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Solution Salt Mining in New York, with Emphasis on Operational, Regulatory and Plugging Innovations in the Tully Valley Brine Field

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SOLUTION SALT MINING IN NEW YORK, WITH EMPHASIS ON OPERATIONAL, REGULATORY AND PLUGGING INNOVATIONS IN THE TULLY VALLEY BRINE FIELD

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ABSTRACT

Five solution mining facilities in New York produce over two billion gallons of saturated brine, or over 1.7 million short tons of salt, per year. Operators of these facilities had drilled 287 wells by the end of 1995. They use the techniques of hydrofracturing, horizontal drilling, and roof padding to develop stable caverns. When caverns become depleted, operators plug the wells in accordance with modern standards and regulations. They had plugged 165 of the 287 drilled wells by the end of 1995. Solution mining has not caused damaging or catastrophic subsidence at any of the five facilities currently active in New York, even though three of the five fields have been in operation since the late 1800's.

Other solution salt miners drilled 264 additional solution mining wells in New York between 1878 and 1985. The Tully Valley brine field in Onondaga County, started by Solvay Process Company in 1888, was the site of 162 of these wells. Solvay Process Company and its successors used techniques such as "simulated horizontal drilling," wild brining, and uncontrolled air padding to create interconnected multi-well caverns with large, unsupported roof spans. Sinkholes and widespread subsidence resulted. No well plugging program was in place until ordered by the State in the late 1980's. The age and condition of the wells in Tully Valley necessitated an innovative approach to well plugging, from both the regulatory and operational perspectives.

Between 1989 and 1995, AlliedSignal Corporation, Solvay Process Company's ultimate successor, plugged 167 wells in Tully Valley. This total includes 158 of the solution mining wells drilled in the valley, along with a hundred-year-old exploratory well, seven coreholes, and a well drilled but never used for fluid disposal. Four solution mining wells and another old exploratory well could not be plugged either because they could not be located or could not be safely accessed. Plugging contractors, company engineers, and an on-site State inspector developed plugging methods in the field as downhole conditions varied from well to well.

ACKNOWLEDGEMENT

The author is extremely grateful for the work of Joseph Yarosz, the on-site State inspector (environmental monitor) for the Tully Valley well plugging project. The sections of this paper on Tully Valley well plugging activities could not have been written without heavy reliance on his thorough and detailed 1994 and 1995 reports on all aspects of the plugging work.

INTRODUCTION

Bedded rock salt is found in the Vernon and Syracuse formations of the upper Silurian Salina group, at depths ranging from 500 to 4,000 feet, under an estimated 8,500-square-mile portion of New York (see Figure 1). Rickard (1969) correlated New York's salt beds to the strata mined in Ohio, Ontario, and Michigan. New York's salt resource has undergone continuous development through both solution mining and room and pillar mining for over 100 years. Today's methodical and efficient solution mining operations contrast sharply with the boom-like atmosphere of the state's salt industry in the late nineteenth century (Sanford, 1996a).

The largest solution mining field in New York was operated in Tully Valley, 20 miles south of Syracuse, from 1888 until 1988 by Solvay Process Company and its successors. During the century-long life of the field, 1.4 billion cubic feet of salt--enough to fill the Syracuse University Carrier Dome 35 times--were removed. Most activity in Tully Valley took place prior to the implementation in 1973 of legislative amendments that gave the state jurisdiction over solution mining wells. Upon abandonment of the Tully Valley brine field in 1988, none of the wells had been plugged in accordance with the state's 1973 legislation. The Division of Mineral Resources within the Department of Environmental Conservation undertook an enforcement initiative that resulted in the plugging of 167 wells between 1989 and 1995. Division staff worked with the operator, AlliedSignal Corporation, to develop special site-specific plugging guidelines that acknowledged the poor condition of old, inadequately cemented wellbores that had been extensively damaged by subsidence.

The Tully Valley is a U-shaped glacial valley with a north-south orientation, similar to the Finger Lake valleys further west. Bedrock formations, Devonian in age and older, generally dip to the south at about 50 to 80 feet per mile. Bedrock is exposed on the valley sides, while the valley itself is filled with up to 500 feet of unconsolidated sediments. Most wells were drilled along the sides of the valley. The Silurian Syracuse salts mined in Tully Valley are generally found between 900 and 1,200 feet beneath the surface. The Tully Valley mudboils, studied by Getchell (1983), Kappel, et al (1996) and others, are located one to one and a half miles north of the brine field. This report focuses on the brine field itself, not the mudboils.

CURRENT STATUS OF THE SOLUTION SALT MINING INDUSTRY IN NEW YORK

Five solution mining facilities, listed in Table 1, are currently active in New York. Wells have been plugged in recent years at two additional brine fields, listed in Table 2. All seven fields listed in the two tables are shown on Figure 1.

Akzo Nobel, Cargill and Morton all produce brine to supply on-site evaporation plants, while Texas Brine supplies brine via pipeline to two chemical manufacturing plants in Niagara Falls. These operators reported 2.1 billion gallons of brine withdrawals to the state's Division of Mineral Resources for 1995. Total annual withdrawal reported for these facilities has increased 25% since 1986 (Briggs, 1996).

Solution mining operators in New York currently use the modern cavern development techniques of hydrofracturing, horizontal drilling, and controlled roof padding summarized by Sanford (1996a). These operators also routinely exceed regulatory completion requirements by cementing all wellbore casing strings from the base of the casing to the surface, as well as exceeding plugging requirements by

Table 1. Status of solution salt mining in New York in 1995

Operator	County	Town	Plugged Wells	Unplugged Wells	Year Started
Akzo Nobel	Schuyler	Reading	51	20	1893 (Glen Salt Co.)
Cargill	Schuyler	Dix	12	9	1898 (Watkins Salt Co.)
Morton	Wyoming	Castile & Gainesville	23	16	1884 (Duncan Salt Co.)
Texas Brine	Wyoming	Middlebury (Dale field)	74	41	1970
Texas Brine	Wyoming	Middlebury (Wyoming Village field)	5	36	1984
		TOTAL	165	122	

Table 2. Recently plugged brine fields in New York

Operator	County	Town	Plugged Wells	Year Started	Final Production Year	Year Plugging Completed
AlliedSignal & LCP Chemicals	Onondaga	Tully	167	1888	1988	1995
International Salt	Tompkins	Lansing	20	1891	1962	1988

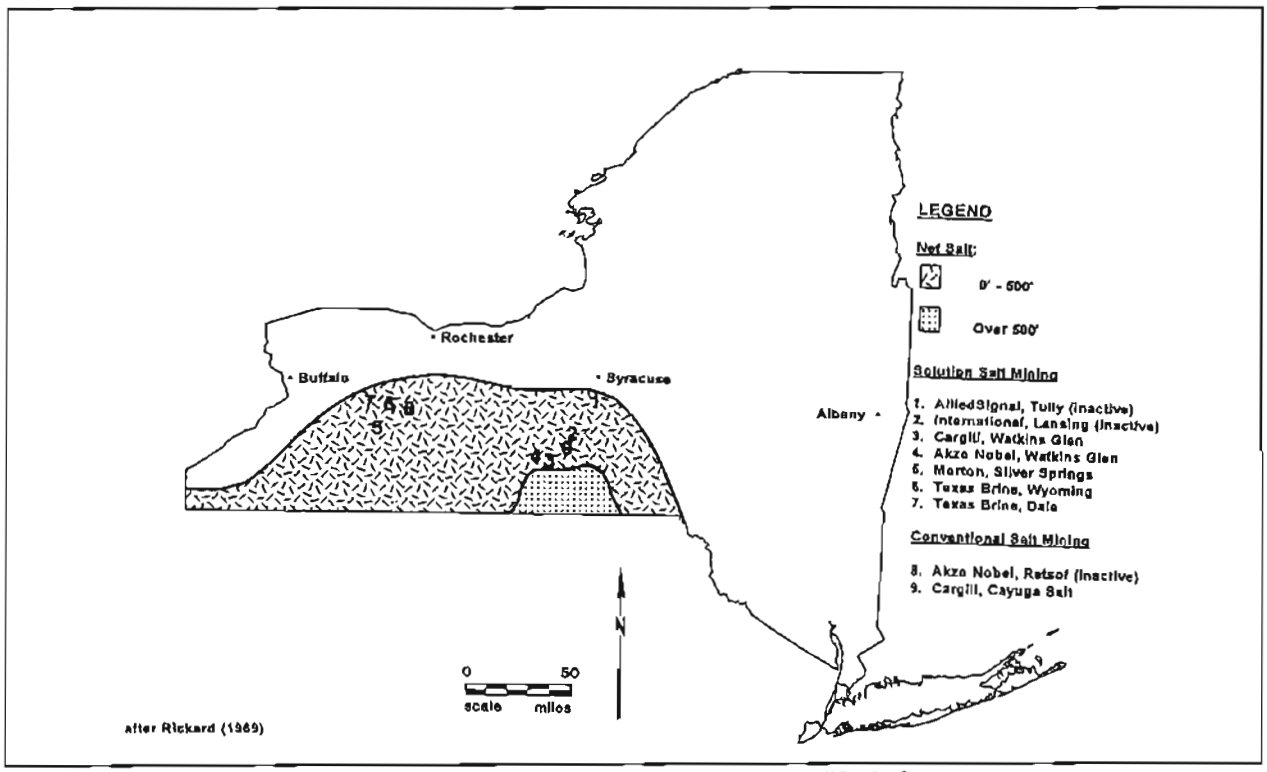


Figure 1. Silurian salt and mines in New York State

filling the entire wellbore above the solution zone with cement. No subsidence damage, sinkholes, or groundwater impacts are known to have been caused by salt extraction and cavern development at any of the five current facilities.

The United States Environmental Protection Agency (EPA) has primacy for implementing the Underground Injection Control (UIC) Program in New York, and has issued Class III UIC permits for all five active solution mining facilities in the state. At the state level, the Division of Mineral Resources within the Department of Environmental Conservation regulates solution mining wells under the Oil, Gas and Solution Mining provisions of the Environmental Conservation Law. Both Briggs (1996) and Sanford (1996b) describe the development of New York's solution salt mining regulatory program.

The EPA has also issued a Class III permit to Avoca Natural Gas Storage, Inc. for solution mining to create caverns for natural gas storage in Steuben County, New York. The ultimate disposition of the brine to be withdrawn during cavern development at this facility is unknown at this time. The project's operator has received an Underground Natural Gas Storage Permit from the state along with brine disposal well permits from both the state and the EPA.

Bath Petroleum Storage, Inc. has submitted an application to the EPA for a Class III UIC permit to solution caverns for liquefied petroleum gas (LPG) and natural gas storage at its existing LPG facility, also in Steuben County. This application is currently undergoing technical review.

The state has issued an Underground Natural Gas Storage Permit to New York State Electric and Gas for utilization of an existing cavern at Akzo Nobel's active solution mining facility in Watkins Glen.

EARLY HISTORY OF SOLUTION MINING IN NEW YORK

Commercial salt manufacture in New York began nearly a century before the first solution mining well was drilled. Many authors, including Luther (1896), Werner (1917), Eskew (1948), and Sanford (1996a), have discussed New York's inland salt manufacturing industry, which was located primarily in the vicinity of Syracuse and Onondaga Lake beginning in 1790. Inland salt manufacture in New York before 1878 was based on evaporation of brine from springs and shallow wells that withdrew brine from unconsolidated sediments or shallow rock formations stratigraphically hundreds of feet above the salt-bearing units. The state of New York controlled salt rights surrounding Onondaga Lake during this time. The state and several salt manufacturers drilled exploratory wells to attempt to locate the subsurface rock salt deposits beginning in 1820. The early search for rock salt, summarized by Sanford (1996a), was unsuccessful, and it was left to oil and gas prospectors to accidentally discover the salt resource.

The earliest well with a record of having encountered subsurface rock salt was drilled in Ontario County in 1865 (Phalen, 1919). In Wyoming County, Vacuum Oil Company in 1878 drilled the first well ultimately used for solution mining in New York; the well, known as the "Pioneer well" was initially operated for solution mining in 1881 by the Wyoming Valley Salt Company (Werner, 1917). The Pioneer well was only active for two years, but solution mining has taken place continuously in Wyoming County ever since that first well was placed into service. Texas Brine's modern Wyoming Village brine field is located near the site of the Pioneer well.

Near Syracuse, the Solvay Process Company began using brine as a raw material in its soda ash manufacturing plant in 1884 (Luther, 1896). The company drilled a series of exploratory wells south of Syracuse, ultimately discovering rock salt in Tully Valley in 1888 at a depth of 1,216 feet (Luther, 1896; Phalen, 1923). Thus began the hundred-year operational history of New York's largest solution mining field, with respect to both number of wells drilled and volume of salt withdrawn. Brine produced at Tully Valley was transported to the soda ash plant near Syracuse via a 20-mile long gravity pipeline.

The fifteen years following the drilling of the Pioneer well were hectic ones for New York's solution mining industry. By 1893, the year Werner (1917) declared the peak of the early solution mining industry in the state, 24 evaporation plants were in operation using 75 wells. Excluding Tully Valley, solution mining wells were located in Wyoming, Livingston, Genesee and Tompkins Counties in 1893 (Merrill, 1893). Brine fields were small, averaging about three wells each.

Werner (1917) states that after 1893, overproduction resulted in industry reorganization and consolidation. Many of the early plants were acquired and closed by the International Salt Company shortly after the turn of the century.

Table 3 summarizes all solution mining facilities known to have existed in New York since 1878.

Table 3. Solution salt mining in New York, 1878-1995

County	Number of active fields	Number of abandoned fields	Number of known solution mining wells drilled	Year first well drilled	Year last field abandoned
Genesee	0	2	11	1878	after 1917
Livingston	0	9	25	1883	after 1917
Onondaga	0	1	162	1888	1988
Ontario	0	1	1	1884	unknown
Schuyler	2	1	88	1893	--
Tompkins	0	3	27	1891	1962
Wyoming	3	24	237	1878	--
TOTAL	5	41	551		

Merrill (1893) and others describe the cavern development methods used at the small Wyoming and Livingston County brine fields during the first few years of New York's solution mining industry. Single well caverns were common, with fresh water introduced through the annulus and brine withdrawn by pumping through the tubing (see Figure 2). Where water-bearing formations were present above the salt, operators typically allowed water to flow from these formations down through the annulus to contact and dissolve salt. When a sufficient water source was not available downhole, operators pumped water from nearby creeks or springs down the annulus to force brine up through the tubing. When caverns at multi-well fields became interconnected, operators began using separate wells for injection and withdrawal. The Division of Mineral Resources is not aware of subsidence damage, sinkholes, or

groundwater impacts associated with any of the small solution mining facilities active in New York in the late nineteenth and early twentieth centuries.

TULLY VALLEY - A UNIQUE CASE HISTORY

In caverns created by the method illustrated in Figure 2, solutioning occurs preferentially at the top of the cavern and insolubles blanket the floor, reducing the surface area of salt available for solutioning (Pullen, 1973). At many of the earliest wells in Tully Valley, as solutioning proceeded away from the wellbore at the top of the cavern, the unsupported roof span would widen and eventually collapse. Wells would have to be shut down and repaired because of tubing damage caused by this caving. Repeated caving and costly workovers would ultimately lead to well abandonment (Trump, 1936). Because of the blanketing effect, salt at the cavern bottom would be wasted.

Figure 3 shows the typical configuration of early well completions in Tully Valley. Minimal or no cement was used, and tubing was suspended from the surface through a few hundred feet of open hole at the bottom of the wellbore. By 1893, Solvay Process Company had drilled over 50 wells in Tully Valley. Typical well spacing was 150 to 300 feet. The associated caverns coalesced very early in the field's history to form large multi-well galleries. Trump (1936) theorized that another means by which wells and caverns connected was by solutioning of salt mixed with the overlying shale.

Originally, the source of fresh water for solutioning in Tully Valley was a series of glacial lakes located south of and upslope from the brine field. Because the lakes were at a higher elevation than the wells, a hydrostatic head existed that was initially sufficient to force brine to the surface without pumping. This gravity-fed pipeline system, with fresh water flowing downhill from the lakes to the well field, and brine flowing downhill 20 miles from the well field to the soda ash plant, was the first of many innovative techniques associated with solution mining in Tully Valley.

Historical company engineering reports indicate that by 1900 it was becoming increasingly difficult to force brine to the surface using only the pressure differential between the lakes and the brine field, and air lift was initiated. Trump (1936) attributed the problem to the hypothesized uncontrolled solution channels through the overlying shales previously described. The historical company reports, however, impute the difficulty to escape of fluids from the interconnected cavern system into the surrounding rocks and sediments. These reports cite a 1926 study which showed that 40 to 60% of the injected water was lost to "underground leakage" (Larkin, 1950).

The cavern development methods discussed below were implemented with the apparent objective of maximizing well life and salt recovery, while minimizing the costs associated with workovers, air lifting, and the need for ever-increasing volumes of fresh water to maintain the desired output. Some of these innovations were successful in the short-term and, with respect to roof-padding, evolved into accepted standard industry practice. Unfortunately, long-term application of these techniques in Tully Valley resulted in widespread subsidence, sinkholes, and groundwater impacts.

Cavern Development Innovations

Roof padding.—Roof padding, the first modern technology implemented by the solution mining industry to control cavern shape, prevent waste of salt at the cavern bottom, and minimize caving during the active life of the well, was invented in Tully Valley by Edward N. Trump. This method involves

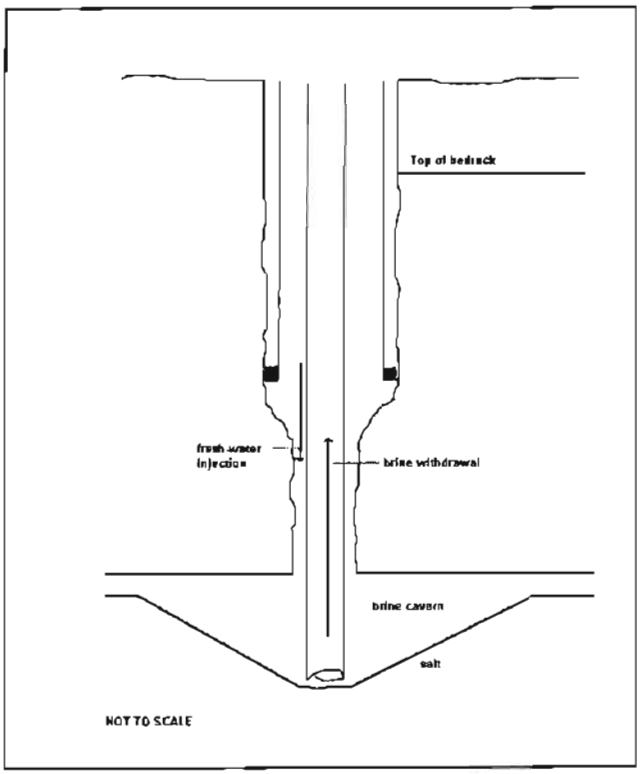


Figure 2. Typical 1890's single-well cavern

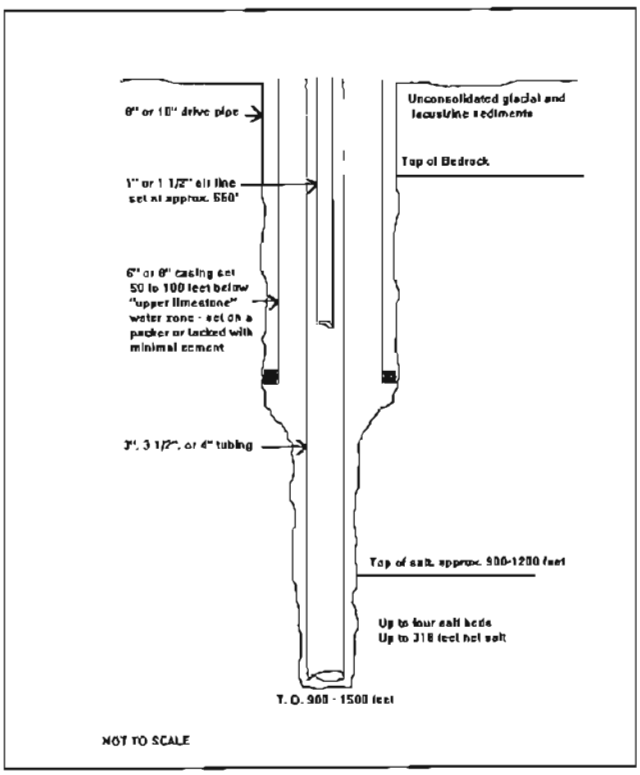


Figure 3. Typical early well completion in Tully Valley

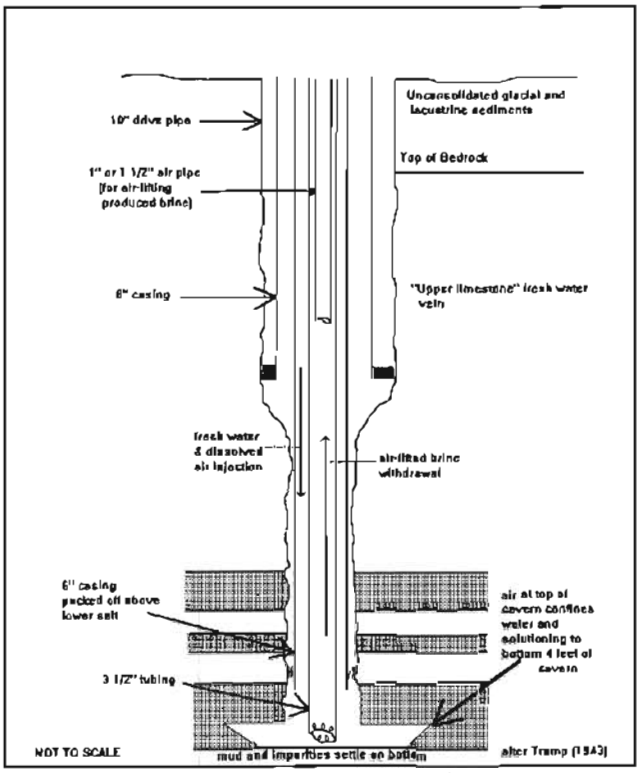


Figure 4. Tully Valley air-padding, 1929

injection of a fluid such as air or oil along with fresh water to form a cushion or pad at the top of the cavern. Solutioning is thus confined to a controlled height at the bottom of the cavern until a desired cavern diameter is attained. Thickness of the cushion is then reduced to allow upward solutioning and development of a cylindrical cavern. Close control of both height and diameter of the cavern enhances cavern stability.

In Tully Valley, roof padding using air as the cushion was first used in 1929 (see Figure 4). The goals were longer well life and greater ultimate salt recovery without repeated caving and workovers (Trump, 1936). The company did not adhere to Trump's well spacing recommendations (Trump, undated), however, and removal of larger volumes of salt from closely-spaced wells in pre-existing interconnected caverns further contributed to the creation of large, unsupported roof spans. Air-padding of wells without close control of the location and direction of solutioning eventually contributed to the formation of sinkholes.

"Wild brining."--Pullen (1973) referred to withdrawal of brine, without the use of injection, as "wild brining." Brine withdrawn via this method is created by solutioning of subsurface salt by naturally circulating groundwater. Because most solutioning occurs where fresh water initially contacts the salt, the location of solutioning is unknown and uncontrolled. The international solution mining industry recognized the subsidence hazard associated with these circumstances and most operators discontinued the practice by 1921 (Solvay Process Company [Brussels], 1921).

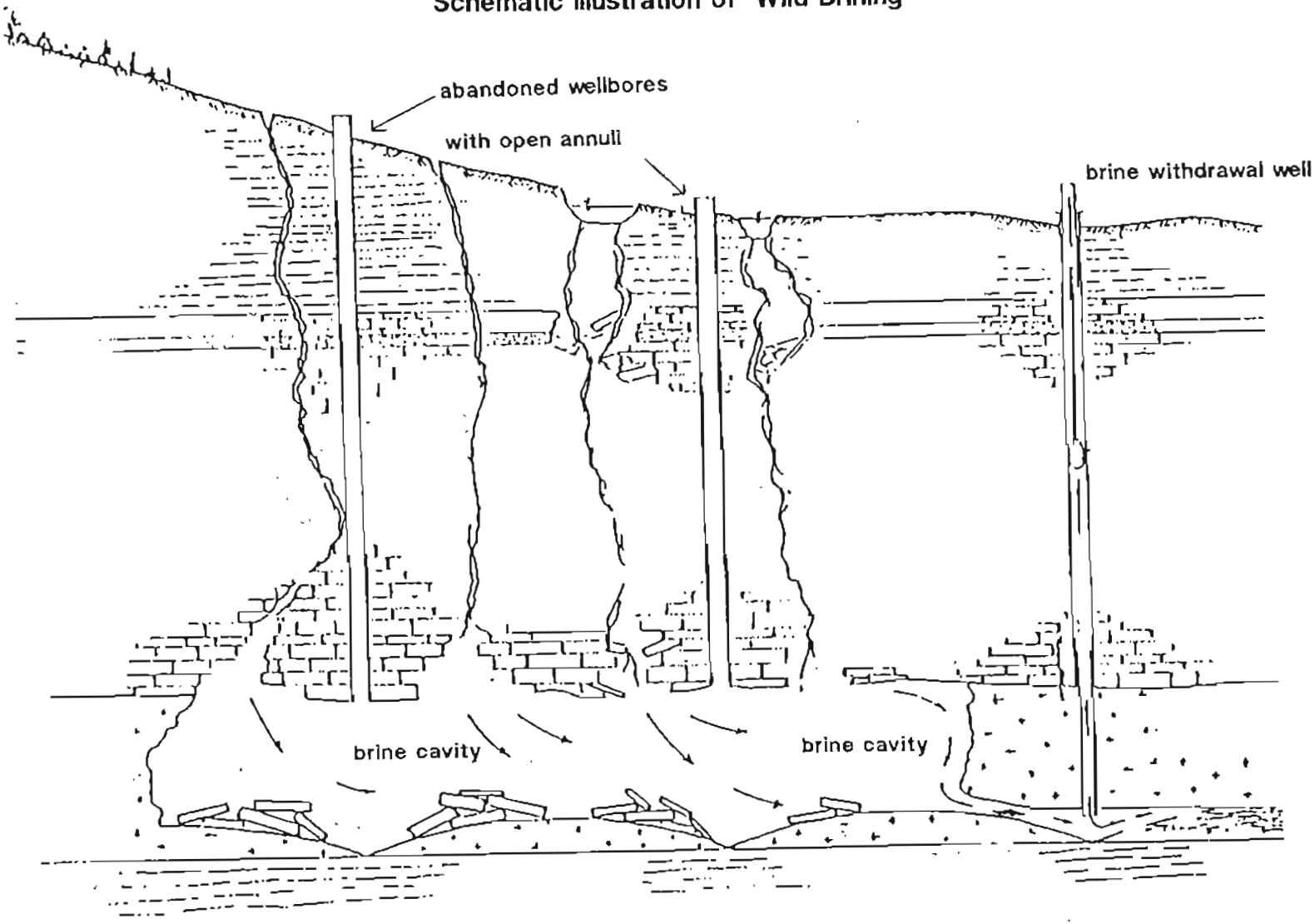
Despite the Solvay Brussels group's recommendation to the contrary, the first intentional use of wild brining in Tully Valley took place for a short time in 1926, according to Larkin (1950):

> In 1926, another study was made to find out if less water could be used to feed the wells as the amount required was 40 to 60% above the theoretical amount, due to underground losses.
>
> The amount of water fed to the various wells was decreased and as the elevation of the water table fell, it was necessary to lengthen the air pipes for the air lifts, and to increase the air pressure.
>
> The water was reduced to a point where less than the theoretical amount was used, *the balance coming from ground water*, but cost for power for compressed air increased to such an extent that after obtaining the data the old water levels were restored.

Well records indicate that, starting in about 1930, casings were removed from closely spaced wells in Tully Valley. This allowed aquifer water to flow down through wellbores and dissolve salt, initiating the process that led to long-term wild brining. As caverns grew, coalesced, and eventually collapsed due to inadequate roof support, the overlying strata became severely fractured. Groundwater recharge to the deep salt strata through these fractures and unplugged abandoned wellbores increased to the extent that by the late 1950's fresh water injection was no longer necessary for sufficient solutioning to occur (Tully, 1985). Circulating groundwater rather than injected fresh water was the cause of solutioning, with the points of fresh water entry to the salt cavern unknown and uncontrolled. The Tully Valley wild brining scenario is illustrated in Figure 5. From the late 1950's through 1986, approximately one billion gallons of brine per year were withdrawn with little or no injection and no control of the location or extent of solutioning.

Figure 5

Schematic Illustration of "Wild Brining"



Modified from Tully (1985). Brine cavity is recharged by water entry through open wellbores and annuli as well as fractures associated with subsidence features.

Absence of injection, the activity regulated by the federal UIC program, is the reason the EPA did not require a Class III permit for Tully Valley in the mid-1980's.

"Simulated horizontal drilling."--The modern technique of horizontal drilling for salt cavern development was first used in New York in 1989, and three operators have used this method to date. However, Solvay Process Company attempted an experimental cavern development method in the late 1920's that can be likened to "simulated horizontal drilling."

Historical company engineering reports describe an investigation conducted in 1926 into the feasibility of sinking a shaft to the base of salt and mining an 800-foot long tunnel along the bottom salt bed. Fresh water would then be introduced through the shaft, with brine withdrawn from a well drilled to intercept the other end of the tunnel (see Figure 6). The proposal for a conventionally mined shaft and tunnel was ultimately rejected because of the high projected cost and because of uncertainty about the regularity of the base of the salt (Shaffer, 1984).

The company in 1927 and 1928 drilled 12 closely spaced wells to the lower salt in an attempt to simulate the tunnel proposal. The plan was to operate the wells as single-well caverns until they connected to form a horizontal channel in the lower salt (see Figure 7). Once the channel formed, fresh water would be injected downdip and brine withdrawn updip. However, this experiment included no mechanism (such as roof padding) to leave salt in the channel roof; frequent caving was the result. Low production capacity and the cost of repeated workovers associated with the caving eventually led to abandonment of this well group, but not before creation of a broad, flat cavity with an inadequately supported roof (Larkin, 1950; Solvay Process Division, 1960).

The group of wells used for the tunnel simulation was also the first group of wells where aquifer waters were intentionally allowed to flood the salt cavern through uncased wellbores in the early 1930's. Thus began wild brining, as previously discussed.

Impacts of Solution Mining in Tully Valley

Use of the three innovative cavern development methods described above all contributed to significant general ground subsidence, sinkholes, and groundwater impacts. The company's historical reports indicate that water or brine of unknown saturation was escaping the system of interconnected wells and caverns by 1900. Shearing of wells by rock movements associated with subsidence was recognized as early as 1928 (Solvay Process Division, 1960). Seven sinkholes formed between 1949 and 1980. The company reportedly repaired a county highway damaged by subsidence in the mid-1960's. Tully (1985) documented increased groundwater recharge through subsidence-induced fractures. Although the results have been inconclusive, many researchers have investigated the possibility of a cause-and-effect relationship between brine field operations and the unique mudboil phenomenon north of the brine field (Kappel, et al, 1996).

It is important to understand that the known and hypothesized impacts of solution mining in Tully Valley are not attributable to the mere act of salt extraction itself, but to the uncontrolled methods by which such a vast quantity of salt was removed. The estimated extraction ratio of 64% to 75% (Shaffer, 1984) is much greater than the 10% to 15% ratio estimated for modern solution mining operations in New York. Because the point of solutioning was usually unknown, expansive unsupported roof spans were created. Hydrologic impacts of solution mining in Tully Valley have resulted from the introduction

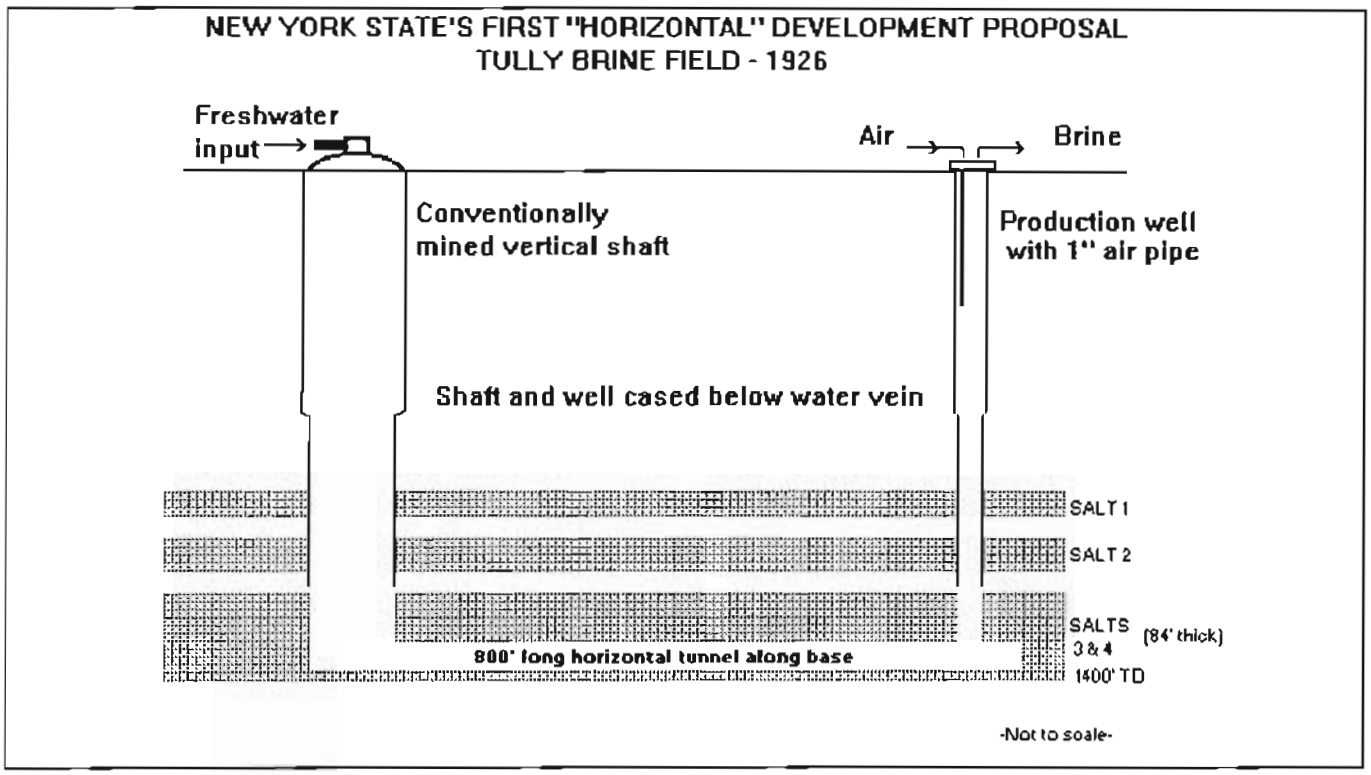


Figure 6. Tully Valley tunnel proposal, 1926

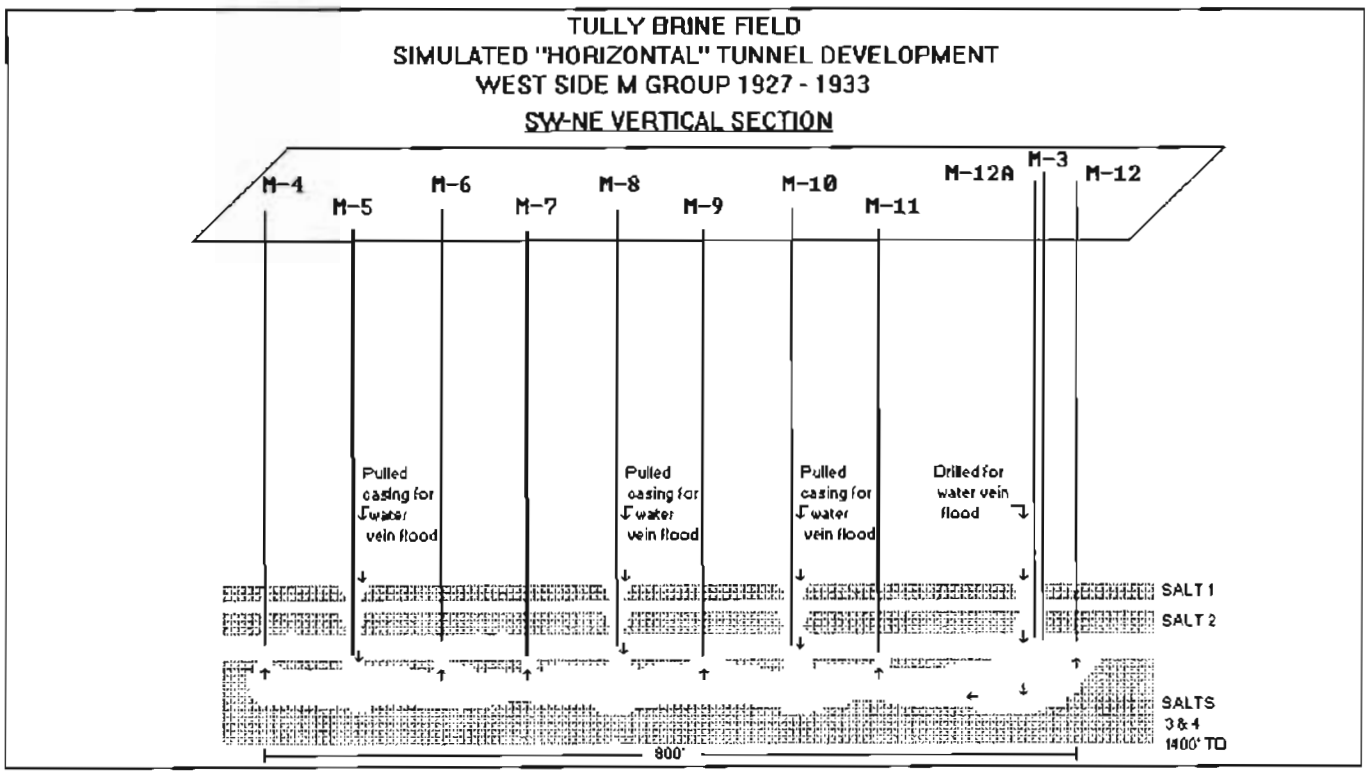


Figure 7. Simulated tunnel development in Tully Valley, 1927 - 1933

of water and increased water pressure to the groundwater system, initially through uncemented and inadequately cased wellbores.

Well Plugging

Solvay Process Company's ultimate successor, AlliedSignal Corporation, announced the closure of the soda ash plant and the sale of four of the brine wells to another operator, LCP Chemicals, in 1986. Although the legislative amendments passed in 1973 require plugging of all solution mining wells, the company proposed to plug only 20 and abandon the remainder. The Division of Mineral Resources rejected this proposal, and AlliedSignal ultimately plugged all 167 wells that could be found and safely accessed, including the four that had been sold to LCP and abandoned in 1986. The wells plugged ranged in age from 10 to 100 years old. The Tully Valley well plugging project transformed AlliedSignal's Solvay staff from a group with no solution mining well plugging experience to the team with the most experience in plugging solution mining wells in New York, particularly old wells.

The goals of well plugging in Tully Valley were to:

1) eliminate the wells as potential conduits for groundwater mixing and aquifer contamination,
2) stabilize the brine caverns with respect to water entry from the surface and/or shallow aquifers, and
3) reduce the potential for future significant subsidence and sinkhole formation by reducing or eliminating uncontrolled solutioning of soluble formations caused by water entry via open wellbores.

Regulatory Innovations.--Plugging of the first 31 wells between 1989 and 1991 revealed the difficulty of plugging in an area that had been so extensively damaged by subsidence and fracturing. The following problems were common:

1) severe lost circulation zones, particularly in the limestone formations found 100 to 500 feet above the salt caverns,
2) extremely corroded or crushed and bent well casings, increasing the difficulty of cleaning out wellbores and/or removing pipe from the hole,
3) sheared well casings, causing cleanout tools in the hole to exit the wellbore and begin drilling rock, and
4) junk, rock, and other debris in the wellbores.

Because of the difficulties encountered during plugging the first 31 wells, along with disagreement between Division of Mineral Resources staff and the company's consultants regarding the effectiveness of plugging, AlliedSignal initially declined to plug the remaining wells. Of major concern to the company was the unpredictable and possibly open-ended nature of the plugging work. The company was reluctant to commit to an unlimited agreement to plug all wells from just above the cavern to the surface. The Division, however, was unwilling to grant a blanket variance to standard solution mining well plugging requirements. Experience with the first 31 wells indicated that the amount of subsidence at any given well was not a reliable predictor of plugging difficulty. This conclusion supported the Division's position that waiver of any requirements must be site-specific, based on actual conditions encountered when the rig was over the hole.

After lengthy negotiations, the Division and AlliedSignal agreed in 1993 to a definition of the work that would constitute a "reasonable effort" to clean out and plug each well as deeply as possible. The agreement was crafted based on the practical experience of technical and field staff in the Division with an intimate working knowledge of field conditions and previous plugging efforts in Tully Valley. Once this agreement was secured and guidelines developed, AlliedSignal committed to plugging the remaining wells.

Under terms of the agreement, the objective at each well was to clean the wellbore out to the salt cavern, remove all uncemented casing and tubing, set a mechanical bridge plug just above the salt cavern, and fill the wellbore with cement. Guidelines for implementing the agreement recognized that subsidence-related field conditions, combined with the age of many of the wells, could preclude attainment of this goal. A "reasonable effort" to plug each well to the deepest attainable depth was defined as 32 hours of "progress-yielding" downhole time. Thirty-two hours was neither a maximum nor minimum required effort, but an evaluation point for assessing downhole progress and determining whether additional work would result in any measurable advancement toward the stated goal. "Progress-yielding" work for the 32-hour calculation included:

1) working down the hole,
2) cutting and pulling casing,
3) milling obstacles,
4) cutting/fishing tubing,
5) tripping associated with progress-yielding work, and
6) running into or out of the hole with:
   - logging tools to estimate downhole conditions,
   - impression blocks, or
   - mills to condition or dress pipe or hole.

Activities not considered "progress-yielding" downhole time included:

1) rigging up/rigging down,
2) fishing to recover lost tools,
3) logging,
4) perforating,
5) cementing,
6) plugging,
7) activities after reaching the deepest attainable depth,
8) conditioning trip to prepare for cementing,
9) making up tools and equipment on the surface,
10) running a cement basket or bridge plug, and
11) tripping associated with excluded work.

The 32-hour time frame was based on prior Tully Valley plugging experience, which showed that four days was generally adequate to clean a wellbore out to the 1,000- to 1,400-foot deep salt cavern when site-specific downhole conditions were such that this could be reasonably accomplished.

The agreement specified that where the Division and AlliedSignal concurred that downhole conditions precluded reaching the salt cavern, the goal was to plug to the deepest attainable depth, but a minimum of 25 feet below the top of bedrock. This objective assured protection of the unconsolidated glacial aquifers that overlie bedrock, and could only be waived in the case of extenuating circumstances if it became apparent that no further progress could be made.

Provisions for departures from the 32-hour time frame and/or the minimum plugging depth were included in the agreement and were only invoked when well-specific circumstances or conditions rendered further work towards the objectives futile or unreasonable. The most common situation where departures were granted occurred in severe subsidence areas where wellbores were sheared by horizontal earth movement associated with subsidence so that the portion of the wellbore below the shear zone had been completely displaced and could not be located.

Another innovative regulatory approach was use of an on-site State inspector, or environmental monitor, paid for by AlliedSignal. The monitor was present in the field full-time for all 136 well pluggings that took place between 1993 and 1995. The Division and AlliedSignal concur that there were many advantages of an on-site State inspector for this project, including the following:

1) The monitor was empowered with on-site decision-making authority on behalf of the Division, saving the company rig and equipment standby costs.

2) The monitor provided on-site one-stop-shopping for all Division of Mineral Resources permits required for the project, increasing scheduling flexibility and further reducing equipment downtime charges.

3) The monitor was experienced in well plugging techniques and regulatory requirements, and therefore provided technical recommendations to the company on well plugging equipment, procedures, and materials, resulting in significant cost savings without sacrificing environmental protection.

4) Pro-active project management involving constant and open communication among Division of Mineral Resources central (Albany) office staff, regional (Avon) office staff, the on-site inspector, and AlliedSignal resulted in project completion, ahead of schedule and within budget, without invoking formal dispute resolution procedures established in the well plugging agreement.

The monitor's continuous presence on the site was especially beneficial to the company because no other State well inspector was based within two hours driving time of the brine field.

Special plugging problems and innovative solutions.--"The task of well plugging in Tully Valley is extremely complicated. Every well is different. Unexpected developments are everyday occurrences" (Yarosz, 1994). Yarosz (1994) further summarized plugging experience in Tully Valley as follows:

> Much of the plugging procedure which has been applied in Tully has involved adaptation of conventional methods. Common practice has not been sufficient to deal with some of the problems which have been encountered. The problems include: a lack of reliable well records, inability to maintain circulation with liquids, the age and resultant

condition of the wells and numerous other, less general topics. When these are combined with the problems associated with subsidence, plugging becomes an always variable and often formidable task.

Following is the baseline plugging procedure:

1) Clean out the wellbore. Field crews occasionally encountered wells with no pipe in the hole, and cleanout consisted of simply circulating debris out of the hole. More often, holes contained one or several strings of uncemented casing and tubing. Tubing ranged in diameter from 1-1/2 inches to 6-5/8 inches. Efforts to pull all tubing from the surface were rarely, if ever, successful, and fishing with a variety of tools was usually required. Factors that hampered tubing removal included: shears, doglegs, squashed or bowed pipe, adhesion of one string of pipe to another, severe pipe corrosion, lack of centralization, and the condition of stubs at depth. In wells without tubing, factors that most commonly limited downhole progress were casing damage, lack of circulation, and junk in the hole. Even in wells without casing, progress could be inhibited by crumbling of formations and sticking of tools (Yarosz, 1994). Based on downhole conditions, a bottom-hole cement or mechanical bridge plug might be set above the salt cavern or at the deepest attainable depth after fishing tubing and otherwise cleaning out the wellbore.

2) Logging. After cleanout, to assist with decision-making regarding casing recovery methods and cementing, the following logs would be run:

Gamma ray	-to identify formations and to provide a basis for correlation
Caliper	-to verify well construction, locate casing damage and provide measurements for computing cement volumes
Collar locator	-to locate casing, casing collars and casing damage
Cement bond log	-to identify cemented pipe, and in wells with uncemented casing, to explore the potential for casing recovery by providing some indication of debris in the annular space (Yarosz, 1994)

Logging was partially or entirely omitted on wells where sufficient information was available from other sources or where downhole conditions rendered the work for which a log or logs were needed impracticable. In later stages of the project, logs were not run when cuttings were purely shale and tools behaved as if drilling solid rock in well groups where shearing was known to be likely (Yarosz, 1995).

3) Casing removal/perforating. After cleaning out the wellbore, including open hole below the deepest casing, as near to the top of the salt cavity as possible and perhaps setting a plug, the goal would be to remove all uncemented pipe. The length of free or recoverable pipe would be estimated from the bond log and a decision would be made regarding the next step. The standard procedure, if downhole conditions allowed, would be to perforate and squeeze cement behind pipe to be left in the hole, if any, and then to either cut the pipe or bust a collar at the depth from which casing would be removed. Factors that commonly limited casing removal were similar to those described above which affected removal of tubing. Once all recoverable casing was removed, a bottom-hole cement or

mechanical bridge plug might be set if not already present and if downhole conditions so warranted.

4) Cementing. The objective at each well was to first place cement through perforations to seal any existing annular spaces and to then fill the remaining wellbore. The most desirable result was to restore formation isolation by placing an open-hole cement plug from just above the cavity to the surface. Attainment of this goal was usually precluded by the problems with cleanout and casing removal previously described. The major complication with respect to placement of cement was the presence of severe lost circulation zones, which in some cases could "take as much cement as is pumped to them" (Yarosz, 1994). When attempting to cement through perforations, uncertainty existed with respect to the distribution of cement through multiple sets of perforations as well as the effectiveness and likelihood of actually sealing the annulus.

The above discussion reveals the difficulties that were frequently encountered at each step of the way through a relatively simple baseline procedure. Deviation from this procedure was often necessary in order to achieve the best possible plug in each well without excessive efforts beyond the 32-hour time frame. As stated by Yarosz (1995), "[t]he variety and severity of the problems with the wells prevented the establishment of a comfortable routine in plugging. Completely new and different situations continued to occur. Project personnel were required to remain flexible."

Creative solutions to the following problems were attempted in the field, with varying degrees of success, and are briefly described in the subsequent paragraphs:

1) Shallow cleanouts, where obstructions prohibited downhole progress beyond several hundred feet above the objective depth.
2) Sheared wellbores, where horizontal movement displaced most of the wellbore so that it could not be directly accessed from casing above the shear zone.
3) Caving after casing removal, eliminating downhole progress that had been made before the casing was removed.
4) Lost circulation resulting in excessive quantities of lost cement.
5) Slanted casings in severe subsidence areas.

Shallow cleanouts: squeeze cementing and "assembly-line" plugging.--On many of the oldest wells, hole problems at depths of 150 to 300 feet frequently precluded cleaning out the wellbore beyond these shallow depths. A squeeze cementing technique was developed which, by the project's second year, had evolved into an "assembly-line" procedure.

Squeeze cementing below the cleanout depth involved two steps following the initial cleanout. The first step was setting a packer or a makeshift packer composed of a modified cement basket run on tubing. The packer and tubing would be cemented in place at or above the cleanout depth by placing grout in the annulus. After the cement was allowed to set, the second step would be the actual squeeze through the tubing, at pressures under 250 psi. Although the path and destination of squeezed cement could not be determined with certainty, many wells plugged in this manner took at least enough cement to fill the calculated wellbore volume below the cleanout depth. Questions remained, however, about whether this method resulted in a plug superior to that which would be achieved by merely filling the wellbore with cement (Yarosz, 1994).

"Assembly-line" plugging consisted of using a large service rig to consecutively clean out and remove casing from several wells. Once several wells were ready for logging and cementing, a smaller hydraulic rig would perform that work. Yarosz (1995) cites the following advantages and disadvantages of the "assembly-line" approach:

Advantages:

1) The rig used for cleanout and casing removal could be quickly moved off the well after performing its part of the work, rather than remaining on-site until logging and cementing services were completed. With one "assembly-line" in progress, expenses associated with waiting time were significantly reduced.

2) Efficiency and cost-effectiveness of service company visits were increased with up to five wells logged and cemented at a time.

Disadvantages:

1) With one set of two rigs at work, supervision by company personnel and the State inspector was manageable. However, when multiple "assembly-lines" were in progress, with up to four rigs at work on eight wells in a single day, effective supervision of concurrent activities became difficult or impossible.

2) Because of the unpredictable nature of the work, sequencing of operations and scheduling of equipment and service crews to avoid excessive standby time were difficult when more than one "assembly-line" was in progress.

3) Use of the "assembly-line" approach lengthened the time between casing removal and cementing, thereby increasing the chances of wellbore caving. Loss of progress resulting from these circumstances had a particularly onerous and costly impact on one well that had been cleaned out relatively deep. Subsequent attempts to reclaim progress resulted in the loss of an entire downhole tool assembly, the bottom-hole plug, and 5-1/2 days. Because of the potential for this type of occurrence, the on-site inspector recommends use of the "assembly-line" procedure only for shallow cleanouts.

Sheared wellbores: "shoot-back-into-and-squeeze" method.--As previously mentioned, subsidence affected some wells in the brine field by displacing wellbores so that the lower portion could not be accessed from the surface. Condition of the displaced wellbore could not be determined. The shear zone was usually in shale, often less than 25 feet into bedrock. An experimental method for placing cement into the displaced lower wellbore was attempted at several of these wells.

Yarosz (1994) described the manifestation of wellbore shearing: "It may be oversimplistic to contend that the wells were actually chopped in half, perhaps repeatedly, but the effect on downhole work is as though that is the case. . . . Evidence provided by means of the appearance of the downhole ends of recovered casing pieces does suggest that some of the wells were in fact completely sheared."

Not surprisingly, the greatest concentration of apparently sheared wells occurred in close proximity to sinkholes and in the group of wells used in the tunnel simulation discussed previously.

Once it was evident that cleanout tools had left the well and were drilling new hole, the crew would replace the cleanout tools with a drilling bit and drill another 40 to 100 feet to verify that the original wellbore had, in fact, been exited and would not likely be reentered by continued drilling. The 40- to 100-foot "rat hole" thus created would be logged with a collar locator log. In some cases, the collar log would detect metal, and field personnel would conclude that the original wellbore was adjacent to the rat hole. Carrier perforating guns, with deeper shot penetration capability, would be combined in 60-degree phasing and lowered into the rat hole. The objective was to perforate into the original wellbore from the outside and establish a pathway. After perforating, a retrievable packer or cement basket with tubing would be set and the rat hole would be squeeze cemented. Results were mixed, with wells taking variable amounts of cement. Some wells accepted far more than the calculated volume of the original wellbore below the shear zone. It was impossible to control or determine the distribution of cement outside the rat hole; prospective results with this technique range from successful sealing of the original wellbore to loss of all cement into lost circulation zones.

The "shoot-back-into-and-squeeze" method was discontinued after attempted on a few wells because of inability to evaluate the uncertain results and because efforts to cement displaced wellbores were not required by the plugging agreement between the Division and AlliedSignal. Subsequent sheared wells were plugged, after cleaning out and drilling of a 40-foot rat hole, by the "assembly-line" squeezing method detailed above.

Lost progress caused by caving: partial plugs before casing removal.--Removal of uncemented casing is essential to assuring the best seal, but carries the inherent risk of allowing exposed formations or annular debris to cave into the wellbore. Such caving could prevent reentry to the previously achieved cleanout depth.

Surface casing would be left in the well to prevent caving before downhole work (cleaning to deepest attainable depth) was completed. Pulling the surface casing immediately after cleanout would incur the risk of losing the hole and having to repeat the cleanout step. The alternative procedure was to place cement in the bottom portion of the hole before pulling the upper casing.

The following paragraphs describe the advantages and disadvantages of setting a partial plug before pulling casing.

Advantages

1) The presence of surface casing in the wellbore facilitates successful reentry to depth with cementing tools.

2) Pipe between lost circulation zones and the wellbore prevents loss of cement when the bottom-hole plug is set.

3) The step of cleaning the well to the deepest attainable depth is only performed once, decreasing rig time and expense.

Disadvantage 1) Setting a partial plug before casing removal and then a final plug after casing removal necessitates two visits by the cementing company for one well, increasing service company costs. This was particularly bothersome for AlliedSignal when it was sometimes found that, for various reasons, significant lengths of surface casing could not be pulled and the well had to be cemented through perforations. In these cases, the period of time between the two cement company visits did not yield any progress toward plugging objectives.

Severe lost circulation: stage cementing and bridging techniques.--Lost circulation was a constant problem, whether cementing an open hole or through perforations. Successful circulation was very rarely achieved on the first attempt, and wells were very rarely cemented from total depth to surface in a single stage. Hundreds of sacks of cement could disappear through a single set of perforations. Even with lost circulation materials mixed into the cement, casing fill-up was often less than half of what it should have been based on the quantity pumped (Yarosz, 1994).

As field personnel gained experience with the lost circulation problems in Tully Valley, emphasis of the cementing process shifted to the use bridging materials in conjunction with stage cementing in order to reduce the quantity of cement needed to fill wellbores to the surface (Yarosz, 1994). Cementing in increasingly smaller stages as the project progressed allowed crews to identify problem zones with less waste of cement (Yarosz, 1995). In addition, cementing engineers adopted the practice of ceasing to pump when it became apparent that fill-up was not occurring. Once a lost circulation zone was identified, cement placed below the zone would be allowed to set. Pea gravel would then be dumped from the surface to fill the wellbore to a level across the perforations or open hole interval identified as the problem. Six cementing stages and over 1,000 sacks of cement were necessary for some wells (Yarosz, 1994).

Slanted casings: excavation, angled entry, reduced tool size and drill string rigidity.--Wellbore deviations from vertical were visible at the surface at eight wells. Four wells were estimated to be slanted more than 20 degrees. Yarosz (1995) describes the following methods used to attempt to gain downhole access in slanted wells. Success using either of these methods was very limited.

1) Excavation — This method involved excavating around the tilted casing to either locate the hole at the bedrock interface and reset the pipe vertically, or to bend the pipe back to vertical with a bulldozer and backfill around it. In one case, the conductor pipe simply fell over as bedrock was approached and further excavation failed to locate the wellbore.

2) Working at an angle — Attempts to enter angled wells were made both with a tilted rig and a hydraulic power swivel. The power swivel was preferred because of safety concerns with the tilted rig. At angles approaching 20 degrees, however, connections were difficult and progress was slow as the swivel banged into the rig or hung away at an unworkable angle (Yarosz, 1995).

Severe downhole bends were occasionally visible from the surface. The challenge at these wells was to get milling or other cleanout tools past the bend without penetrating the casing and leaving the wellbore. If this could not be accomplished, and the bend was otherwise impassable, tool size and length would be reduced in a final attempt to attain greater depth of access for perforating tools and cement tubing. At least one well was perforated and cemented below the original cleanout depth using this technique (Yarosz, 1995).

Other noteworthy events.--Yarosz (1994, 1995) reports a number of additional noteworthy occurrences during the Tully Valley plugging project. Some of these are briefly described in the following paragraphs.

Foreign substances in wells.--As stated by Yarosz (1995), "[i]t is a commonly held suspicion that open wellbores, particularly those in rural, isolated locations, provide attractive ways for those so inclined to cheaply dispose of liquid waste." Significant quantities of contaminates were encountered in only two of the 167 wells plugged in Tully Valley. Those contaminates were creosote and diesel oil.

The creosote was found inside casing, beneath a wooden plug at about 285 feet in a well that had been drilled in 1956 and abandoned in 1957. The dark greenish, intensely odorous liquid was circulated out of the well and stored in three lined pits on location until removed by vacuum trucks and properly disposed. Sludge that remained once the liquid was pumped from the pits was consolidated with cement on-site and then also removed for proper disposal.

The diesel oil was also encountered inside casing, above 300 feet, in a well that had been drilled in 1962 and abandoned in 1964. An estimated 500 gallons of oil were circulated out of the well and removed from the site for proper disposal. A vacuum truck later removed 3,200 gallons of oil-contaminated water from the lined pit.

Other substances found in very minor quantities included oil from ruptured submersible pumps that had been abandoned downhole, and a foaming agent suspected to be a nitrate compound formed by decaying wood in the well. Analyses of the pump oil showed it to contain non-hazardous quantities of PCB's. The foaming agent was found only at one well.

Locating a century-old exploratory well.--Historic records had described an exploratory well drilled by Solvay Process Company in 1888, prior to the discovery of rock salt in the valley. Based on the old reports, including Luther (1896), it was believed that the well had been drilled to 400 feet in unconsolidated sediments and that no pipe had been placed in the hole. An unsuccessful attempt was made to locate the well using a metal detector in the late 1980's or early 1990's. Although the state had relieved AlliedSignal of any responsibility to locate and plug the well, known as the "Solvay Road well," the company did so anyway in 1995, using a recently discovered nineteenth-century field notebook to pinpoint the well location. There was no surface expression of the well at the surveyed location, but a metal detector scan yielded positive readings. Eight-inch casing was found at a depth of 13 feet, and the well was open to 279 feet. After ascertaining that there would be no negative impact on a residential water well located 100 feet away, AlliedSignal filled the well with cement.

Plugging success and benefits.--Eighty percent of the wells plugged in Tully Valley are plugged at least 25 feet below bedrock. Twenty-five percent are plugged to the top of the salt cavern. All 167 wells which could be located and safely accessed are plugged at the surface. The benefits are listed below.

1) The safety hazard of unplugged wells at the surface has been completely removed.

2) One hundred sixty-seven potential sites for dumping of liquid waste have been eliminated.

3) Depending on the plugged depth of each well, the potential for aquifer contamination caused by mixing of groundwaters in open wellbores has been either greatly reduced or eliminated at every unsheared well plugged below bedrock. Success in sealing the displaced portion of sheared wells is uncertain.

4) The possibility of surface water entry to the brine caverns or other soluble formations via open wellbores has been eliminated, and access to the cavern or other soluble formations through wellbores from shallow aquifers has been greatly reduced.

For the period of time during which such statistics were tracked (1993-1995), successful plugging to the top of the salt cavern required an average of 18 hours of progress-yielding work, as described above. This result demonstrates the adequacy of the 32-hour time frame for defining a reasonable effort to realize the plugging goal in wells where conditions were such that plugging to the cavern was likely to be achieved.

SUMMARY

The various unique aspects of solution mining and its aftermath in Tully Valley combine to tell an interesting and educational story. Operations in Tully Valley commenced concurrently with the nineteenth-century salt boom in western New York, and continued for many decades after most of the early evaporation plants closed down. The high demand for brine to supply Solvay's soda ash plant motivated the implementation of several inventive but untested techniques to maximize salt recovery. One of these methods, roof padding, evolved into standard industry practice and is successfully executed at modern facilities to control cavern size and shape and create stable caverns. Unfortunately, the grand scale and uncontrolled nature of salt extraction using the roof padding, wild brining, and "simulated horizontal drilling" techniques in Tully Valley resulted in significant and damaging subsidence, sinkholes, and groundwater impacts.

Equally interesting and educational is the story of well plugging in Tully Valley. Myriad challenges were presented by the number, age, and condition of the wells and the effects of subsidence. Success at meeting the challenges required dedication, imagination and flexibility on the part of the operator, contractors and regulators. All involved parties agree that the environmental objectives of well plugging were achieved to the maximum extent practicable.

Many lessons can be learned by examining the history of the Tully Valley brine field, from startup through plugging of the last well. With respect to well construction, timely plugging, and controlled cavern development, today's solution miners demonstrate mastery of these lessons. Nevertheless, vigilant attention to all matters related to design and development of stable caverns and to timely plugging of depleted wells is necessary on the part of both industry and regulators to successfully prevent unforeseen recurrence elsewhere of problems and impacts similar to those seen in Tully Valley.

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