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Technical Class Paper

The Ups and Downs of Post-Closure Subsidence Monitoring at the Tully Valley Brine Field, New York

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ABSTRACT

The Solvay Process Company's solution mining operations in Tully Valley, located approximately 18 miles south of Syracuse, New York, commenced in 1888, flourished for one hundred years and resulted in the drilling of 167 wells. Allied Chemical Company and its successor, AlliedSignal, continued operations started by The Solvay Process Company and produced more than one billion gallons of brine annually for the half-century ending in 1986. In 1988, all of the abandoned wells were ordered plugged at the direction of the New York State Department of Environmental Conservation's ("NYSDEC") Division of Mineral Resources.

A formal subsidence monitoring program for the brine field was instituted by Allied Chemical Company in 1959 and continued until1991. A post-closure subsidence monitoring program, required by the State in conjunction with the well plugging agreement, started in 1993. Results to date have been both unexpected and interesting. Questions persist as to the validity and value of the post-closure monitoring data, requiring a retrospective analysis of the short and long-term objectives and methods of post-closure subsidence monitoring at the Tully Valley brine field.

ACKNOWLEDGMENT

The authors are grateful to D. W. Hannig, the licensed professional surveyor who has performed all the post-closure subsidence surveys since 1993. Mr. Hannig assisted us not only by providing survey line locations and electronic data, but also by patiently explaining the surveying and data verification methods used in Tully Valley.

INTRODUCTION

Near Syracuse, New York, 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history of New York's largest solution mining field, with respect to both number of wells drilled and volume of salt withdrawn.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.

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 New York 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. See Figure 1 for location and distribution of wells within the Tully Valley brine field.

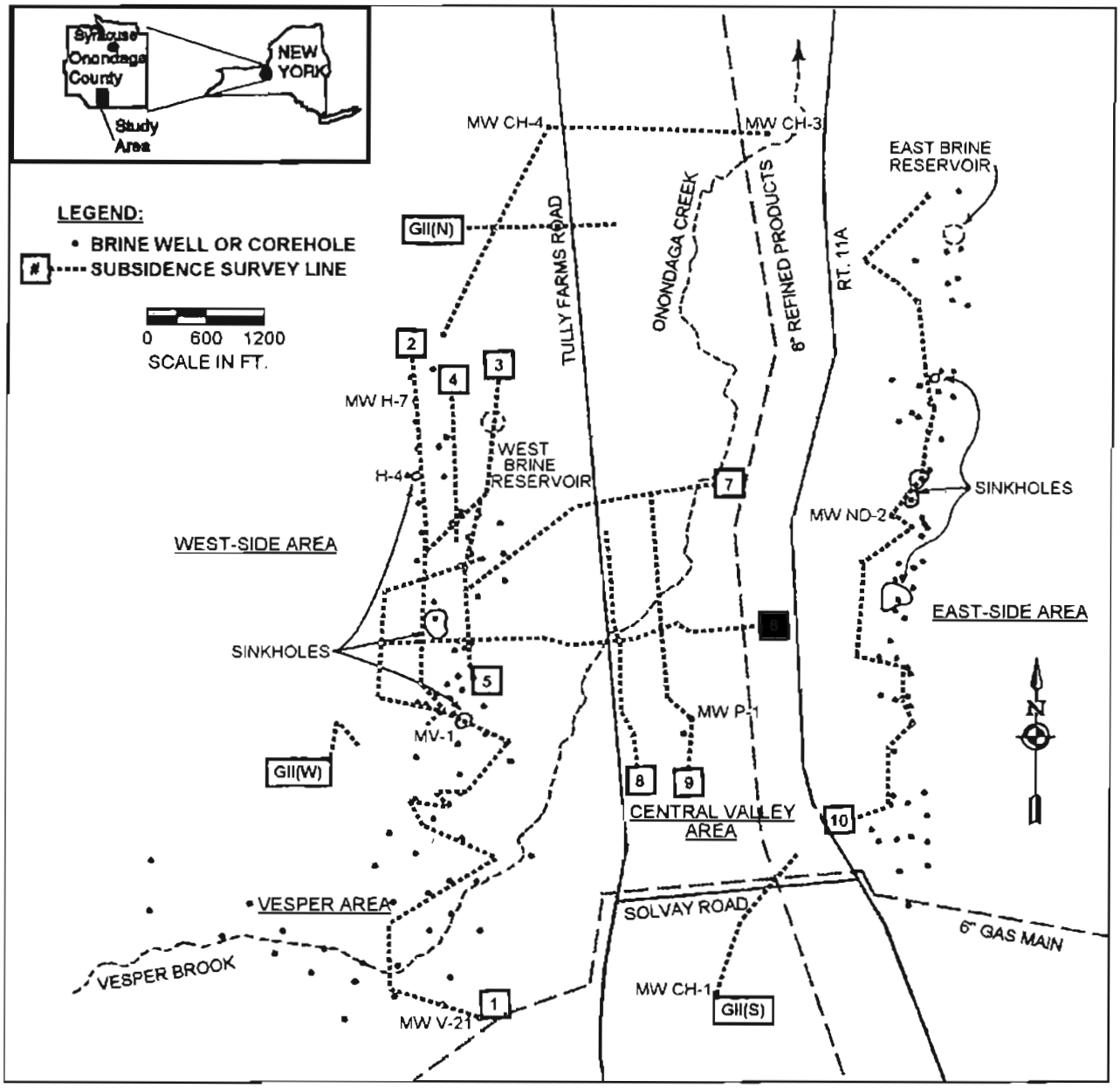

Figure 1. Tully Valley Brine Field - Well & subsidence survey line locations (Adapted from Walker et al. 1993).

Division staff worked with the owner of the brine field, AlliedSignal Inc. (The Solvay Process Company's ultimate successor), 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 enforcement initiative or "1993 Well Plugging Agreement" also included provisions for post-closure subsidence monitoring of the Tully Valley brine field with specific thresholds for increasing, reducing and discontinuing the subsidence monitoring frequency. This report presents subsidence monitoring methodology and results to date, and explores possible options and next steps for further analysis of existing data and continued surveillance of the Tully Valley brine field.

GEOLOGIC SETTING

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. The focus of this report is on subsidence within the brine field itself, not subsidence occurring in the vicinity of the mudboils which was observed as part of a field trip to the Tully Valley brine field during SMRI's 1993 Spring Technical Meeting in Syracuse.

IMPACTS OF SOLUTION MINING

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) at Tully Valley is much greater than the ratio estimated for modern solution mining operations. Because the point of solutioning was usually unknown at the Tully Valley brine field, expansive unsupported roof spans were created. Hydrologic impacts of solution mining in Tully Valley have resulted from the introduction of water and increased water pressure to the groundwater system, initially through uncemented and inadequately cased wellbores. In stark contrast, wells at today's solution mining fields are fully cased and cemented with multiple strings of casing thus preventing fluid movement behind pipe.

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. Dr. 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).

BRINE FIELD OPERATING HISTORY

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. Unfortunately, the grand scale and uncontrolled nature of salt extraction at Tully Valley using the roof padding, wild brining, and "simulated horizontal drilling" techniques, all discussed below, resulted in significant and damaging subsidence, sinkholes, and groundwater impacts. Other less innovative operating practices that also contributed to subsidence and sinkhole formation were infill drilling and overproduction at individual wells. Overall, Tully Valley brine field development over its one-hundred-year history is best characterized as exploited resource recovery with little regard to surface and subsurface impacts.

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 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 in Sanford, 1996). 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.

The air cushion production technique enabled wells to produce for longer periods of time and helped maximize salt production. Problems and collapse occurred when areas developed by the air cushion technique were later infill drilled. When air injection ceased at a particular well, the air cushion protecting the salt cavern roof dissipated over time, and the salt roof supporting the laterally extensive cavern was removed by exposure to undersaturated brines. AlliedSignal continued to use the air cushion technique during initial well development until it ceased solution mining in 1986. Despite the problems experienced at Tully Valley, roof padding has evolved into standard industry practice and is successfully executed at modern facilities to control cavern size and shape and create stable caverns.

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 hence, "wild brining" could also be referred to as "blind brining." 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 (Larkin, 1950).

Well records indicate that, starting in about 1930, casings were removed from closely spaced wells in the brine field. 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 Sanford (1996). 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. In effect, AlliedSignal's "blind brining" production technique greatly limited its ability to control subsidence in the brine field.

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 in Sanford, 1996). 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. 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.

SUBSIDENCE AND SINKHOLE FORMATION

Individual well cavern diameters exceeding 500 feet are common in many areas of the Tully Valley brine field. Large-span caverns coalesced with smaller caverns to form combined spans of over one thousand feet (Ackenheil & Associates, 1983). Frequent roof cave-ins caused operating problems at wells in the early development years at the Tully brine field. The cave-ins collapsed the casing and/or lower tubing in the brine wells and frequently shut off production at new wells in less than a year. Infill drilling in structurally weakened areas contributed to brine field subsidence. Many of the brine wells on both sides of the valley were drilled as infill wells or with very close well spacing. Brine wells with well spacings of less than 150 feet were common in both the East-side and West-side areas of the brine field. This brine well spacing allowed development caverns to join one another quickly to facilitate saturated brine production, but in turn removed the supporting pillars between wells.

In addition to the sinkholes discussed below, CS/H&A (1992) and Walker et al. (1993) described 5 to 30 feet of general subsidence over the brine field. In making this determination and contour plot (see Figure 2) of total surface settlement from commencement of operations in 1888 through 1991, CS/H&A and Walker et al. relied on:

> *...a detailed review of the mining operations records, records of original ground elevations at each well, the settlement survey data, 1988 photogrammetric mapping of the Allied property, and several sets of stereo aerial photographs pairs from the years 1936, 1938, 1959, 1967, 1972, 1988, and 1991.*

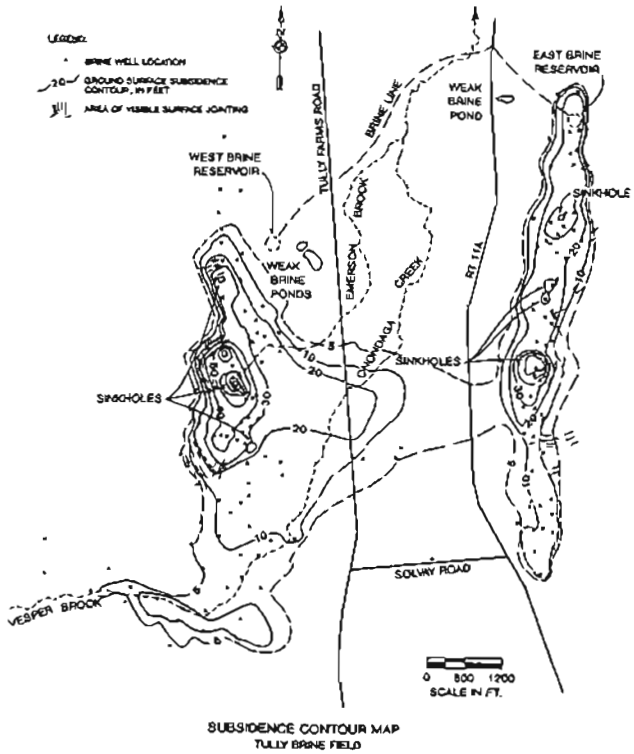

Figure 2. Total settlement 1888-1991 (Walker et al. 1993).

East-side Sinkholes

NYSDEC records and aerial photographs of the Tully Valley brine field show that four major sinkholes developed in the East-side area between 1949 and 1954 (see Figure 2). Shaffer (1984) described the 1949 sinkhole event:

> *In January 1949, without any previous warning, the ground just north of the "D-Group" of wells and opposite the "S-3 and S-4" undercut wells suddenly began to settle down in the shape of an inverted cone and in less than an hour, it had cut off three brine collecting lines, the 12" high pressure water line and the brine wells road. The electrical power line was also downed when one pole dropped into the hole. In a matter of a few hours, the "sink hole" was 200' in diameter and soundings that day or two later indicated that the ground had dropped about 60' for the entire diameter.*

The other East-side area sinkholes have diameters up to 300 feet and current depths of 25 to 50 feet, but some may have been partially sediment filled and thus initial depths may have been greater. All of the

East-side area sinkholes were filled with impounded surface water, and in some cases artesian discharges from brine wells, resulting in small to fairly large sized ponds. The ponds are fed by precipitation and surface runoff from the steep valley slope. Impounded waters in the sinkholes are thought to allow greater infiltration into the subsurface aquifers through the fracture system associated with sinkhole formation. Prior to the extensive subsurface and surface disruption in this area, the percentage of precipitation runoff was greater. Subsidence-induced fractures and sinkholes have increased recharge to both the surficial valley sediments and the subsurface bedrock aquifers (Tully, 1985).

West-side Sinkholes

In the West-side brine field area between the years 1962 and 1980, three major sinkholes (see Figure 2) formed that also impounded precipitation, intercepted surface runoff, and fed the fracture network in this area (Tully, 1985). Tully (1985) reported that the two sinkholes that formed in the southern section of the West-side area measured 150 feet and 900 feet in diameter and were both approximately 50 feet deep. Dr. Tully did not report the dimensions of the third sinkhole which formed in the northern end of the West-side area at brine well No. H-4 but it is estimated that this sinkhole was 100 feet in diameter and 50 feet deep. Reportedly, the H-4 sinkhole formed while the brine field crew was out of the area on a lunch break, without any warning signs; fortunately no personnel were injured. The dramatic and damaging effects of this catastrophic event to the brine field infrastructure and subsurface are clearly seen in Figures 3 and 4 which are photographs taken in 1980 and 1986 of the H-4 sinkhole area. The 1980 photograph shows an access road intersected by the sinkhole (top of photograph) and extensive surface fractures. On the left side of the photograph taken during the winter of 1986, the broken brine line can be seen sticking up out of the sinkhole. The brine line has subsequently been removed from the sinkhole and the sinkhole "reclaimed" in 1995 using soil fill from adjacent land to eliminate it as a public safety hazard (see photograph labeled Figure 5).

Figure 3. H-4 sinkhole and surface fractures(1980).

Figure 4. H-4 "snow-filled" sinkhole (1986).

Figure 5. H-4 "reclaimed" sinkhole (1995).

PRE-1993 SUBSIDENCE MONITORING PROGRAM

A formal program for monitoring the changes in surface elevations throughout the brine field was not initiated until 1959, seventy years after mining started. The subsidence monitoring program which began in 1959 consisted of surveying the initial elevations of approximately 120 newly installed driven monuments located primarily in the East-side and West-side areas. Only a limited number of subsidence monitoring monuments were installed in the Vesper well area, making it difficult to determine the extent and magnitude of subsidence in that area. However, subsidence in the Vesper area is thought to be minimal because of greater well spacing (Tully, 1985). Initial coverage of the Central Valley area was also limited.

Post-1959 additions to the pre-closure monitoring program included 55 monuments added in the Central Valley area in 1965 after subsidence reportedly hindered a school bus traveling on a county road traversing the brine field, and 20 new monuments incorporated with 21 existing monuments in 1980 into a "Close Watch" series as a result of the previously described catastrophic collapse at well H-4 in the West-side North area. Monuments in the "Close Watch" series were spaced much closer together than monuments in the other sections of the brine field and provided more information and detail on subsidence activity in the area. In addition, AlliedSignal resurveyed the "Close Watch" monuments every six months from 1980 through 1984 and measured horizontal distance changes between monuments as well as elevation changes.

A total of 195 subsidence monitoring stations were installed between 1959 and 1980 with surveys performed by an independent surveyor every one to two years. None of the monuments were surveyed during the time period between 1984 and 1988. Most were resurveyed in 1988 and/or 1989, with the last pre-closure survey conducted in the brine field taking place in 1991. All pre-closure surveys consisted solely of shallow (i.e., non-bedrock) monuments.

Subsequent to brine field shutdown in the late 1980's, Fernandez (1992) reported on Tully Valley brine field subsidence and concluded:

> *. . . the data collected in all monuments systematically shows an almost complete arrest of the ground movements once solution mining was discontinued in the field. Only small ground movements with a progressively decreasing rate have been detected in the most recent surveys after solution mining was ceased. These movements are most likely generated by slow consolidation of the debris pile below, and are expected to continue to decrease with time.*

Using the same pre-1993 data analyzed by Fernandez in 1992, Walker et al. (1993) also described production-related subsidence followed by little or no significant settlement following cessation of brining operations. Walker et al. (1993) predicted a leveling off of the rate of subsidence using the graphical presentation reproduced as Figure 6 and concluded that "current and future settlement rates are expected to range from a few inches to 'nil' " per year.

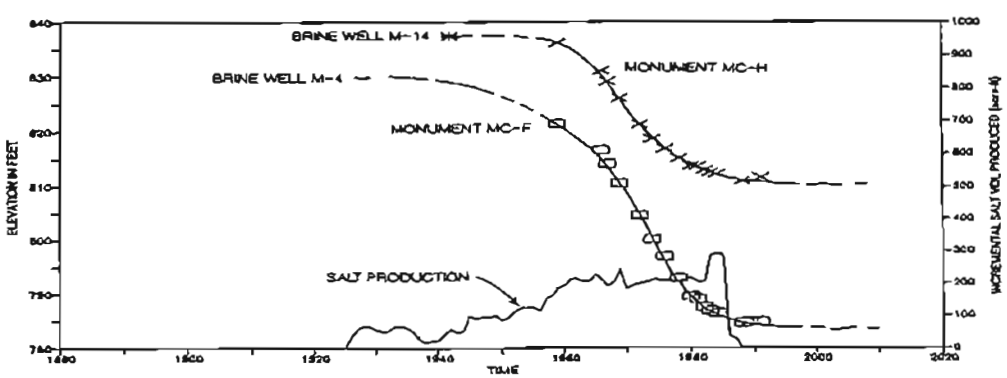

Figure 6. Typical subsidence (Walker et al., 1993).

1993 WELL PLUGGING AGREEMENT

Well Closure

The objective of the well closure program under NYSDEC's 1993 Well Plugging Agreement with AlliedSignal was to plug each of the remaining 135 unplugged wells and cement each back to one foot below the ground surface (or four feet in areas where farming was likely to take place in the future). An attempt was to be made to plug as deep as was practicable, with a minimum plugging requirement of 25 feet below the top of rock. To the extent that it could be accomplished with a reasonable effort, wells were to be cleaned out to the top of the salt cavity. A quantity of cement equivalent to 150% of the borehole volume from the surface to the clean-out depth was to be placed in the hole after casing had been ripped, perforated, or otherwise deemed "open" (breached or penetrated). Over 30,000 total sacks of cement were used to plug the wells under the 1993 Well Plugging Agreement. Well plugging operations were completed in 1995.

In summary, the goals of State-required 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.

Well plugging operations were complicated by the presence of subsidence and sinkhole features which disrupted downhole well conditions and presented difficulty in the surface siting of drilling rigs used to plug the wells. In a few cases, wells were completely inaccessible because they were located either at the bottom of water-filled sinkholes or at the edge of water-filled or dry sinkholes. Plugging was excused in areas which posed an equipment and personnel safety hazard and instead a payment was made to the State's well plugging fund. Some interested parties outside of the NYSDEC expressed concerns regarding the utility and value of plugging accessible wells adjacent to areas of subsidence-related fracturing between the surface and the salt. Division of Mineral Resources staff believed an attempt to plug all accessible wells as deeply as possible was warranted. Figure 7 is a photograph showing plugging operations on Well No. MV-1 adjacent to a sinkhole in the West-side well area.

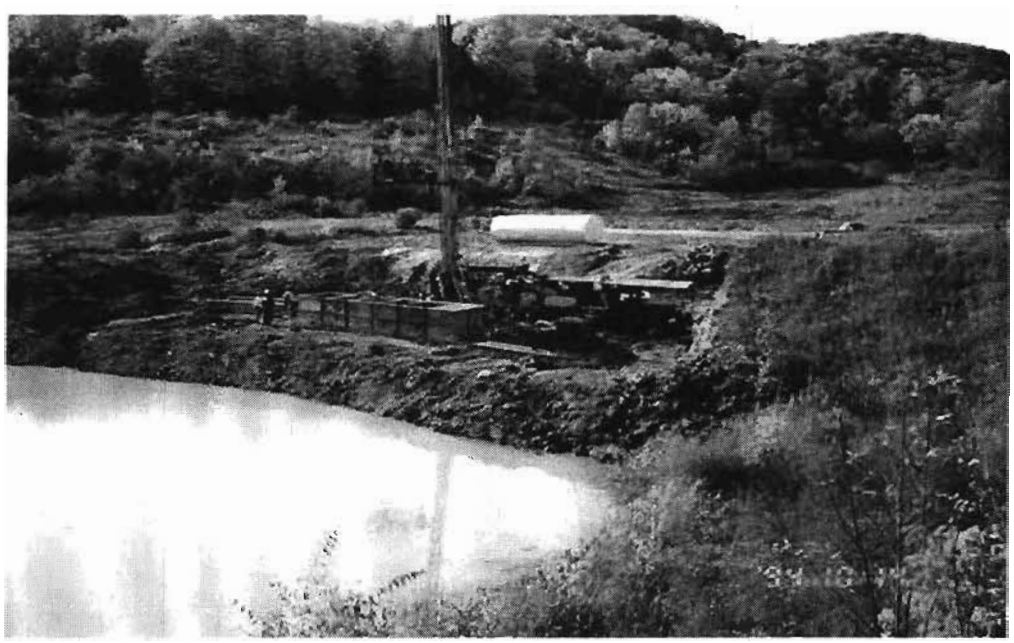

Figure 7. MV-1 well plugging next to water-filled West-side sinkhole (1994).

Subsidence Monitoring

The design of the post-closure subsidence monitoring program was based on pre-plugging subsidence measurements, brine field production records and projected brine field subsidence, and took into consideration the recommendations of AlliedSignal consultant Gabriel G. Fernandez. Dr. Fernandez's 1992 study of the Tully Valley concluded: 1) the potential for sinkhole formation in the area ceased to exist once solution mining was discontinued; 2) future surveying frequency should be dependent upon magnitude and rate of detected subsidence; and 3) installation of bedrock monuments may be beneficial. NYSDEC concurred with these conclusions.

The post-closure subsidence monitoring program required by NYSDEC and incorporated into the 1993 Well Plugging Agreement is shown in its entirety in Appendix 1 and consists of 141 total monuments. Figure 1 shows the location of survey lines noted in Appendix 1 which are currently used to detect and monitor subsidence in the brine field. The individual lines shown in Figure 1 actually consist of numerous "mini" loops. Adequate closure within surveying tolerances for the first "mini" loop must exist before surveying can progress to the second "mini" loop, and so on, for each line. This process is repeated until elevations are determined for all monuments on a line, thereby preventing errors from being carried and compounded further along the line. To eliminate potential seasonal effects on surveying, a plugged well cemented into bedrock from each well group was converted to a monument, incorporated into a survey line and included in subsequent monitoring. A total of 21 plugged brine wells and coreholes throughout the brine field and surrounding areas were ultimately converted to monuments between 1992 and 1995 and included in yearly surveys. Figure 8 shows AlliedSignal's surface construction specifications for plugged-well monument conversion. In addition to plugged bedrock wells incorporated into the program, numerous survey lines intersect one another which provides repetitive measurement and survey adjustment of individual monuments. Wong (1982) recommends the use of bedrock monuments to reflect the actual movement of rock layers, and redundant measurements to increase the precision of the leveling and to provide field and office checks on the precision of the survey.

At this time, the post-closure subsidence monitoring program at the Tully Valley brine field conforms with most, but not all, of the recommendations contained in SMRI's Research Project Report No. 81-0003A-SMRI entitled "A Manual On Ground Surveys For The Detection And Measurement Of Subsidence Related To Solution Mining" (Wong, 1982). See Table 1. In particular, statistical analysis of the survey data was neither contemplated nor required under the State's 1993 Well Plugging Agreement with AlliedSignal. The need for statistical analysis is not believed to be crucial at this time, based on measured subsidence of inches per year, absence of salt extraction, and the improbability of additional sinkholes forming in the brine field.

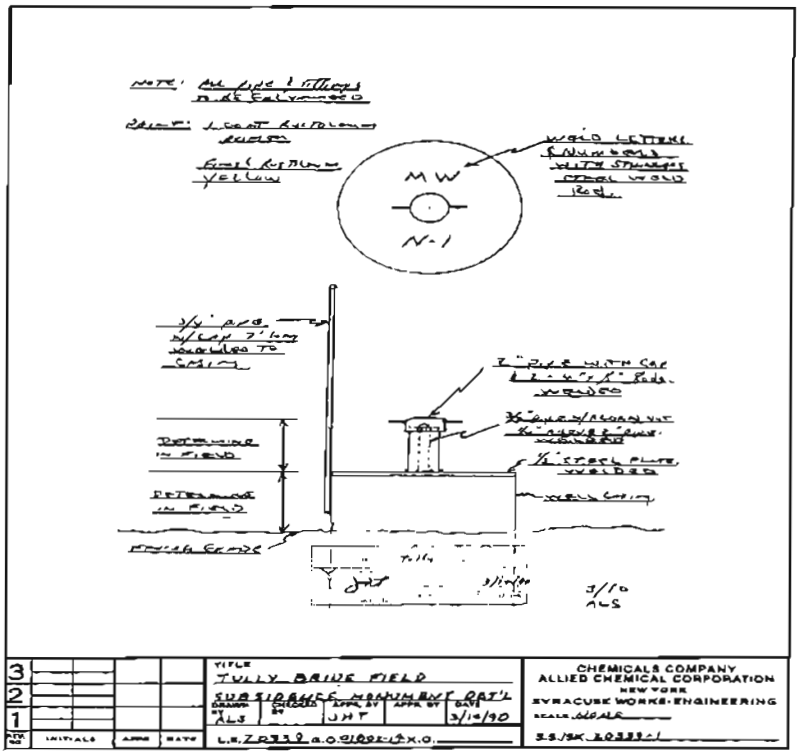

Figure 8. Well conversion specifications.

Table 1. Subsidence monitoring program considerations.

Subsidence Monitoring Program Considerations & Procedures	SMRI Research Project Report No. 81-0003A-SMRI Recommendations	Tully Valley Post-Closure Monitoring Program	
Monument Construction	Constructed to Reflect Rock Movement	✔	Plugged Wells Incorporated
Benchmarks	Use of Government Benchmark, Minimum of 2 to 3 Bed-Depths from Cavity	✔	Distant (4 Bed-Depths) USGS Benchmark & Additional Confirmation Run to 2nd Remote USGS Benchmark
Initial Survey Accuracy (elevation)	Second-Order (Class I)	-	Primarily Second-Order (Class II), Some Third-Order
Initial Survey Accuracy (horizontal control)	Third-Order (Class III)	-	Not Performed
Survey Run	Survey Performed in Loops, Otherwise Forward & Backward	✔	Lines Run Forward & Backward
Redundant Measurements	Monument Measurement Verification	✔	Numerous Monuments on More than One Survey Line
Subsequent Survey Accuracy (elevation)	Second-Order (Class II)	✔	Primarily Second-Order (Class II), Some Third-Order
Subsequent Survey Frequency (elevation)	Dependent Upon Subsidence Rate, Salt Extraction & Need for Early Detection	✔	Subsidence Rate Dependent, Production Ceased in 1988
Survey Analysis	Statistical Analysis	-	Not Yet Performed
Graphical Plots	Plots Showing Elevation Changes	✔	Graphs Prepared
Contour Maps	Illustrate Subsidence Rate and Areal Extent	-	Not Yet Performed

POST-CLOSURE SUBSIDENCE MONITORING RESULTS

Since inception of the post-closure monitoring program in 1993, measured rates of subsidence have been greater than anticipated for all areas of the brine field, but within the prediction of "nil" to a few inches per year (Walker et al., 1993). Annual resurveying of all monuments has been required in accordance with the protocol detailed in Appendix 1, which compels the resurveying of all monuments on a survey line if any of the monuments on that same line register a movement greater than 0.15 feet, or 1.8 inches, in a year. The protocol also includes provisions for increasing the measurement frequency to every six months if observed rates of subsidence accelerate for three consecutive surveys and, conversely, discontinuing surveys on an individual line if all monuments on that line move less than 0.075 feet, or 0.9 inches, per year for two consecutive 2-year periods. Annual survey measurements since 1993 have not resulted in invoking either of these provisions for any lines.

Table 2 is a summary of cumulative (1993 - 2000) post-closure subsidence recorded at each survey line in the Tully Valley brine field. Only those monuments with a relatively complete set of surveys since 1993 are included in the tabulation. Survey data from damaged monuments are also excluded.

1993 - 2000 Cumulative Subsidence (Inches)	Survey Line Number												
	1	2	3	4	5	6	7	8	9	10	G-II(N)	G-II(S)	G-II(W)
Number of Monuments	12	19	11	4	5	12	7	4	12	23	14	3	3
Minimum at Monuments	3.18	2.58	5.58	5.64	8.10	3.48	7.80	8.46	6.54	2.52	6.48	4.20	-13.08
Maximum at Monuments	15.06	15.36	8.94	9.00	9.96	9.66	9.96	14.40	12.96	11.58	17.40	5.58	19.32
Monument Average	5.78	9.46	7.81	8.10	8.76	8.12	8.44	10.20	9.24	7.82	8.40	4.86	3.20

Table 2. Cumulative subsidence 1993-2000.

1994 Survey Anomaly

The 1994 survey was the first survey performed after the initial base survey in 1993. The results of the 1994 survey were unexpected, and to date are unexplainable from geomechanical and surveying standpoints. All but a few of the 107 monuments surveyed in 1994, including bedrock monuments, indicated an upward ground movement or "negative subsidence" of, on average, 4 inches. A number of individual monuments surveyed in 1994 showed an upward ground movement of approximately 8 inches. The surveyor has performed multiple checks on the 1994 survey procedure and computations but has not found any errors in either. Even though the 1994 survey data is clearly anomalous relative to surveys performed in 1993 and 1995, data points from this survey are included in following subsidence graphs to provide a complete record of post-closure subsidence monitoring.

Piper (1981) defined "negative subsidence" as:

Negative subsidence is thought to be the result of cavity development undermining rocks of significant stiffness. Downwarping in response to cavity enlargement can also result in peripheral uplift in the rocks around the cavity as a reaction to leverage of these stiff rock layers. If translated to the surface, uplift or negative subsidence will be observed until cavity development progresses past the zone of influence of the affected monument.

The negative subsidence recorded in the Tully Valley brine field in 1994 does not parallel the negative subsidence and its causes described by Piper (1981). The 1994 data indicating an uplift is not limited in areal extent and was recorded at monuments on survey lines both directly above caverns and in remote areas not likely to be above caverns (i.e., Survey Line Nos. G-II (N) & G-II (S)). Because of the unexplained anomalous survey results in 1994, it was agreed by the NYSDEC and AlliedSignal that the monuments would not be resurveyed in 1994 but that an additional benchmark confirmation survey, starting with the 1995 survey, be performed and run to tie the currently used USGS benchmark into another distant government-installed (USGS) benchmark a mile further away from the brine field in the Town of Tully. Since 1995, this benchmark-confirmation run has been an integral part of the post-closure monitoring program, and similar widespread anomalous results have not occurred. In addition, despite the 1994 anomaly, net movement at the vast majority of monuments has been downward, as shown in Table 2 and Figures 9 and 10.

East-side, West-side, Vesper & Central Valley Brine Field Areas

As shown in Table 2 above, the average cumulative subsidence since 1993for the East-side, West-side, Vesper & Central Valley Brine Field Areas (Survey Line Numbers 1 -10) ranges from 5.78" to 10.20" or an average subsidence rate of 0.83" to 1.50" per year. The typical trend of recorded subsidence for all four brine field areas is presented in Figure 9. Recent yearly (1999 - 2000) subsidence rates at most monuments in these areas continue to be in the predicted range (Walker et al., 1993) of "a few inches to nil" with monuments on Survey Line Number 10 (East-side Area) subsiding the most at an average of 3.21". In addition, many rates recorded for 1999 - 2000 indicate that leveling off may have started but no multi-year trend has yet been observed. All of the monuments included in Figure 9 are plugged bedrock wells.

Group II Monument Areas

The cumulative (1993 - 2000) subsidence survey data for Group II monument areas is included in Table 2 under the headings of Survey Line Numbers G-II (N), G-II (S) and G-II (W). Many of the G-II (N) and G-II (S) monuments are remotely located more than 2,000 feet away from any brine wells and outside of possible mining-affected areas defined by the maximum "angle of draw" as discussed in 1969 by Panek (see Figure 1). No solutioning mining is likely to have occurred in these areas although it cannot be completely ruled out because of the previously discussed production technique of "wild brining" employed at the brine field. The average cumulative subsidence for the G-II (N) and G-II (S) monuments is 8.40" and 4.86", or an average subsidence rate of 1.20" and 0.69" per year, respectively. The average cumulative subsidence for the G-II (W) monuments located west of the "M-Group" of wells in the West-side area is 3.20", but whether this average is meaningful is called into question by the extreme negative subsidence

shown at one monument and the magnitude of the variation between "Minimum" and "Maximum" results recorded for the line. These results demand a field investigation of monuments on the line and an additional computational check at some future date.

The graph of recorded subsidence for plugged bedrock wells in the G-II (N) & G-II (S) areas is presented in Figure 10. No plugged wells exist on Survey Line Number G-II (W) and subsidence measurements from this line are not included in Figure 10 because of the need for further investigation of this widely varying data set as described above.

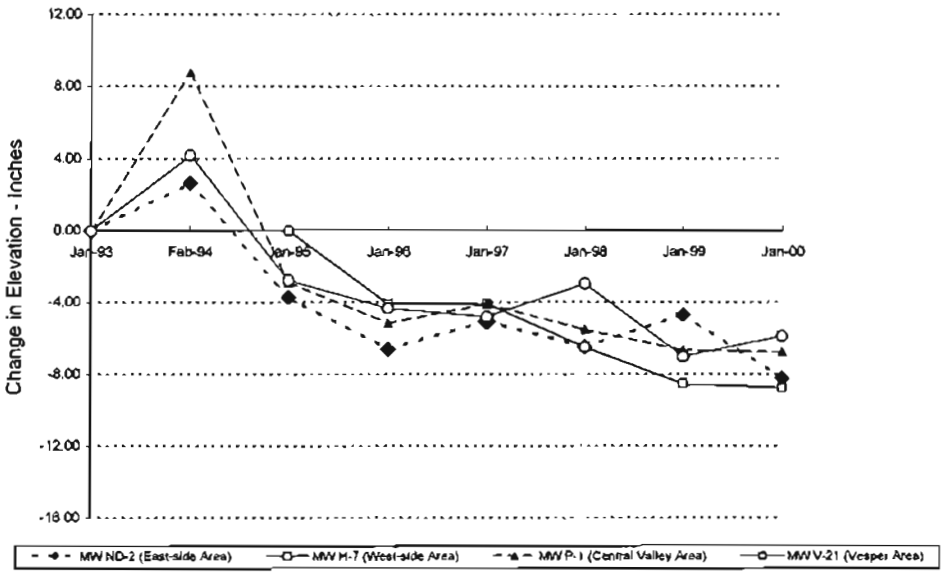

Figure 9. Typical post-closure brine field subsidence 1993-2000.

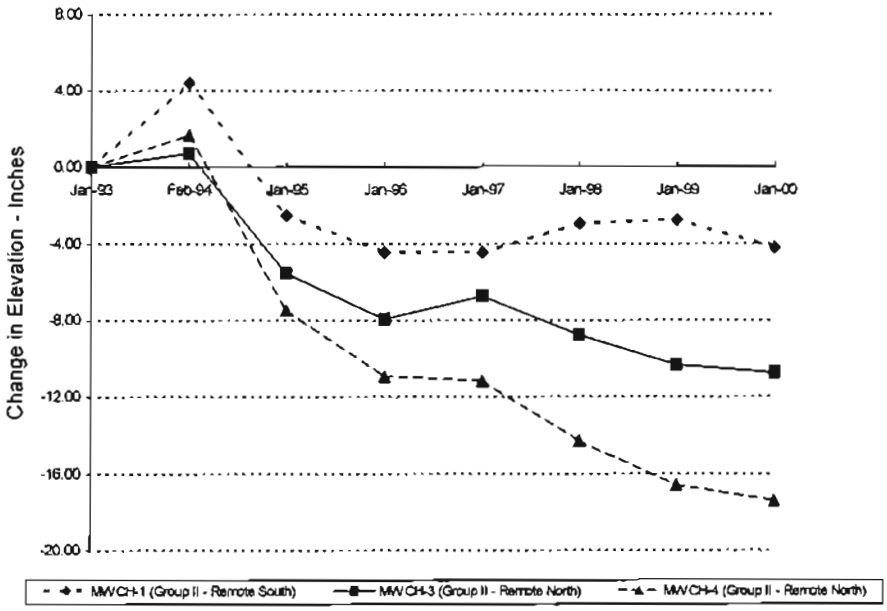

Figure 10. Subsidence outside brine field proper 1993-2000.

POST-CLOSURE MONITORING CONCLUSIONS

1. Downward movement continues to occur. Even without statistical analysis, subsidence data collected since 1993 supports the conclusion that downward movement continues more than a decade after solution mining ceased. Most monuments show cumulative subsidence of more than five inches, exceeding the maximum error of computed elevation change of ±0.09' (±1.08") for Second-Order (Class II) leveling and ±0.12' (±1.44") for Third-Order leveling (Wong, 1982).

2. The magnitude of post-closure subsidence above solutioned areas exceeds expectations. Cumulative post-closure subsidence in all brine field areas, while within the projected range of "nil" to a few inches per year (Walker et al., 1993), is greater and of longer duration at the "few-inch" level than anticipated by NYSDEC when the program began. It is unclear how the recent magnitude of subsidence relates to the observations by Fernandez (1992) and Walker et al. (1993) of little or no significant settlement following the cessation of brining but prior to plugging of the wells.

3. Unexpected subsidence is occurring outside known solutioned areas. Up to 17.4" of subsidence have been measured from 1993 - 2000 as far as 2,000 feet away from any brine wells, equaling or exceeding brine field subsidence considerably beyond areas defined by the maximum possible angle of draw. It is unknown whether this reflects brine field-related solutioning of the salt in that area, or some other phenomenon unrelated to the brine field.

4. The predicted leveling off of subsidence rates has not been observed. No field-wide multi-year trend of decelerating subsidence is observable in the raw data. It is unknown whether such a trend would be revealed by statistical analysis, nor is it understood how lack of such a trend relates to the apparent leveling off observed by Fernandez (1992) in the raw data after solution mining ceased.

5. New sinkholes are unlikely. No sinkholes have occurred since cessation of brining operations; in fact, the catastrophic event at well H-4 in 1980 was the last time a sinkhole formed. Thus, the prediction that additional sinkholes are unlikely appears to have been correct.

6. Anomalous data exists. Field investigation and further computational verification is required of the remote group of monuments west of the brine field, G - II(W). In addition, measurements of widespread, large-scale "negative subsidence" in 1994 are anomalous and remain unexplained.

SUBSIDENCE MONITORING IN THE FUTURE

When the post-closure monitoring program was developed, AlliedSignal and NYSDEC expected that, by the year 2000, decelerated subsidence rates would have allowed the monitoring program to be significantly reduced or discontinued. No catastrophic events have occurred despite the unexpected magnitude and duration of downward movement. However, based on survey data collected thus far, no permanent relief from post-closure subsidence monitoring is in sight. AlliedSignal's successor, Honeywell, remains bound by the 1993 Well Plugging Agreement, including the subsidence monitoring protocol detailed in Appendix 1.

Retrospective analysis, now that several years' worth of data have been collected, suggests that it may be worthwhile to consider the below listed alternative approaches for continued monitoring. NYSDEC recognizes the validity and potential benefits of each of these approaches, and is in discussion with Honeywell.

1. Perform statistical analysis of existing and future survey data. Statistical analysis would confirm or deny the current belief that the downward movement measured to date is significant. It might also aid in the interpretation of apparent leveling off of subsidence rates such as that perceived in the most recent survey or which may be seen in future surveys.

2. Reevaluate the thresholds for reducing survey frequency. Modification of the thresholds could be considered if an analysis and evaluation of the results to date show that different limits are more appropriate.

3. Focus on infrastructure monitoring. In addition to the previously mentioned roadways, a 6-inch natural gas main and 6-inch refined products pipeline are present in the valley (see Figure 1), which is rural in character. NYSDEC is not aware of any subsidence-induced pipeline problems to date, nor is it known by NYSDEC whether the pipeline operators have conducted any analysis of this issue. Evaluation of the cost-effectiveness and public safety benefits of an infrastructure-focused program may be warranted.

Finally, although the Tully Valley brine field is recognized as unique with respect to operational history and the resultant impacts, one lesson learned is applicable to other brine field closure projects. The lesson is that site-specific conditions may preclude accurate prediction of future ground behavior based on general expectations and past experience at other locations. To design a cost-effective, optimally informative and beneficial subsidence monitoring program requires that the unique characteristics of a site must be fully considered before and during program implementation.

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-Appendix I-

Well Plugging Agreement

Post-Closure Subsidence Monitoring Program

April 23, 1993

The objective of the subsidence monitoring program is to evaluate the Tully brine field for post mining stabilization. The monitoring program consists of 138 survey monuments located throughout the brine field with the majority of the monuments in the most recently mined West-side and Central valley well groups. The following program provides adequate brine field subsidence monitoring coverage, bedrock subsidence monitoring and an efficient surveying frequency.

Subsidence Monuments

Designated survey monuments (138) are shown in Appendix I and include all monuments in Group I and Group II.

Surveying Frequency

Group I Monuments

- Perform "initial" survey of all designated monuments within one hundred eighty (180) days of the effective date of this Order. Plugged wells converted to bedrock subsidence monuments shall be incorporated into existing survey lines and shall be included in the first survey following their conversion.

- After 12 months re-survey all designated monuments. If movement of any monument within a survey line is:
  (a) Greater than 0. 15 feet per year, resurvey line in 1 year; or
  (b) 0. 15 feet or less per year, resurvey line in 2 years.

- With respect to all subsequent years, the survey schedule will be as follows. If movement is:
  (a) Greater than 0.15 feet per year, return to 1 -year schedule; or
  (b) 0.15 - 0.075 feet per year, continue 2-year schedule; or
  (c) Less than 0.075 feet per year, resurvey line after 5 years.

Note: Individual monuments on the 5-year survey schedule may be eliminated from the survey line at Allied-Signal's discretion when a verification survey run anytime within 2 to 5 years after the 5-year survey shows movement of less than 0.075 feet per year.

- For all monuments, if acceleration is occurring after three or more measurements, survey every six months. When three consecutive surveys record decreasing measurements of subsidence, return to 1year survey schedule.

- Monuments within a survey "line," will be surveyed on the same schedule, regardless of individual monument activity within the line except where noted.

Group II Monuments

- Perform "initial" survey of all designated monuments.

- After 12 months re-survey all designated monuments.

- After an additional 12 months re-survey all designated monuments. If monument movement is:
  (a) Greater than 0. 15 feet per year, resurvey in 1 year; or
  (b) 0.075 feet to 0. 15 feet per year, re-survey in 2 years; or
  (c) Less than 0.075 feet per year in 2 consecutive 2 year periods, discontinue monument survey.

- For all monuments, if acceleration is occurring after three or more measurements, survey every six months. When three consecutive surveys record decreasing measurements of subsidence, return to 1-year survey schedule.

Note: Group II monuments may or may not be incorporated into Group I survey lines; in either case Group II monuments will not be used to determine Group I survey frequency.

GROUP I SUBSIDENCE MONUMENTS SURVEY LINE NO.										
West-Side						Central/Cross Valley				East-Side
1	2	3	4	5		6	7	8	9	10
MWV-21	MC-F	R812 *	MC-U	MC-G		MD-70 *	MD-3	MD-10	MD-9	MD-19
MD-38	MC-H	R813	R816 *	MD-4 *		MD-4 *	MD-36	MWRX-3	MWP-1	IP 13+25
MC-D	MC-L	R814	MD-59	MD-3		MD-49	IP-44 *	IP-6	IP-26	IP 11+00
MWV-18 ^	R812 *	R815	MC-V	MD-2		IP-1	IP-45	IP-8	IP-28	IP 6+00
MC-E	MC-M	R816 *	MD-58	MD-1 *		IP-2	IP-46	IP-10	IP-30	IP 2+00
MD-74 ^	MD-52	R817				IP-5	IP-47	IP-22 *	IP-31	MC 0+00
MD-75	MC-S	R818				IP-22 *	IP-48	MWCH-6	IP-34	MD-22
MD-76 ^	R801	R819				IP-23		MWCH-7	IP-35	MD-23 *
MWN-1 ^	R802	MD-1 *				MWCH-2		MD-37	IP-36	MD-24
MC-J	R803	R820				IP-53		IP-19	IP-37	IP 14+40
MD-69	R804	MD-60				IP-55		IP-21	IP-41	MWND-2
MD-70 *	MD-53	MC-X				MD-23 *			IP-42	IP 18+50
	R805	MD-61				MD-71			IP-43	MC 21+67
	MC-T								IP-44 *	IP 22+66
	R806									MWNE-3
	R807									IP 29+71
	R808									IP 33+41
	R809 #									MWF-5
	R810 #									MD-30
	MD-54									MD-17
	R811 #									MD-31
										MWG-2

From the list of wells to be plugged, add one bedrock monument (a well plugged below top of bedrock and suitable for use as a monument) from the A or B group, one bedrock monument from the C group, two bedrock monuments from the M group- -one each from M-3 through M-12A and M-22 through M-24, one bedrock monument from the W group (W-2 or W-4), and one bedrock monument from the H group (H-5, H-6 or H-7).
NYSDEC shall designate a bedrock replacement monument in the same or adjacent well group whenever Allied Signal is unsuccessful in converting a well to a bedrock monument from the above specified well groups.

GROUP II SUBSIDENCE MONUMENTS			
MD-46	MD-55 #	MD-72	MD-11
MD-47	MD-56 #	MD-73	MD-40~
MD-48	MD-57 #	MC-Q	MWCH-1~
MWCH-3	MD-63 #		
MD-33	MD-64 #		
	MWCH-4 #		

Notes:

* - monument located on more than one survey line.
^ - monument offset from survey line.
# - monument on LCP property; survey subject to authorization.
~ - monument on Valley Realty property; survey subject to authorization.