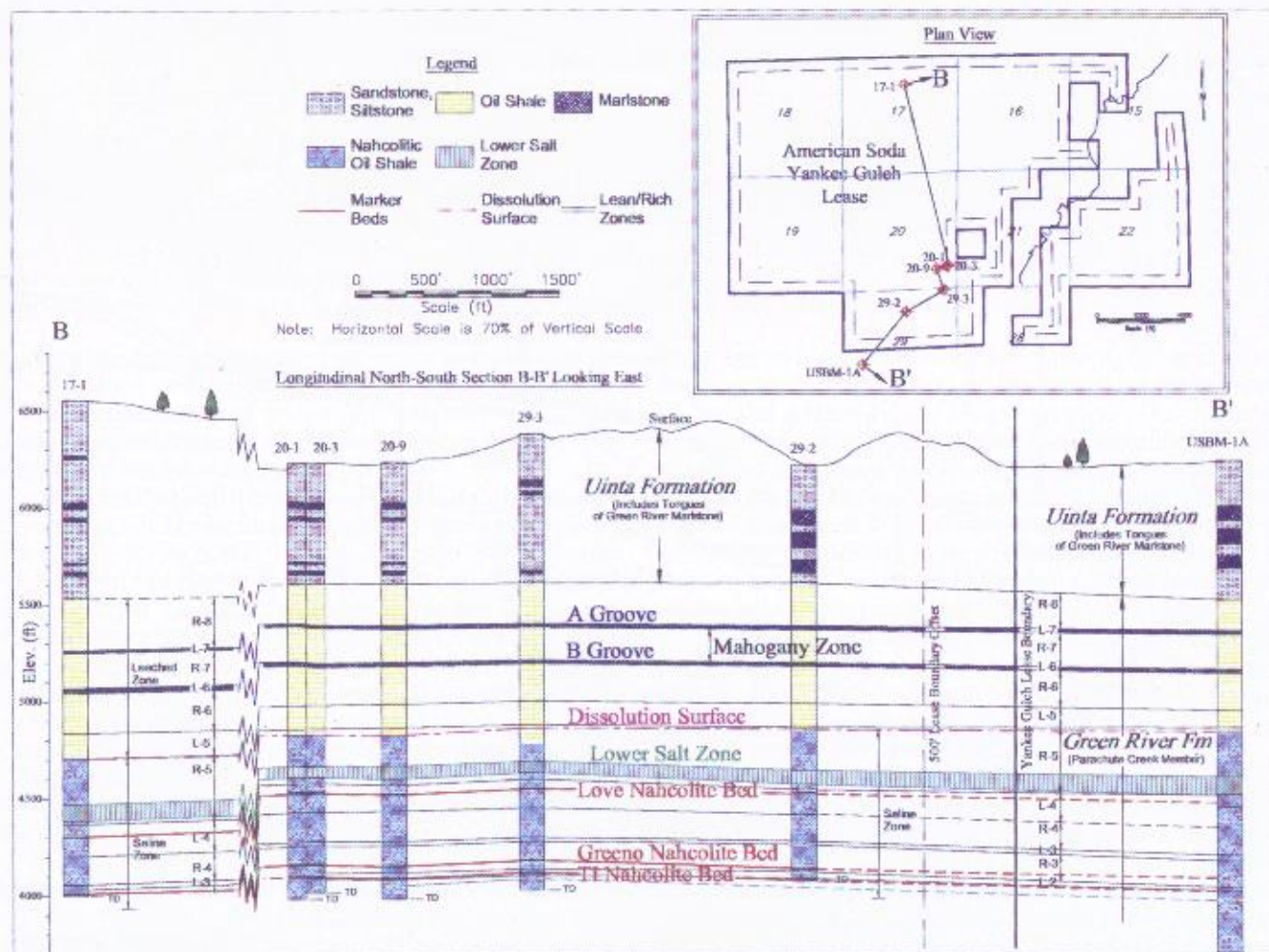


FIG. 4

Photo of the Yankee Gulch pilot plant area.



nated nahcolite. The second was to raise the solubility of nahcolite. The saturation of nahcolite in water is temperature dependent. The saturation concentration of nahcolite in water is more than 35 percent at temperatures of more than 176° C (350° F), whereas the saturation concentration is less than 20 percent at 93° C (200°

F). The growth rate of the cavern, which depends on the nahcolite grade and the extent of the thermally induced cracking, is accelerated at higher temperatures.

Issues of concern in the design of the well field included:

- The maximum extent of the cavern and the resource recovery per well, essentially the size and shape of the cavern.
- The impact of solution mining on overlying aquifers.
- The potential for subsidence and the impact of subsidence on the overlying aquifers and on the mining of overlying oil shale resources.
- The impact of solution mining on the oil shale resources within the solution mining intervals.
- The hydraulic conductivity of the host rock and the ability of the host rock to contain the high fluid pressures within the cavern without leakage.
- Well design to minimize drilling and completion costs while satisfying the operational requirements of the well.
- The location of the injection and production strings to optimize recovery without producing adverse contaminants such as halite.
- Selection of injection temperatures and target flow rates to establish the number of wells to meet the production targets.

Laboratory testing, analysis and pilot testing were

FIG. 5

Pilot test wells, the plant, the disposal well and the water supply well.

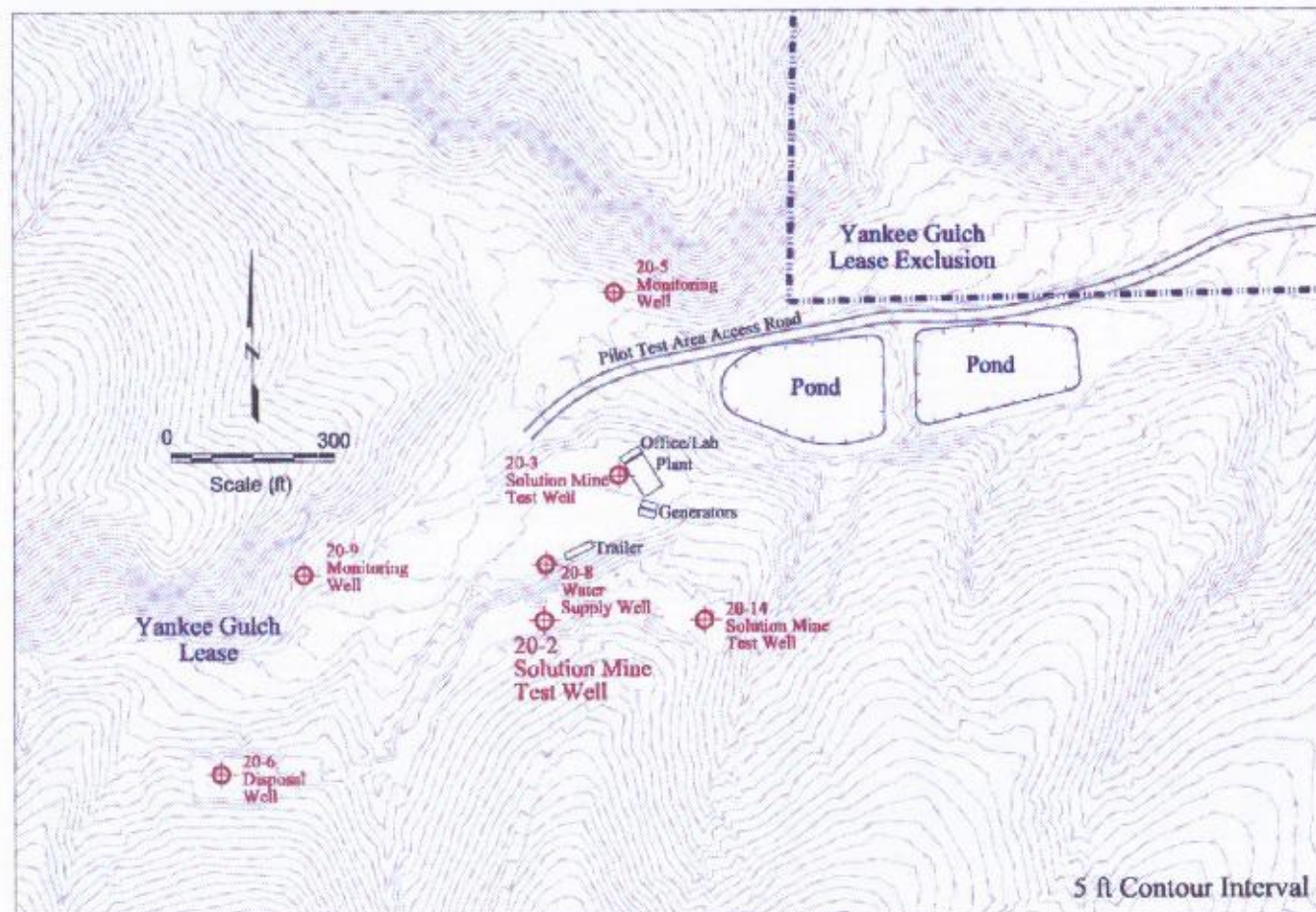


Table 1

Summary of the American Soda lease ground water monitoring wells.

Monitoring No.	Well ID	Borehole ID	Location relative to 0-5 panel ¹	Primary position relative to 0-5 panel ^{1,2}	Secondary position relative to 0-5 panel ^{1,2}	Completion zone	Aquifer monitored
1	19-2	19-2	Out of panel	Cross-gradient	Up-gradient	A Groove	Upper
2	19-3	19-3	Out of panel	Down-gradient		Alluvium	Alluvial
3	20-4A	20-4A	In panel	Cross-gradient	Up-gradient	A Groove	Upper
4	20-4B	20-4B	In panel	Cross-gradient	Up-gradient	B Groove	Lower
5	20-5	20-5	In panel	Down-gradient		Uinta	Upper
6	20-8	20-8	In panel	Down-gradient		Uinta (water supply well)	Upper
7	20-9	20-9	In panel	Down-gradient		B Groove	Lower
8	20-10	20-10	Out of panel	Cross-gradient		Uinta	Upper
9	21-2	21-2	Out of panel	Down-gradient		Alluvium	Alluvial
10	21-3U	21-3	Out of panel	Down-gradient		Uinta	Upper
11	21-3A	21-3				A Groove	Upper
12	21-3B	21-3				B Groove	Lower
13	21-3D	21-3				Dissolution Surface	Lower
14	21-4A	21-4	In panel	Down-gradient		A Groove	Upper
15	21-4B	21-4				B Groove	Lower
16	21-4D	21-4				Dissolution Surface	Lower
17	21-4U	21-4U				Uinta	Upper
18	21-5	21-5	Out of panel	Down-gradient		Alluvium	Alluvial
19	28-1	28-1	Out of panel	Cross-gradient	Down-gradient	Alluvium	Alluvial
20	29-2B	29-2B	Out of panel	Up-gradient		B Groove	Lower
21	29-3	29-3	In panel	Cross-gradient	Down-gradient	A Groove	Upper
22	29-4U	29-4	Out of panel	Up-gradient		Uinta	Upper
23	29-4A	29-4				A Groove	Upper
24	29-4D	29-4				Dissolution Surface	Lower
25	29-4B	29-4B				B Groove	Lower
26	34-1 ³	34-1	NA-Parachute site	NA-Parachute site	NA-Parachute site	Alluvium	Alluvial

¹Assumes ground water flow direction is N65°E.²Up-, down- and cross-gradient are with respect to the potentiometric surfaces for respective aquifers.

undertaken to provide answers to these and other questions related to the design and permitting of the proposed solution-mining concept. The process of collecting data, pilot well testing and permitting the project was completed between 1996 and 2000.

As a first step in establishing feasibility of the high-pressure, high-temperature solution mining technique, the core holes drilled in 1997 were pressure tested over the interval of interest for solution mining. These tests evaluated the hydraulic conductivity of the formation and would confirm that the formation would contain pressurized fluid without leakage. Five of the six core holes completed the pressure test. The sixth core hole encountered difficulties with the packer seating and the test was abandoned. The hydraulic conductivity indicated from these tests was in the 10^{-7} to 10^{-8} cm/sec range. This indicated tight conditions with minimal leakage at the planned operating pressures.

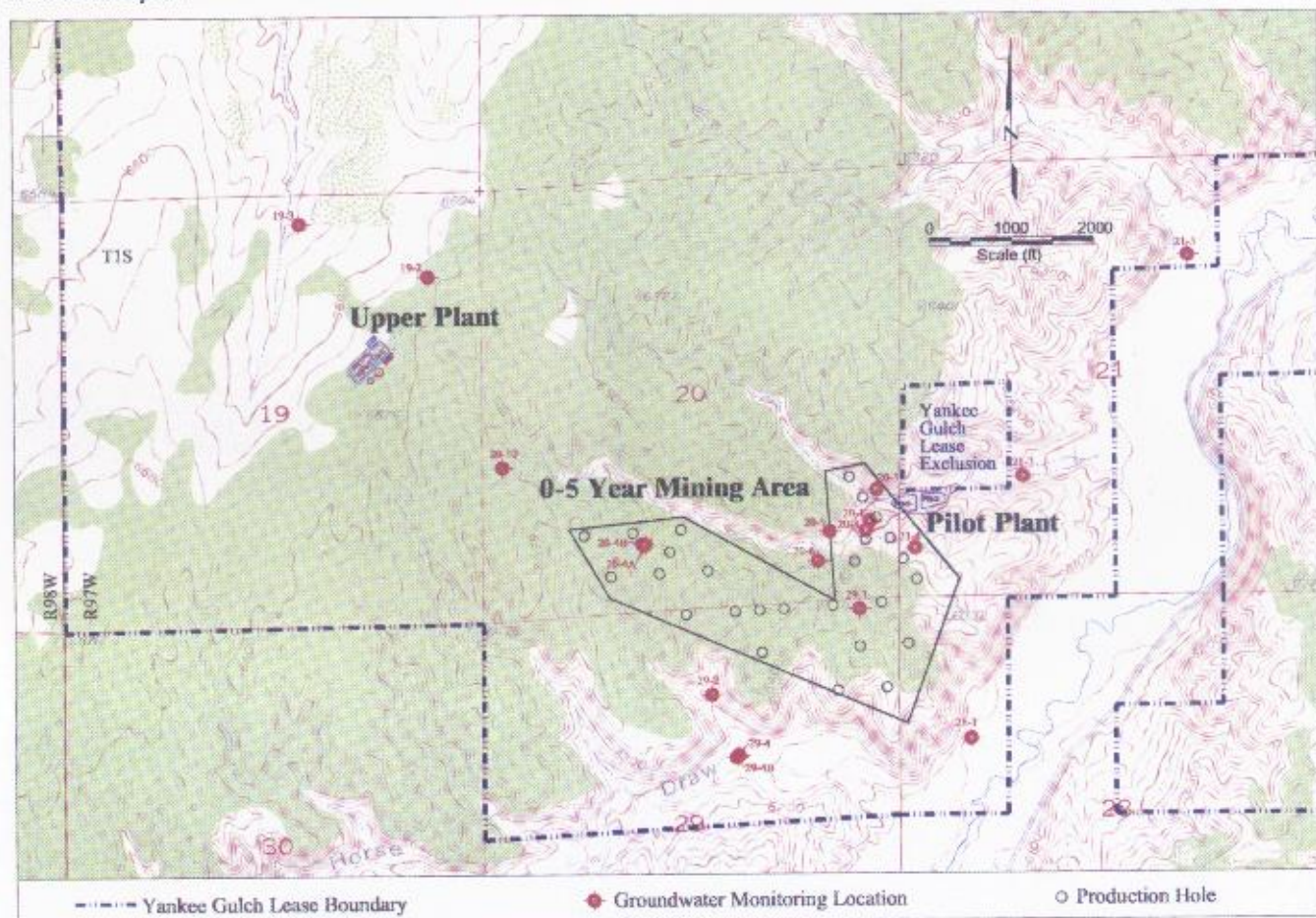
Laboratory testing and analysis

Core recovered from the 1997 coring program was assayed and tested for thermomechanical properties. Tests were completed to determine the influence of tem-

perature on strength, deformation properties and thermal expansion coefficient of the cored oil shale, nahcolite and nahcolitic oil shale samples. The thermal conductivity of selected samples from the core was determined as a function of temperature. This data was used to predict the temperature field around the cavern, the projected heat losses from the cavern and the extent of fracturing around the cavern. These analysis were also used to assess the potential interaction between caverns and to select the spacing between caverns.

Thermal cracking is induced because of the high thermally induced stresses developed around the cavern and the reduction in strength of the nahcolitic oil shales at elevated temperature. The reduction of strength of oil shale is well documented (Miller et al. 1979).

Tests on core from the Yankee Gulch lease confirmed the reduction in strength of the nahcolitic oil shale at elevated temperatures. Oil shale also has a high thermal expansion coefficient, in the range of 6 to 200 microstrains/°F. The combination of reduced strength and increased thermally induced stress results in cracking, fracturing, and/or yielding of the rock at the perimeter of the cavern. And it allows fluid to penetrate the

FIG. 6**Well field layout.**

fractured rock and dissolve the disseminated nahcolite. This process is confined to a local area adjacent to the cavern.

The low thermal conductivity of the nahcolitic oil shale results in relatively high temperature gradients around the cavern and limits the heat loss to the host rock. Temperatures within the caverns are less than injection temperatures. They are restricted to minimize the impact of solution mining on the residual oil shale.

Pilot testing

This mining method had not been demonstrated on a commercial scale. So American Soda recognized that a pilot test of solution mining would be required before designing the commercial well field and plant. Issues to be resolved in the pilot testing phase were to verify plant feed concentration, chemical quality and production rate. Associated issues, such as energy consumption and cavern growth rate, could be demonstrated and well completions could be tested.

The pilot plant was built in early 1997. The first test well (20-3) came onstream in late July 1997. Figure 4 shows the pilot test area, the well pad, the plant and the ponds in the background. The plant included a gas-fired boiler to heat the injection liquor and pumps. In all, three solution mining test wells were developed (20-3, 20-2 and 20-14). They produced brine that was discharged to a pond or to an underground disposal well completed above the Dissolution Surface.

Figure 5 shows the layout of the pilot tests wells, the

plant, disposal well, and water supply well (20-8). Heated pressurized water at temperatures up to 204° C (400° F) was injected for over two-and-a-half years. Injection rates of up to 6.3 L/sec (100 gpm) were achieved. But, because of water supply and plant boiler limitations, the injection rate was typically 3.1 to 4.7 L/sec (50 to 75 gpm). The water supply, from a well (20-8) completed in the Uinta Formation, was augmented by recirculated, cooled, sodium-enriched liquor from the ponds.

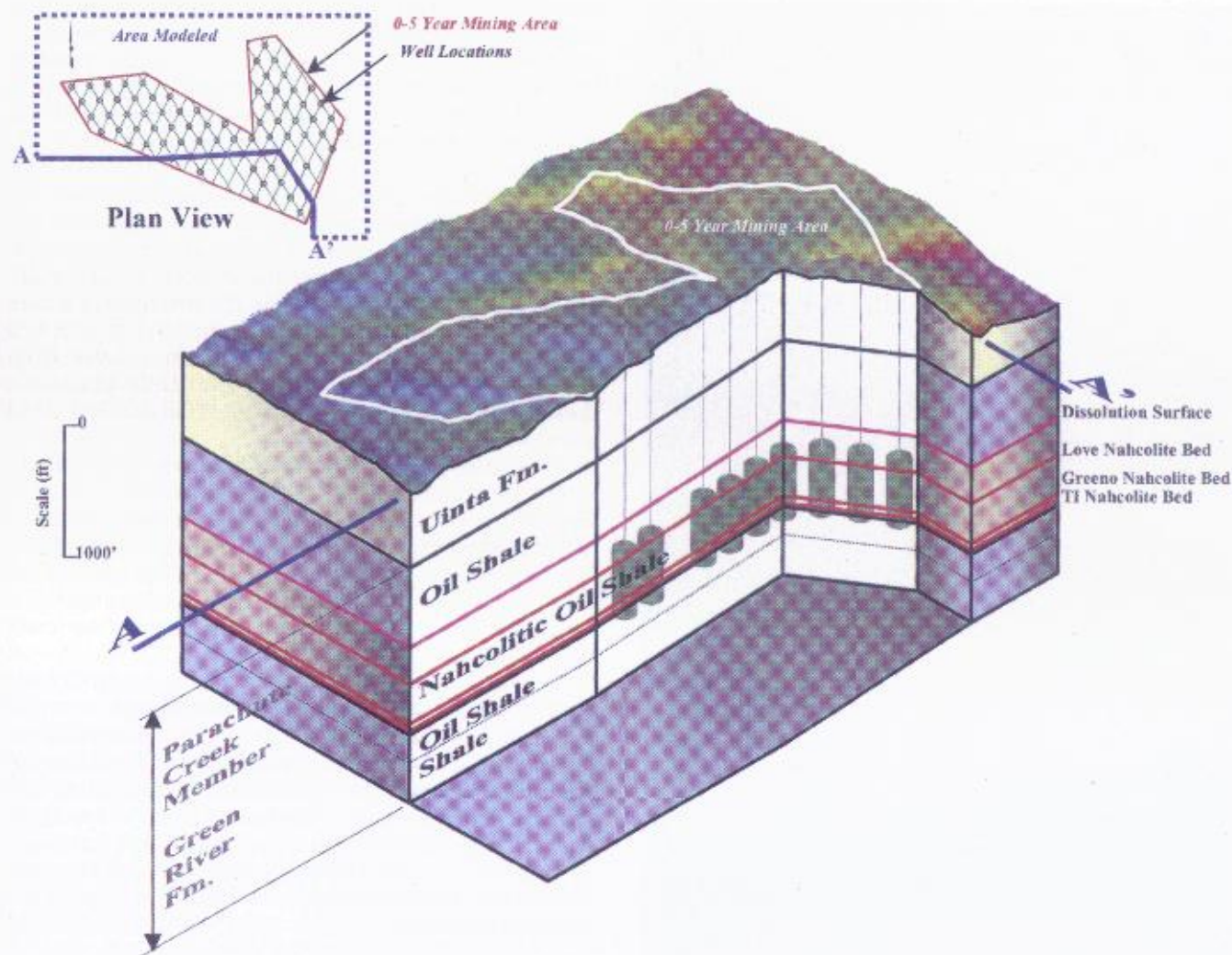
During the pilot plant's two-and-a-half years of operation, about 22.7 kt (25,000 st) of sodium bicarbonate was produced and caverns (or leached zones) of equivalent diameter to 10 and 10.6 m (33 and 35 ft) were developed, based on an assumed cylindrical cavern shape and produced tonnage of nahcolite. The pilot test confirmed product quality and cavern growth rates. The well completion design was refined to minimize heat losses to the formation and the final well completion design selected for the commercial well field demonstrated in the third pilot well (Well 20-14). Injection into the pilot wells was terminated in early 2000 when the upper plant was in construction. Two of the pilot test wells (20-2 and 20-14) were reactivated in November 2000 and have continued to produce feed liquor to the commercial plant.

Commercial mine plan

The well field proposed by American Soda was based on a well spacing of 90 m (300 ft). This would allow growth of the caverns to up to 60-m- (200-ft-) diam, leaving sufficient, unleached material between caverns

FIG. 7

Schematic three-dimensional sketch of the well field.



for fluid containment and subsidence protection. The caverns are each about 157 m (515 ft) high, with the roof at a depth of about 550 m (1800 ft). Figure 6 shows the production well locations, the location of the pilot plant, the upper plant site, the exploration core holes and the ground water monitoring wells. Future wells will be located between the existing wells to fully populate the area with wells on a 90-m (300-ft) spacing.

A goal for economic planning was for each cavern to develop to the equivalent diameter of 40 m (135 ft). Figure 7 shows a schematic, three-dimensional sketch of the mature well field. The well field is designed for long-term stability by spacing the wells so that the remaining undisturbed nahcolitic oil shale between "caverns" is able to support the overlying strata. The term "cavern" is a misnomer, as the solution-mined volume is more correctly described as a leached zone.

After solution mining, the caverns (or leached zones) will contain the residual undissolved oil shale, which will resist deformation of the walls and immediate roof of the cavern. The impact to the overlying aquifers is expected to be undetectable and no impact to the overlying Mahogany Zone is expected. Several ground water monitoring wells are part of the mine plan.

The residual oil shale in the "cavern" is enriched because of the removal of the nahcolite and is permeable.

This enhanced permeability may later be used in in-situ recovery of the oil shale or other minerals such as dawsonite.

The mine plan included initial development of 26 wells to support a plant capable of producing 813 kt/a (896,000 stpy) of soda ash equivalent. The processing plant is designed to produce soda ash (726 kt/a or 800,000 stpy) and sodium bicarbonate (136 kt/a or 150,000 stpy). After the first year of solution mining, it was anticipated that production could be sustained from fewer wells, possibly as few as 13 wells. The larger, mature caverns are capable of producing higher tonnages of nahcolite because the production rate is proportional to the surface area of the cavern.

Replacement of wells was scheduled at 15 wells per year. A well life of three years was anticipated. Each wellhead is instrumented to monitor temperature, pressure and mass flow rate for the injection stream and the production stream. Figures 8a and 8b shows a typical wellhead and the skid containing the instrumentation and the valving. The instrumentation was designed to detect leakage from a cavern and to determine the tonnage of nahcolite produced from each well.

Pressurized nitrogen is provided at each wellhead for injection and development of a gas cap at the top of each producing cavern. The gas cap inhibits upward cav-

ern growth and it can be used to focus solution mining to specific horizons. Surface features of the well field include roads, well pads and piping. The access roads and pipeline routings were selected to minimize surface disturbance. Some potential well locations were avoided to protect tree stands, archeological sites or raptor habitat.

The commercial plan included an upper plant and a lower plant, shown in Figs. 9 and 10, respectively, and sited in Fig. 1. The upper plant is located near the center

FIG. 8A (TOP) AND B (BELOW)

Typical wellhead and instrumentation skid.

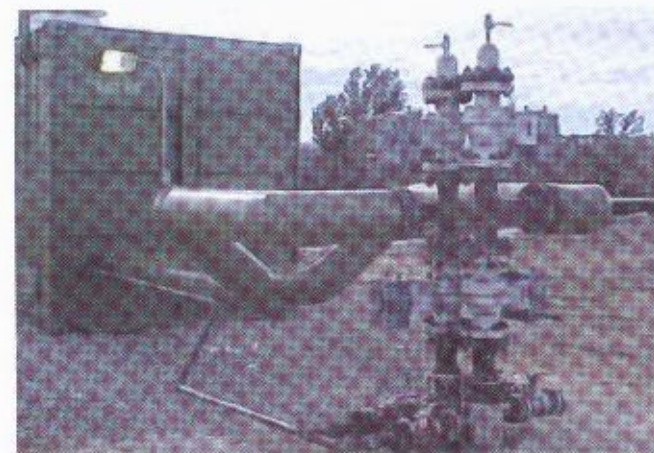
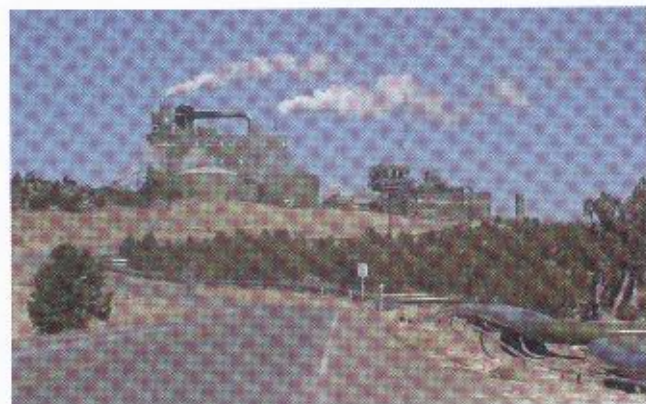


FIG. 9

Upper plant located on the Yankee Gulch leases, T1SR97W.



of the lease (Fig. 6). The lower plant, located near the town of Parachute, is sited on land purchased from Unocal at the former site of an oil shale upgrade facility. Two insulated pipelines — one for product liquor and the other for return water — connect the two plants.

The upper plant receives high-temperature, pressurized liquor from the well field. It strips the liquor to produce a sodium carbonate brine. In the stripping process, the liquor is depressurized and cooled. Carbon dioxide and water, in addition to sodium carbonate, are produced from the stripping of the sodium bicarbonate. Some carbon dioxide is collected and trucked to the lower plant for use in reconstituting sodium bicarbonate.

The buried, insulated pipeline delivers an intermediate brine of sodium carbonate to the lower plant where sodium carbonate is crystallized and up to 137 kt/a (150,000 stpy) of sodium bicarbonate is produced. Construction of the pipeline across the Roan Plateau is shown in Fig. 11. The pipeline route is about 70 km (44 miles) long (Fig. 1).

The solubility of sodium carbonate is insensitive to temperature and can be piped long distances in insulated pipe. The pipeline was constructed to avoid a potential problem in trucking product out of the Piceance Basin. The return pipeline provides a source of water for the upper plant from the Colorado River with water rights secured from Unocal. Product is shipped from the lower plant by rail and truck.

Permitting and ground water monitoring

The primary permits for the project involved application for Underground Injection Control Permits from the U.S. Environmental Protection Agency (EPA) and an environmental impact statement (EIS) by the BLM. Additional permits were required from the local counties and the Colorado Division of Minerals and Geology. The permitting issues of concern for the design of the well field included:

- Leakage from the solution mined caverns and the potential for contamination of the overlying aquifers.
- Subsidence of the overlying strata.
- Mining of the oil shale and associated generation of organics in the production stream.
- Minimizing surface disturbances.

The first concern was fundamental to the design and layout of the well field. The baseline ground water quality had to be established by monitoring. The ground water regime in the Piceance Basin had been regionally characterized during the oil shale boom of the 1970s and early 1980s (Weeks et al., 1974; Robson and Saulnier, 1981).

The ground water monitoring program required monitoring the Dissolution Surface, the A Groove, the B Groove, the Uinta Formation and the alluvium. These aquifers were monitored upstream, downstream and in the well field. And the alluvium was monitored downstream from surface storage pond locations. In addition, American Soda agreed to monitor domestic water wells in the immediate area of the leases. This monitoring program, and associated data acquisition system, had to be in place for five quarters before startup of commercial operations.

The resulting program included 18 holes monitoring 25 locations. Some boreholes were completed with up to four monitoring horizons. Table 1 lists the monitoring wells and boreholes, their location relative to the well field and the completion zone. The location of the wells is shown in Fig. 6. The wells were completed with 50-mm (2-in.) fiberglass tubulars to a depth up to 439 m (1,442 ft) below ground level.

Early observations from the monitoring wells during pilot testing indicated that the ground water quality in the A and B Groove aquifers at the Yankee Creek test site were not similar to the expected water quality indicated from regional data (Weeks et al., 1974) and data local to the Natural Soda lease area (Welder and Saulnier, 1978). Specifically, the water quality near the pilot plant test area deteriorated in the A and B Groove aquifers (with tds of 10,000 ppm). But regional and Natural Soda data indicated generally good quality water in the A Groove and USDW quality water down to near the Dissolution Surface.

This anomaly at the American Soda site caused concern and triggered studies to identify the causes of the anomaly (Saulnier, 1999). The first potential cause of the anomaly was contamination during completion of the monitoring wells.

This cause was dismissed after extensive pumping from each monitoring well did not result in significant improvement in water quality. Other possible causes included natural ground water upflow in the vicinity of the Piccance Creek; contamination from the Horse Draw shaft located upstream of the Yankee Gulch leases (Fig. 2); contamination from earlier off-site drilling, testing and underground injection (pilot testing completed by Prats et al., 1977); and, possibly, contamination is from old core holes drilled in the 1960s within the property — for example, the core hole Neilsen 20-1.

Subsidence above the solution mined caverns was a concern regarding the disturbance of the overlying aquifers, the disturbance of the minability of the oil shale resource and potential damage to the casings and tubulars in the injection/recovery wells. The cavern's size and spacing were designed to allow ample undisturbed material surrounding each cavern to form a seal for each cavern and to support the overlying strata. The roof of the cavern is at least 45 m (150 ft) below the Dissolution Surface. This crown pillar provides adequate protection against leakage from the cavern to the Dissolution Surface.

Surface subsidence is not expected with the approved mine plan. The cavern spacing results in a low areal extraction and the residual material in the cavern will stabilize the cavern walls. However, a subsidence monitoring plan was developed. This plan includes surface subsidence monitoring, cavern shape determination, subsurface monitoring using time domain reflectometry technology (Dowding et al. 1988) and geophysical logging to monitor the upward growth of the cavern.

Current status

The well field has operated for more than two years with production increasing each year. Startup difficulties associated with the plant and well field have been overcome and production in 2002 was about 70 percent plant design capacity at 544 kt (600,000 st) of soda ash equivalent.

FIG. 10

Yankee Gulch's lower plant near Parachute, CO.

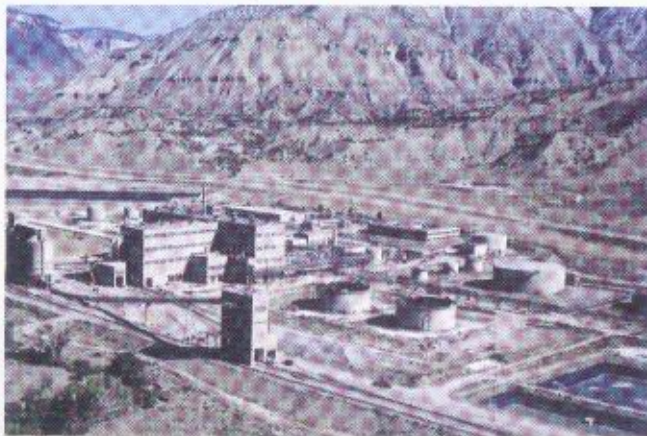
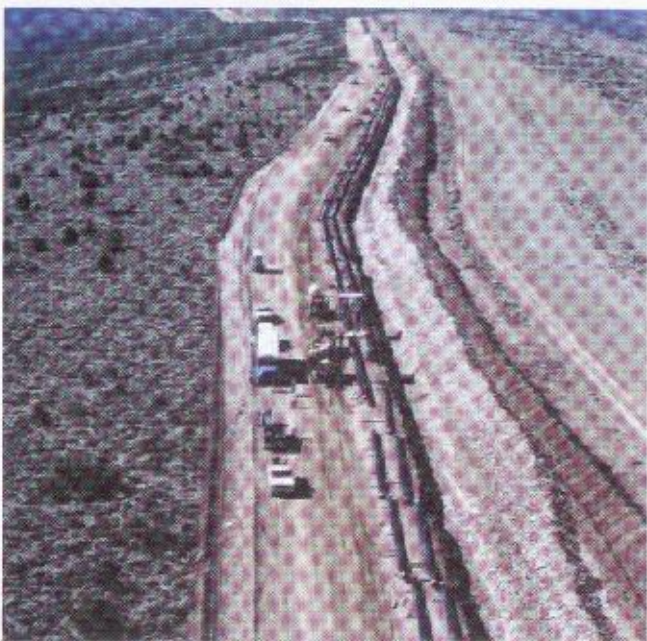


FIG. 11

Construction photo of the 71-km- (44-mile-) long pipeline connecting the upper and lower plants.



Cavern growth has been near what was projected. Caverns of more than 50-m- (160-ft-) equivalent diameter were developed as of January 2003. The equivalent diameter is calculated from the tons of nahcolite produced, the in-situ nahcolite grade and the height of the cavern, assuming that 80 percent of the nahcolite in the cavern is recovered and that the shape of the cavern is a right cylinder.

Production from each well has been variable, reflecting differing injection flow histories and local geologic variability. Some of the best producing wells in terms of production (tons per day) and product concentration were from the largest caverns. This suggests that these wells may be able to produce up to and beyond the 60-m- (200-ft-) diam design limit. Four production wells were drilled in late 2002 and additional wells were planned for 2003. Currently, 28 wells are in production. ■ (References are available from the authors.)

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This cause was dismissed after extensive pumping from each monitoring well did not result in significant improvement in water quality. Other possible causes included natural ground water upflow in the vicinity of the Piceance Creek; contamination from the Horse Draw shaft located upstream of the Yankee Gulch leases (Fig. 2); contamination from earlier off-site drilling, testing and underground injection (pilot testing completed by Prats et al., 1977); and, possibly, contamination is from old core holes drilled in the 1960s within the property — for example, the core hole Neilsen 20-1.

Subsidence above the solution mined caverns was a concern regarding the disturbance of the overlying aquifers, the disturbance of the minability of the oil shale resource and potential damage to the casings and tubulars in the injection/recovery wells. The cavern's size and spacing were designed to allow ample undisturbed material surrounding each cavern to form a seal for each cavern and to support the overlying strata. The roof of the cavern is at least 45 m (150 ft) below the Dissolution Surface. This crown pillar provides adequate protection against leakage from the cavern to the Dissolution Surface.

Surface subsidence is not expected with the approved mine plan. The cavern spacing results in a low areal extraction and the residual material in the cavern will stabilize the cavern walls. However, a subsidence monitoring plan was developed. This plan includes surface subsidence monitoring, cavern shape determination, subsurface monitoring using time domain reflectometry technology (Dowding et al. 1988) and geophysical logging to monitor the upward growth of the cavern.

Current status

The well field has operated for more than two years with production increasing each year. Startup difficulties associated with the plant and well field have been overcome and production in 2002 was about 70 percent plant design capacity at 544 kt (600,000 st) of soda ash equivalent.

FIG. 10

Yankee Gulch's lower plant near Parachute, CO.

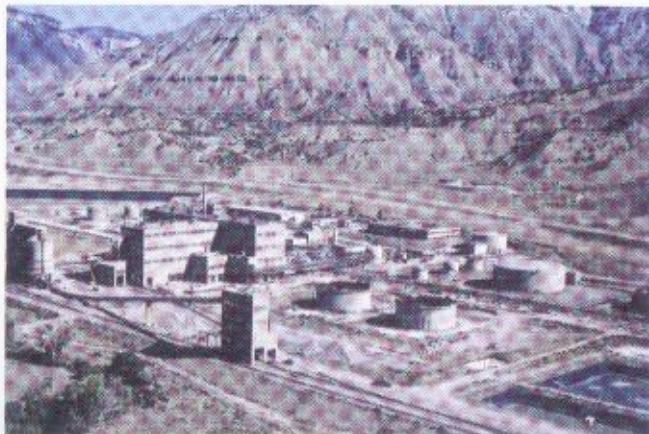
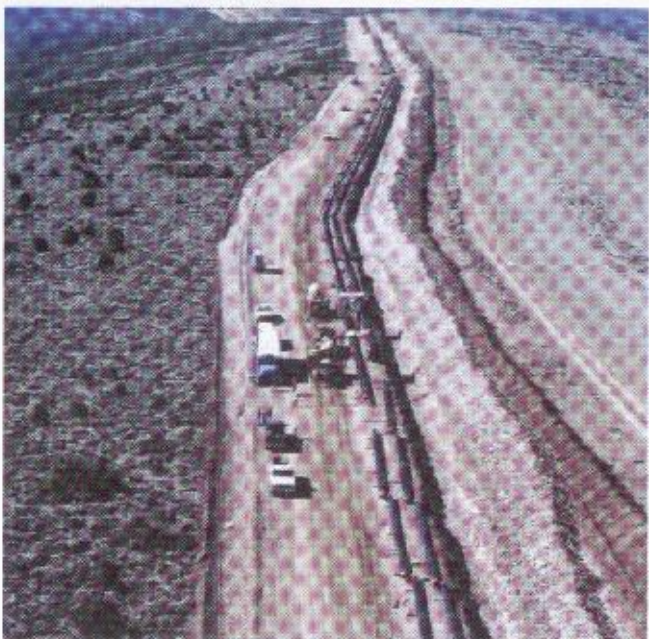


FIG. 11

Construction photo of the 71-km- (44-mile-) long pipeline connecting the upper and lower plants.



Cavern growth has been near what was projected. Caverns of more than 50-m- (160-ft-) equivalent diameter were developed as of January 2003. The equivalent diameter is calculated from the tons of nahcolite produced, the in-situ nahcolite grade and the height of the cavern, assuming that 80 percent of the nahcolite in the cavern is recovered and that the shape of the cavern is a right cylinder.

Production from each well has been variable, reflecting differing injection flow histories and local geologic variability. Some of the best producing wells in terms of production (tons per day) and product concentration were from the largest caverns. This suggests that these wells may be able to produce up to and beyond the 60-m- (200-ft-) diam design limit. Four production wells were drilled in late 2002 and additional wells were planned for 2003. Currently, 28 wells are in production. ■ (References are available from the authors.)