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Final Report on Weeks Island Monitoring Phase - 1999 through 2004

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Final Report on Weeks Island Monitoring Phase -- 1999 through 2004

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ABSTRACT

This Final Report on the Monitoring Phase of the former Weeks Island Strategic Petroleum Reserve crude oil storage facility details the results of five years of monitoring of various surface accessible quantities at the decommissioned facility. The Weeks Island mine was authorized by the State of Louisiana as a Strategic Petroleum Reserve oil storage facility from 1979 until decommissioning of the facility in 1999. Discovery of a sinkhole over the facility in 1992 with freshwater inflow to the facility threatened the integrity of the oil storage and led to the decision to remove the oil, fill the chambers with brine, and decommission the facility. Thereafter, a monitoring phase, by agreement between the Department of Energy and the State, addressed facility stability and environmental concerns. Monitoring of the surface ground water and the brine of the underground chambers from the East Fill Hole produced no evidence of hydrocarbon contamination, which suggests that any unrecovered oil remaining in the underground chambers has been contained. Ever diminishing progression of the initial major sinkhole, and a subsequent minor sinkhole, with time was verification of the response of sinkholes to filling of the facility with brine. Brine filling of the facility ostensively eliminates any further growth or new formation from freshwater inflow. Continued monitoring of sinkhole response, together with continued surface surveillance for environmental problems, confirmed the intended results of brine pressurization. Surface subsidence measurements over the mine continued throughout the monitoring phase. And finally, the outward flow of brine was monitored as a measure of the creep closure of the mine chambers. Results of each of these monitoring activities are presented, with their correlation toward assuring the stability and environmental security of the decommissioned facility. The results suggest that the decommissioning was successful and no contamination of the surface environment by crude oil has been found.

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EXECUTIVE SUMMARY

As the final activities for the decommissioning of the Weeks Island Strategic Petroleum Reserve (SPR) Mine were completed in 1999, an agreement was reached between the Department of Energy (DOE/SPR/PMO), the Morton Salt Company, and the State of Louisiana (State) for a post-decommissioning Monitoring Phase, through 2004. The principal action item in the Monitoring Phase agreement concerns the determination of the environmental containment and safety of the unrecovered oil remaining underground. Monitoring was conducted through various above ground monitoring activities that reveal the underground conditions.

The Weeks Island Mine has a long history. A member of a chain of islands formed by salt domes along the Louisiana Gulf Coast, Weeks Island Mine was first developed in 1902. The mine was operated commercially until 1977. The DOE then acquired the existing mine for conversion into an SPR storage facility. While it was designated as the Weeks Island SPR Storage Facility or Site, for simplicity because the storage facility has been decommissioned it will be commonly referred to herein as the Weeks Island Mine. At that time, the mine consisted of two levels, at 535 ft and 735 ft, of room and pillar excavations, with a total excavated volume of approximately 89 MMb. The conversion process involved sealing certain shafts and access drifts, incorporation of submersible pumps in sumps placed to permit flow from the mine, fill hole construction, placement of underground and surface piping required for oil and brine transfer, and construction of necessary surface structures to support the facility. This conversion process was completed in 1980 and filling of the facility with crude oil began in October of that year. The filling process was completed in April 1982 with 73 MMb of sour crude, a volume that was maintained nearly constant until November 1995 when drawdown started in preparation for decommissioning. Operational conditions in the storage facility were essentially quiescent, marked only by small transfers of oil as maintenance or special demands required and periodic demonstrations of emergency drawdown capabilities.

As a part of the acquisition agreement, DOE permitted Morton Salt to maintain a mining activity at Weeks Island. Initially an interim mine, the Markel, a shallow mine, at 530 ft, single level development to the northwest, produced commercial salt through access drifts to the Weeks Island production and service shafts. The interim mine permitted the development of shafts and facilities for an independent mine, the Morton Mine, beneath the Markel. Mining in the Markel ceased in 1980 and the Markel Mine excavations were filled with brine in 1999. The Morton Mine now consists of three levels, 1000 ft, 1200 ft, and 1400 ft, of room and pillar excavation.

In May 1992, the discovery of a sinkhole above the southeastern periphery of the underground workings influenced the future of the Weeks Island facility. The sinkhole was the surface manifestation of salt dissolution by a freshwater inflow into the oil storage levels caused by a fracture structure. Fresh groundwater inflow directly into the mine threatened the environmental security of the facility, with the potential for driving the stored oil into the overlying sediments and to the ground surface. Attempts to control

the dissolution growth of the fracture structure were relatively successful, this involved injection of sufficient brine into the fracture throat to block any fresh water flow. It was realized however that any control measure could not fully guarantee the safety of the facility over time. Consequently, at that point the decommissioning decision was taken. In addition, to provide better absolute control of the isolation of the sinkhole from the ground water during the decommissioning process, a freeze wall was established that entirely encompassed the sinkhole system.

Decommissioning was a complex process, involving the sealing of access drifts, shafts, and drill holes from the ground surface into the DOE facility. While the intent of decommissioning included the recovery of as much of the crude oil as practicable, it was also necessary to seal the man-made shafts and drill holes, except for the East Fill Hole, into the former facility from the biosphere and to assure as much as possible the permanent isolation of any unrecovered oil. Decommissioning required initially the drawdown of the crude oil, and eventually, the filling of the facility with brine. Drawdown by pumping started in November 1995, followed by brine filling in November 1996. Brine filling was a complicated process, stopped periodically to permit skimming of oil from the brine surface at key times. Periodic interruptions of the filling operation allowed repositioning of the skimming pumps as necessary. Of a beginning inventory of 72,544,342 bbl of crude, drawdown and skimming recovered 71,074,257 bbl. Unrecovered oil was 1,469,977 bbl, or about 2 % of the initial inventory. Analysis indicated the unrecovered crude oil was contained in the interstices of large piles of crushed salt remaining from the former mining activities. The rest was trapped in the irregular roof undulations as the brine filled the rooms or was retained as a coating adhering to salt surfaces and cracks.

A critical need to trace any potential movement of the unrecovered oil and to monitor the behavior of the underground chambers formed the basis for the Monitoring Phase agreement. Certain surface observations and monitoring studies could provide the required information. The monitoring encompassed (1) groundwater hydrology measurements and hydrocarbon contamination analysis, (2) observation of the continued dropping of Sinkhole #1 surface with time, (3) surveying of surface subsidence over the Weeks Island mine and the Morton-Markel Complex, and (4) brine out flow quantities from the instrumented East Fill Hole (EFH). Consequently, four wells in proximity to the Sinkhole #1 spanning the watertable and extending to the top of salt remained open for groundwater monitoring, as did the EFH. Samples collected routinely from these sites were analyzed for total petroleum hydrocarbon content (TPH). Eventually, groundwater samples began to yield spurious results, which were traced to unknown, non-petroleum, induced instrument errors. The problem was resolved after a thorough comparative study. As a result, the problematic IR (infrared) instrument was replaced by a more accurate GC (gas chromatograph) method. It was demonstrated that groundwater and EFH samples did not exceed the 5.0 mg/l threshold for TPH contamination during the Monitoring Phase.

The amount of surface drop in Sinkhole #1 was monitored since the initial discovery. Growth of the sinkhole essentially stopped while the freeze wall was in place, however, maintenance of the freeze wall ceased at the time of decommissioning. As a result, a sharp and sudden drop of about 24 ft occurred coincidently with the complete thawing of the freeze wall. However, the most realistic analysis suggested that the continued drop in the sinkhole resulted from recompaction of voids in the soil produced by the thawing process. This process would be self-limiting and would diminish and stop with time. Indeed, the drop rate has decreased from rates exceeding 1.0 ft/month after the sudden 24 ft drop until at the end of the Monitoring Phase it is less than 1.0 inch/month. While the behavior of the major sinkhole is as expected, a closely associated subsidiary sinkhole was found in November 2004. This appears to be a smaller related collapse of a pre-existing void [Ehgartner and Munson, 2005].

Optical level surveys of surface monuments over the Weeks Island Mine and the Morton-Markel Complex have been made routinely before and after decommissioning. The maximum subsidence rate prior to decommissioning was about 0.20 ft/yr. That rate experienced a marked transitional increase during the time of brine filling, but then returned to a lower rate of about 0.13 ft/yr after the mine was filled with brine. Although individual monuments could show erroneous readings, they were not persistent. Moreover, the subsidence contours essentially remained contiguous and continuous indicating no areas of structural concern within the mine workings. Integration of the volumes of the subsidence depressions shows that the volume loss prior to decommissioning was roughly 140,000 bbl/yr, in good agreement with a field measurement of 160,000 bbl/yr. After decommissioning the integrated volume loss is a nearly constant 100,000 bbl/yr, which translates to just 0.12 % per year volume creep closure of the mine. While subsidence continues because the creep closure of the mines continues, the subsidence appears to be stable over the monitoring period.

At decommissioning, the East Fill Hole (EFH) was instrumented with a flowmeter to measure the out flow of brine from the underground chambers. Very small out flow volumes called into question the accuracy of the flowmeter measurements, however, repeated recalibration and laboratory evaluation suggested the instrument was operating correctly. Flowmeter measurements of 300-400 bbl/yr are significantly smaller than out flow quantities suggested by the subsidence measurements. The discrepancy between expected and observed brine flows from the EFH may be the result of flow constraints in the casing perforations or unknown instrument problems. Although the impact of these measurements is thought to be small relative to the results of the overall monitoring effort, the lack of significant measured flow from the EFH suggests brine outflow is occurring elsewhere.

In summarizing the Monitoring Phase results, it appears that the decommissioned Weeks Island facility is performing as expected with respect to containing the unrecovered oil, eliminating concern that observe sinkhole behavior would result in residual oil entering the environment. Furthermore, the facility exhibits predictable and well-behaved creep closure as shown from surface subsidence.

1. INTRODUCTION

Decommissioning activities at the Weeks Island Strategic Petroleum Reserve (SPR) site, in Iberia Parish, Louisiana, were essentially completed at the end of 1999. This effort, managed and supported by the Department of Energy Strategic Petroleum Reserve Project Management Office (DOE/SPR/PMO), required about six years of intense efforts from the multiple organizations involved. The Weeks Island Mine Integrity Management Group (WIMIMG), a committee led by DOE/SPR/PMO, formulated most of the decisions on the decommissioning and subsequently the necessary operational tasks for the Weeks Island SPR facility and site. The culmination of the decommissioning efforts in late 1999 resulted in a final report in 2000. This document, "Final State of the Strategic Petroleum Reserve (SPR) Weeks Island Mine," [Molecke, 2000] is a precise and extraordinarily detailed account of the history of the Weeks Island site and reserve oil storage, including all aspects of site operation and the decommissioning processes. We will draw liberally from this report, and in some cases summarize important aspects of the decommissioning process particularly relevant to the monitoring phase.

While the decommissioning activities were completed in 1999, by agreement with the State of Louisiana and Morton Salt Company, the DOE/SPR/PMO was to further monitor the behavior of the Weeks Island Mine for an additional five years, through the year 2004. This activity was designated the Monitoring Phase and has now been completed. The results and conclusions of this phase are the subject of this report. In this monitoring activity the DOE/SPR/PMO provided management and direction for the support entities involved. DynMcDermott Petroleum Operations Company provided operational and engineering support. Sandia National Laboratories provided scientific guidance for geotechnical and related activities.

The objective of this Final Monitoring Phase report is to present the results and analysis of the activities subsequent to the decommissioning of the Weeks Island SPR Storage Facility. Because results from these monitoring activities will form the critical basis for judgment on the adequacy of the isolation and stability of the decommissioned facility in the longer term, they will be described in detail. Moreover, in order that this report may stand alone, sufficient history and background of the mine and repository documents, together with relevant surface and underground conditions, or status, at the time of decommissioning, will be provided as necessary.

2. BASIS FOR POST-DECOMMISSIONING MONITORING PHASE

Completion of the drawdown operation, together with the subsequent filling of the mine with brine, was designed to produce the maximum long-term stability within the decommissioned underground facility. The final decommissioned state of the Weeks Island Department of Energy Facility was formally documented in the Final State of the Strategic Petroleum Reserve (SPR) Weeks Island Mine [Molecke, 2000], a report required by the State of Louisiana (State). This report was the culmination of a number of steps and activities as agreed upon between the DOE and the State. In summarizing these events, in 2000, Molecke [2000] gives the following account: "In July 1999, the DOE SPR Project Management Office [Gibson, 1999] sent a letter to the Louisiana Department of Natural resources, Office of Conservation. This letter formally informed the State of Louisiana of the ongoing closure of the Weeks Island facility's oil storage chamber and provided a status of the closure operations. It also advised that almost 1.5 million bbl of oil was being abandoned, far more than initially envisioned; information was provided on why this situation was unavoidable. The Department's decision to abandon this much oil had been formally communicated to the public in a Press Release dated November 24, 1998. The letter to the State of Louisiana also requested that the Office of Conservation should now proceed to void Conservation Order No. SDS-8, which approved the use of the facility for the storage of oil, effective as of February 16, 1979. The State of Louisiana, Department of Natural Resources, Office of Conservation acknowledged and agreed [Asprodites, 1999]:

- That the U.S. DOE, its successors or assigns, will continue monitoring the Weeks Island Strategic Petroleum Reserve site as described in its March 1996 decommissioning plan [PB-KBB, 1996] through calendar year 2004. This monitoring includes sampling the ground waters to verify containment of the remaining oil, and monitoring the mine subsidence due to salt creep, both to be conducted on a quarterly [sic] basis, and anticipated yearly surface inspection walk arounds. Based on the monitoring results, a decision will be made on whether to continue monitoring activities.
- That the U.S. DOE, its successors or assigns, will maintain liability for any future problems that may result from the past storage of crude oil at the former Weeks Island Strategic Petroleum Reserve site in the Weeks Island salt dome.

- The Office of Conservation then ordered, effective on and after September 1, 1999 [Asprodites, 1999]:
- Due to the closure of the upper and lower mine levels of the U.S. DOE Weeks Island Strategic Petroleum Reserve site at the Weeks Island salt dome in Iberia Parish, Conservation Order No. SDS-8 issued and effective February 16, 1979, is hereby terminated.
- The U.S. DOE, its successors or assigns, will submit copies of any monitoring reports obtained from the monitoring program.
- The U.S. DOE will notify the Louisiana Office of Conservation, Injection & Mining Division of any change in the management or ownership of the former Weeks Island crude oil storage facility.

Appreciation is extended to all personnel and organizations that participated in the successful operation, engineering, geotechnical guidance, and management of the Weeks Island site and facility over its SPR lifetime, particularly over the period of decommissioning and abandonment, 1994-1999."

The principal action item in the Monitoring Phase agreement between the DOE and the State concerns the environmental monitoring. The DOE/SPR/PMO [1997] was initially responsible for establishing an environmental monitoring plan. This plan can be divided into four monitoring activities (1) periodic surveys in the four monitoring wells and the open East Fill Hole for hydrocarbon contamination evidence, (2) periodic monitoring of the surficial response of Sinkhole #1 and Sinkhole #2 with the walk-around examination of the perimeter of the Weeks Island Mine for further sinkhole development, (3) periodic surveys of the subsidence of the ground surface adjacent and over the Weeks Island Mine, and (4) monitoring of the fluid flow, fluid level and pressure in the instrumented East Fill Hole. Even though these are all surface related observations, they can be interpreted as reflections of the behavior of the decommissioned underground facility. These activities were to continue through 2004.

3. BACKGROUND OF WEEKS ISLAND MINE AND DOE SPR FACILITY

This brief historical background summarizes the early utilization of the mine, the selection of the mine for conversion to an oil storage facility, and the operational life of the facility. As noted previously, a more detailed and authoritative discussion, upon which the summaries are based, is available [Molecke, 2000]. Ultimately this background information will be used for further expansion, where necessary, of those aspects peculiar to the Monitoring Phase.

3.1 Brief History of Weeks Island Mine

Knowledge of and limited utilization of the salt dome deposits, especially those of the Five Island chain, of the Gulf Coast of Louisiana date back to the time of the Civil War, or before. The Five Island chain is the surface expression of salt domes that include Belle Isle, Cote Blanche, Weeks, Avery, and Jefferson Islands, respectively from south to north. Weeks Island dome is located 14 miles south of New Iberia, LA. All of these domes have been mined, initially for the near-surface salt, and then with well-developed underground mines. Of these mines, Belle Isle has been abandoned and intentionally flooded and the Jefferson Island mine, which was situated beneath a lake, was inadvertently flooded during a drilling penetration from the ground surface [van Sambeek, et al., 1994].

The Weeks Island mine has a long history. It was opened in 1902 and operated as a commercial salt mine until 1977. In September of that year, the mine was condemned and acquired by the U.S. Department of Energy Strategic Petroleum Reserve Program for the purposes of storing crude oil. The acquisition consisted of 382.92 subsurface acres and 6.63 acres of surface land [DOE, 1995a]. At that time, as shown in the plan view of Figure 1, the mine had become a room and pillar mine with an upper level at 535 ft depth developed between 1902 and 1952. Although the upper level remained open and unmined for some time after 1952, it was eventually closed for safety reasons. A lower mine level at 735 ft depth was opened that operated between 1952 and 1977. Rooms were nominally 75 ft high and from 50 to 70 ft in width. The estimated volume of the underground excavations in the Weeks Island mine at the time of acquisition was 89 million barrels (MMb).

The Strategic Petroleum Reserve (SPR) was authorized by Congress [Public Law 94-163] to store up to one billion barrels (1000 MMb) of crude oil. This reserve would temper any marked interruption of the critical oil supply during a national emergency and also

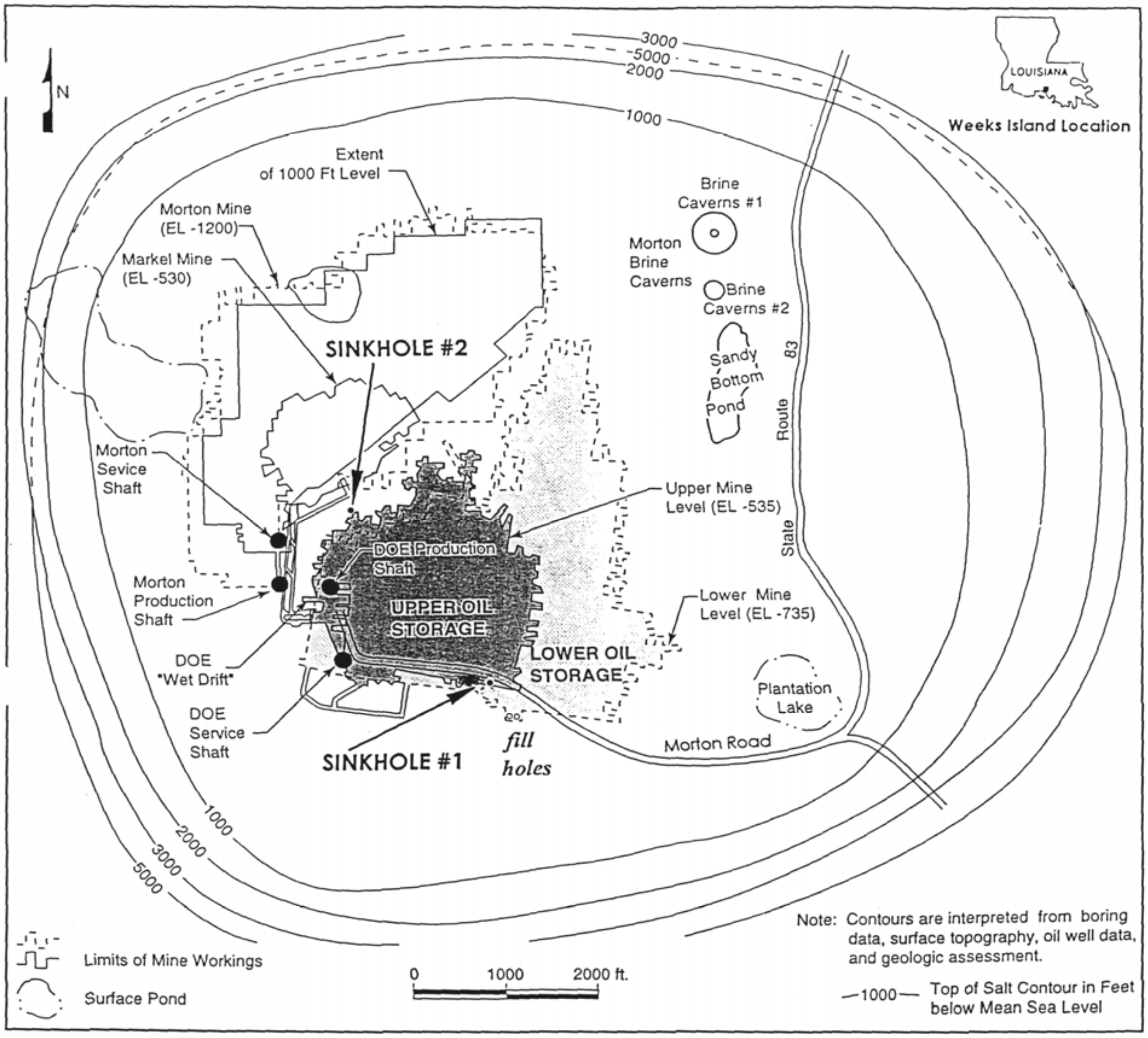

Figure 1. Footprints of Weeks Island SPR Facility and Markel-Morton Mine Complex.

fulfill the storage agreements under the International Energy Program. Subsequently, the total authorized storage limit was decreased to the current value of 700 million barrels (MMb). While a number of existing commercial leached salt caverns were eventually purchased and used, it was also recognized that existing mines, such as Weeks Island, could be developed quickly and multiple withdrawals could be made without enlarging the cavities [Neal, et al., 1996]. Adequacy of the Weeks Island dome for oil storage was one of the salient conclusions of the Site Characterization Report [Acres, 1977, 1987; Neal, et al., 1993] for the proposed crude oil repository, leading to the acquisition and conversion of the facility.

3.2 Conversion Period

Acquisition of the Weeks Island Mine by the DOE set the stage for the conversion of the mine into the SPR crude oil storage facility. Greater detail of the conversion process is found in The Weeks Island Strategic Petroleum Reserve Geological Site Characterization Report [Acres, 1987]. Greater historical detail on the acquisition and conversion process is available [Molecke, 2000]. The modification of the Weeks Island Mine to receive and store crude oil took place during an 18-month conversion interval prior to 1980. A Swedish storage concept was used for the conversion. This concept called for bulkheads in the shafts, through which submersible pumps were suspended from accessible mined manways above the bulkheads, with pump casings passing through the bulkheads [FEA, 1976, 1977]. Thus, the conversion required the installation of shaft bulkheads and pumps, and construction of various mined manways and cross drifts to permit maintenance access and proper oil communication and flow. Necessary construction and modification of surface buildings was carried out above ground, as was the installation of necessary surface piping. Surface piping transported oil to and from the site and to the underground facility, providing access to the storage chambers within the site boundaries.

3.3 Operational Period

Filling of the Weeks Island SPR facility with crude oil began in October 1980, and proceeded to completion in April 1982. Operation of the facility involved the normal activities of a facility for the strategic storage of crude oil. Because of the nature of the storage requirement where the Reserve would be used only in the case of a national emergency, as approved by Congress, the oil in storage was essentially quiescent. Thus, operation required the normal routine maintenance and occasional facility modification to update or improve the facility capability or function. Minor withdrawals and fills occurred commensurate with facility operations and special demands. To assure readiness, periodic demonstrations of the facility to perform to the required emergency withdrawal rates were staged. During the time of operation of this facility, Weeks Island storage volume was maintained essentially at a constant 73 MMb of sour crude oil. Storage volume remained at that level until November 1995, when drawdown began as a part of the decommissioning process.

Even though the normal operations of the facility could be considered as routine, there were commercial mining activities within the Weeks Island salt dome that require additional explanation. Specifically, the development and operation of commercial salt mines progressed concurrently with the operation of the oil reserve facility.

3.4 Markel and New Morton Mines

Even while the Weeks Island Mine was operating as a SPR crude oil storage facility, as part of the acquisition agreement, the DOE permitted the Morton Salt Company to continue commercial salt mining. Initially this occurred from an interim mine, the Markel Mine, interconnected to the Weeks Island Mine, and then from the Morton Mine, an independent mine, but closely adjacent to the Weeks Island Mine. Development details and physical configurations of these commercial facilities may be of importance because of their proximity to the decommissioned Weeks Island Mine, and bear further discussion.

As part of the conditions of the 1977 acquisition, the Federal Energy Administration (FEA) (subsequently DOE) agreed to allow Morton to continue salt mining operations utilizing the Weeks Island Mine until Morton could develop an independent, new Morton Mine. This process involved continued mining through the Weeks Island mine during the 18-month conversion period, while haulage and access drifts were excavated for the interim Markel mine location. These excavations would permit the use of the Weeks Island production and service shafts for mining salt from the Markel. The footprint of the Markel Mine, as shown in Figure 1, is to the north and west of the Weeks Island Mine. It is a relatively shallow room and pillar mine at a 530 ft depth. The bench mining method produced room heights of 25 ft around the mine periphery, which then increase to a height of 90 ft throughout the center of the mine. The pillar and room widths were approximately 25 ft. Morton extracted salt from the Markel mine through 1980, with removal of some 1.9 million tons of salt. The mine was then abandoned, after brine filling, in 1999, as will be discussed later.

While the Markel Mine served as the transition source of commercial salt production, new production and service shafts were constructed for a new Morton mine. The Morton Mine, while completely independent of the DOE Weeks Island SPR storage facility, is adjacent to it. Since 1980, the new Morton Mine has mined salt initially from the –1200 ft level, then from the -1000 ft level, and finally from the –1400 ft level. Currently this mine maintains active operations. This room and pillar mine configuration has approximately 65 ft square by 75 ft high rooms and 125 ft wide pillars. Footprints of the 1000 and 1200 ft levels are shown in Figure 1. The southeastern edges of the Morton excavations align vertically with the edge of the Markel Mine excavation. The quantity of salt excavated from the Morton Mine is currently unavailable.

In 1977, while the Weeks Island mine conversion was in progress, several "wet spots" were noticed during routine drilling and blasting of the access drift to the Markel Mine at an elevation of -370 ft. Mining activity continued but water leaks developed, initially at about 3 to 7 gal/hr. This led to a halt in development of this drift. Subsequently, new access drifts were developed into the Markel Mine location. Initially, the brine leakage was attributed to mining this drift too close to the top of salt, thereby intersecting interconnected fracture zones in the salt that allowed meteoric water to enter the mine. However, because neither the Markel, nor the new Morton Mine, had yet been developed, the wet salt has been recently attributed to salt dilatant damage induced by subsidence over the Weeks Island SPR facility [Beasley, et al, 1985; Neal, et al., 1996].

While the routine operation of the SPR facility and the commercial salt mining activities progressed, there were several significant events that required special note, these were the formation of sinkholes, general subsidence of the ground surface over the facility, and some observations of structural damage to surface structures. The sinkhole development would have special impact.

4. TECHNICAL CONCERNS PURSUANT TO DECOMMISSIONING

During the operational period of the Weeks Island SPR facility, and subsequently after the completion of the decommissioning process, technical concerns arose regarding the stability of the mine, the assurance that the remaining unrecovered oil was secured in the mine, and the ability to define movement of saturated brine as the mine cavities closed in response to salt creep.

4.1 Sinkhole Development

During the operation of the SPR facility, two sinkholes developed that influenced the history of the facility. In May 1992, Sinkhole #1, some 30 ft in diameter and 30 ft deep, was observed, as shown Figure 1. It was well removed from surface facilities and structures, but was within 50 ft of a Morton Mine access road. Analysis suggested that the sinkhole had existed for at least a year. Sinkholes can occur over mines, as is the case here. The sinkhole location is directly above where the edges of the upper and lower levels of the Weeks Island Mine coincide. It appeared that groundwater inflow to the mine was associated with the sinkhole and the surface subsidence resulted as progressive dissolution of salt took place in the fracture or channel leading to the mine [Neal, et al., 1995a, 1996, 1997, 1998]. A period of extensive observation and geotechnical analysis followed during which growth of the sinkhole was carefully monitored and possible mitigation studied [Bauer, 1994]. The diagnostic effort utilized the drilling of exploratory slant boreholes and wells around and into the throat of the sinkhole to permit dye injections, downhole flow measurements, and seismic measurements, among others, as detailed by several reports [Bauer, 1994; Neal, et al., 1996, 1997, 1998]. Analytic numerical studies using rock mechanics models confirmed the potential for fractures to develop from the mine to the salt surface in areas where the sinkhole was found [Ehgartner, 1993; Hoffman, 1994; Hoffman and Ehgartner, 1996]. Such fractures tend to develop progressively over many years, and can eventually lead to potential fresh water conduits into the mine [Neal, et al., 1996, 1997, 1998]. During the period of observation, the sinkhole was periodically filled with sand, but sinkhole growth continued indicating further growth of the fracture throat.

So long as fresh groundwater flowed into the mine, the sinkhole would continue to grow. Consequently, Diamond and Mills [1994] proposed that the growth could be controlled if the flow of fresh water into the mine could be slowed or stopped. This required injection of saturated brine into the salt throat of the sinkhole well below the level of the sand fill. To accomplish this, a number of cased holes were drilled into the salt throat and adjacent area. Consequently, brine was injected in BH7A, as shown in Figure 2, beginning in August 1994 and then into EH3 after 1995. As determined by flowmeters in the injection holes, brine flow not only occurred downward into the mine, but an excess of injected brine also produced upward flow to displace the fresh surface water.

In late 1994 it was determined that progressive development of a sinkhole was potentially inevitable, the stability of long-term brine injection was unknown, and possible effects of oil displacement by water on the surface environment were unacceptable. While these considerations led to the decision to decommission the facility, the activity in the sinkhole continued to be of concern. As a result, this concern led to an additional measure to limit development of the sinkhole by establishing an ice wall around the sinkhole extending from the ground surface into the volume of salt [Rousseau, 1995]. While a freeze wall adds strength to the surface soils, it also can prevent flow of surface

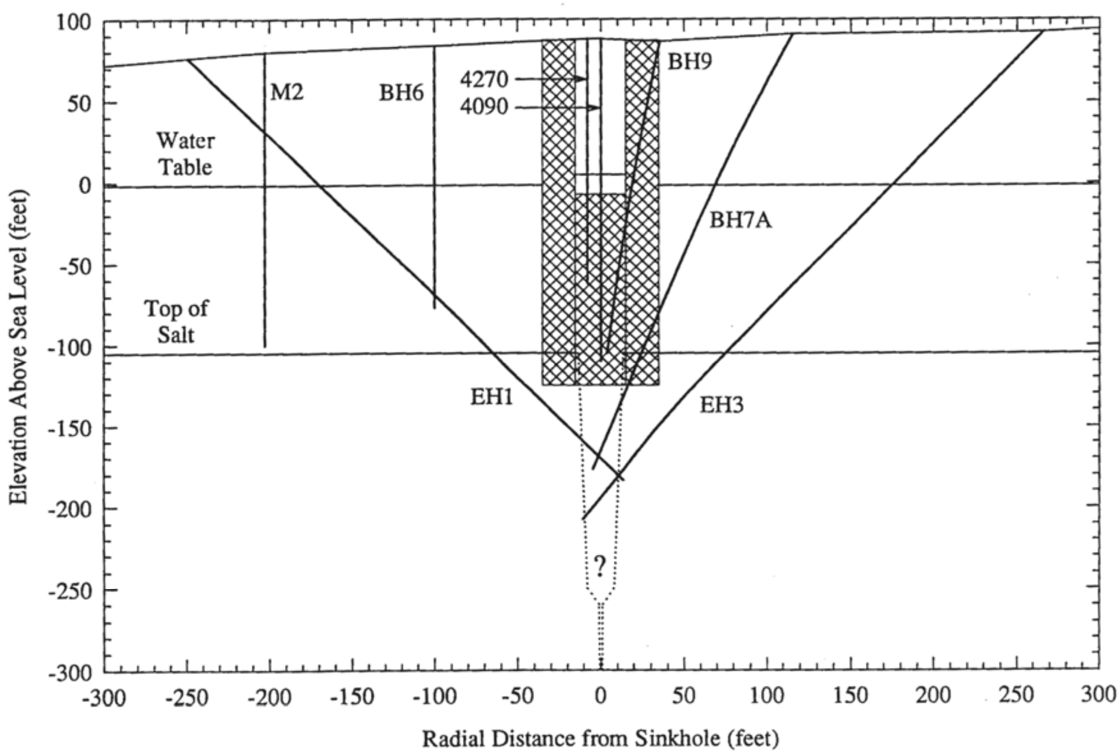

Figure 2. Drill Holes around and into the Throat of Sinkhole #1 [Molecke, 2000].

water through the frozen volume, and thus perhaps avoid sudden detrimental increases in mine inflow volumes. The Weeks Island freeze wall construction began in June 1995 and was completed within five months [Neal et al., 1996]. Three concentric rings of cased holes were drilled: 22 holes on a diameter of 54 ft were drilled through the 185 ft of overlying material and about 10 ft into the salt, another 22 holes on a diameter of 48 ft were drilled slightly into the salt, and the final 10 holes on a 40 ft diameter were drilled just short of the top of salt. A calcium chloride refrigerant at $-38^{o}C$ ($-36^{o}F$) was circulated through the drillholes. After an initial period during which the ice wall was established, the circulation scheme was altered to produce an ice cap at the top of salt. The freeze wall and ice cap were maintained for over three years and the ice cap subsequently became a complete plug. Measurements in adjacent drillholes indicated the freeze wall was effective in isolating the sinkhole throat. The final configuration of the freeze zone was an ice cylinder 70 ft in diameter extending some 230 ft through the unconsolidated overburden into the salt, as indicated by the cross-hatched area in the figure [Ehgartner, 2002a]. During the period that the freeze wall was maintained, no further drops or subsidence were observed in Sinkhole #1.

Routine inspections of the surface overlying the perimeter of the Weeks Island mine were started on a quarterly basis in 1995 and continued through 1999. Sinkhole #2 was found [Neal, 1995b] nearly three years after the discovery of Sinkhole #1. Sinkhole #2 was a much smaller feature about 14 ft in diameter and 10 ft deep located on the opposite side of the mine but again directly above the periphery of the mine chambers, as shown in Figure 1. The analysis in terms of rock mechanics models again supported the general sinkhole location. The sinkhole was filled with sand and surface monitoring stations were installed. No further remedial action was taken at Sinkhole #2. The sinkhole remained stable until 1998 when it suddenly fell by 3 ft, but then again stabilized. In the 1999 inspection, Sinkhole #1 was stable, and Sinkhole #2 had not grown further [Bauer and Williams, 1999].

Subsequent events, as discussed later, led to the withdrawal of the crude oil from the mine chambers and the filling of the mine chambers with brine. The oil withdrawal was started in November 1995, brine filling started in November 1996, and brine filling was completed in July 1999. When the excavations were brine filled to hydrostatic pressure, sinkholes ceased to pose a threat because freshwater inflow was no longer possible. No further changes in the sinkholes were observed up to August 1999. Of significance, however, the chillers were also turned off in August 1999, and the freeze wall naturally began to gradually thaw. When the Weeks Island facility was decommissioned in November 1999, the status of the sinkholes at that time became the baseline condition for the Monitoring Period activities.

4.2 Decommissioning

Only a condensed account of the complete decommissioning process is given here. It was realized that Sinkhole #1, found in 1992, was the result of the inflow of fresh water into the mine. Potentially, any water inflow would displace the stored oil. The prospect of such displacement presented a critical threat to the function of the Weeks Island SPR oil repository and to the surface environment. In response to this realization, the DOE Weeks Island Mine Integrity Management Group, WIMIMG, began in 1994 to consider various options for decommissioning the Weeks Island facility. There were a number of decisions and actions required for eventual decommissioning [DOE, 1995b]. A major decision involved the manner of the oil drawdown and the decision on the final state of the underground chambers. Oil drawdown actions also necessitated preparation for movement of the oil to other SPR sites. Another major decision, filling the facility with brine to better stabilize the underground chambers, ultimately made the construction of a brine cavern and a schedule for brine filling necessary. Many actions were required in preparation for brine filling, the sealing of shafts, and sealing of some access drifts and manways. Of special importance was the sealing of access drifts to the Markel Mine to assure isolation between the Weeks Island and the Markel Mines. Numerous boreholes, including those around Sinkhole #1 and the fill holes, were plugged and abandoned. However, a few well holes around Sinkhole #1 were left open for monitoring and the East

Fill Hole itself remained open. Moreover, the East Fill Hole was reconditioned and prepared as an eventual overflow relief for brine from the mine. Such an outflow from the mine could be discharged into a surface formation with high salinity groundwater. Other actions included dismantling of the underground oil booster pumps and associated piping and equipment. Above ground, certain of the shaft and hoist structures and selected service buildings were dismantled, as were the surface piping systems. The mine gas vent flare structure was dismantled. While these actions are easily summarized, the actual decommissioning actions were very detailed and crucial to the final condition of the facility. The exceptional attention to detail on how the numerous activities were accomplished, and the final status, may be found elsewhere [Molecke, 2000].

4.3 Drawdown

Clearly, the drawdown of the oil was one of the most critical operations. Two principal concepts were examined: (1) sequential drawdown involved initial emptying of the mine using normal withdrawal practice followed by brine filling of the mine, which did not necessitate adjustment of pump elevation, or (2) concurrent drawdown where the withdrawal of the oil occurred simultaneously with the brine filling, which required reconfiguration of the pumps. Greater detail of these methods and the critical elements of the selection process are given by Molecke [2000]. Of the methods proposed, the one chosen was sequential drawdown, which accomplished removal of oil using the operational configuration of the oil booster pumps as emplaced. These pumps were installed in sump pits, which, as the low points of the facility, allowed the oil to drain readily from the facility into the pumps. It was realized that even with this drainage system, some oil would be trapped locally on the floor of the mine, on the mine pillar surfaces, and perhaps in or around abundant crushed salt piles that remained within the mine from the earlier commercial operation [O'Hern, et al., 1999].

The drawdown operation began in November 1995. Accountability records indicated the facility contained 72,544,342 bbl of crude oil (within a ¼ % uncertainty) based on normal oil custody transfer metering [Eldredge, 1999]. Of this initial inventory, the drawdown resulted in the recovery of 68,869,955 bbl, again based on oil custody transfer metering. While the expectation was that only 0.03% of the original oil inventory, or 20,500 bbl, would remain after drawdown, this proved not to be the case. However, in the sequential process, after drawdown was completed, the mine was then filled with brine. Further recovery of the remaining oil would depend upon skimming of the floating oil as the mine cavities were filled with brine.

4.4 Brine Filling and Oil Recovery Skimming

The recovery of the remaining crude oil after the initial drawdown was accomplished in four stages and a detailed summary of this process is available [Neal, et al., 1996]. The process is briefly summarized here, complete detail is found in Molecke [2000].

Backfilling of the mine with brine began in November 1996. Sofregaz, through a contract from the SPR, supplied the brine by developing a brine cavern on Morton Salt Company property elsewhere in the Weeks Island dome, shown in Figure 1. The maximum delivery rate of brine was about 200,000 bbl per day, with a specified value of 85% of that of saturated brine. Delivery of brine with this saturation gave a final specific gravity of about 1.17, compared to the saturated specific gravity of 1.2, and met the conditions of the contract.

The brine backfill process progressed through several phases [Walk-Haydel, 1999], primarily determined by the need to reconfigure the pumping system for skimming the oil from the brine surface as the brine level rose. Pump reconfiguring, as well as the skimming activity, required periodic pauses in the brine backfilling process. Phases I and IB utilized the same crude oil booster pumps as used for the initial drawdown. As brine continued to fill the mine, these pumps would no longer be effective. For Phase II, as the brine level nearly filled the lower level of the mine, backfilling halted and new skimming pumps were emplaced. Skimming at this new level occurred until November 1998, when brine backfill started again. At this point, the efficacy of skimming was diminished by persistent emulsion of the oil layer. Also an unintentional overfilling blocked flow of the oil layer to the pumps, although this overfill situation was corrected by removing the excess brine from the mine. Consequently, the recovery rate of the remaining oil diminished and proved to be costly and eventually uneconomic. The economic question and the desire to achieve an increased stability of the mine led to the decision to proceed

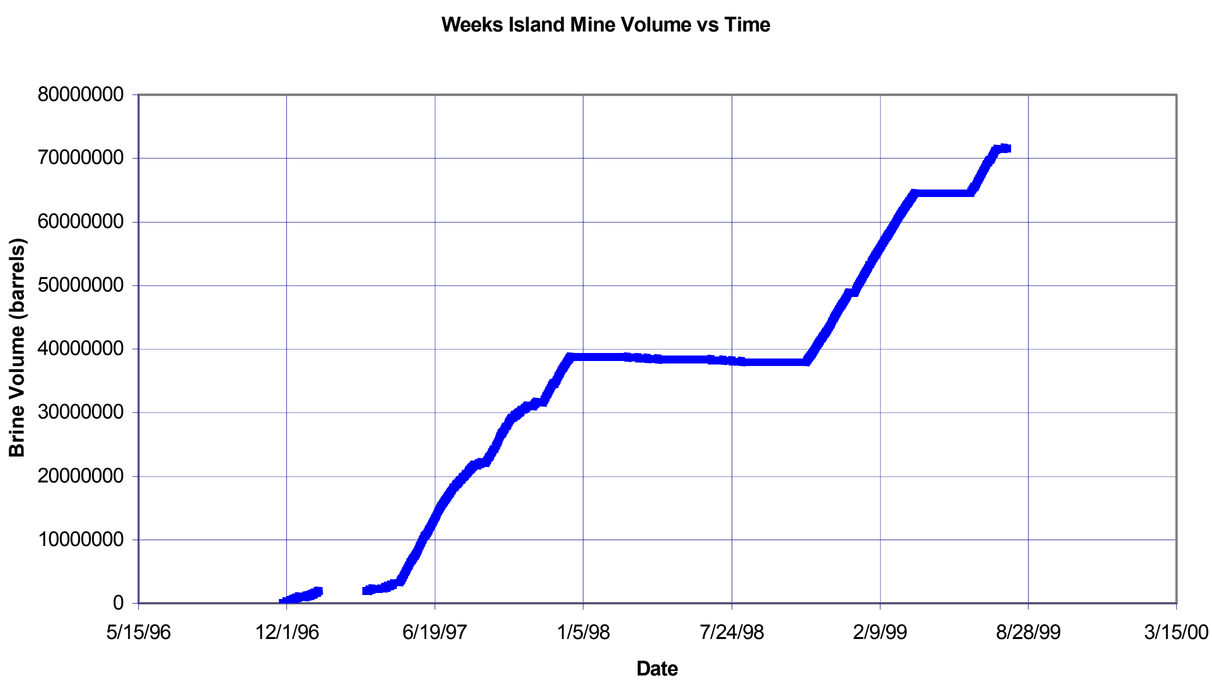

Figure 3. Brine Fill as a Function of Time, showing Skimming Phases [Molecke, 2000].

with brine backfill. This decision was released to the public in late November 1998. It was acknowledged that more than a million barrels of unrecovered oil would remain underground in the decommissioned facility. Regardless, during Phase III skimming in January 1999, there was an attempt to skim residual oil at the bottom level of the upper mine, before brine filling of the mine continued. Phase IV, the final phase of skimming, required the installation of a skimming pump in the vent hole. This phase ended in June 1999, with the completion of filling of the mine with brine. The mine was then "topped off" with the injection of small amounts of fresh water to bring the mine to hydrostatic pressure, which is equivalent to filling the mine completely with fluid.

The progress of brine filling can be traced through Figure 3, which gives the brine volume as a function of time. The graph shows periods of brine level increase, separated by periods of constant brine elevation when skimming occurred.

Recovery amounts during each phase are as follows [Molecke, 2000]:

Phase I	584,213 bbl	
Phase IB	1,146,432 bbl	
Phase II	459,383 bbl	
Phase III	684 bbl	
Phase IV	13,590 bbl	
Sub Total	2,204,302 bbl	Skimming recovery
Drawdown	68,869,955 bbl	Drawdown recovery
Total	71,074,257 bbl	Total recovery

Compared to the total repository oil inventory of **72,544,342 bbl**, the total recovered oil was **71,074,257 bbl**. The amount of oil abandoned was **1,469,977 bbl** or about 2 % of the initial inventory.

Mechanisms have been advanced for the disposition of the unrecovered crude [Molecke, et al., 1998]. An identifiable portion of the unrecovered oil was associated with the oil layer that remained on the brine surface, perhaps in partially emulsified layers, and was not skimmed. This floating oil was forced upward into pockets in the irregular roof of the mine as the brine filled the chambers. Based on the layer thickness, Eldridge [1999] indicates some 168,750 bbl of oil was potentially trapped in this manner. Clearly, a relatively large amount of oil was not accounted for in the floating oil surface layers, yet still remained in the mine, but was apparently immobilized. Reasonable arguments suggest that most of the abandoned oil is trapped in the interstices of the piles of crushed salt that existed throughout the mine when it was acquired [O'Hern, et al., 1999]. Some smaller quantities of oil also were thought to coat or adhere to salt surfaces and in salt cracks.

While the decommissioning process involved many activities, one should remember that the intent of the decommissioning was to permanently seal, except for the EFH, all manmade openings into the underground chambers of the former SPR oil repository, to isolate unrecovered crude oil from the environment, and prevent any access of this oil to the biosphere through these openings. As a result, the oil skimming process eventually became the most critical decommissioning activity because it determined the final condition of the underground cambers. Although the decommissioning activities were intended to leave the Weeks Island Mine in a status as benign as possible, the status of the unrecovered crude oil became of concern.

While it was believed the remaining, unrecovered oil is trapped and immobile, periodic monitoring of the open boreholes and East Fill Hole for potential releases of oil to the groundwater and biosphere was deemed essential .

4.5 Surface Subsidence

Subsidence of the ground surface in response to underground mining and extraction of minerals is common. Indeed, it is a widely observed natural response and was expected at the Weeks Island Mine. Normal practice, which was followed at this facility, is to place surface monuments over the site and to make periodic optical level surveys based on benchmarks sufficiently removed from the site to be unaffected by subsidence.

The earliest known survey data for Weeks Island, which is understandably of uncertain quality, dates back to 1931. However, beginning in January 1983, the elevations of new subsidence monuments emplaced over the Weeks Island Mine had been surveyed 20 times prior to decommissioning [Bauer and Ehgartner, 1999; Bauer, 2004]. Although the monuments locations are somewhat sparse, the observations indicate, as expected, general subsidence over the underground facility. The surface subsidence is the reflection of the closure of the underground openings of the mine caused by the time-dependent creep deformation of salt following the mining. As is common in subsidence the surface depression extends laterally away some distance from the mined underground footprint (vertical projection of the underground boundary to the ground surface). Actual determination of this distance on the ground is difficult, but if used with caution some indication can be obtained from numerical calculations of subsidence [Hoffman, 1996]. These show that subsidence trough extends some 10 to 30 % beyond the footprint of the mine. The principal concern prior to decommissioning was the affect that subsidence could have on site operations and safety. Because Weeks Island is higher above sea level, in contrast to other SPR sites, the increased potential for subsidence to enhance surface flooding was of no concern.

Upon decommissioning, a new focus of subsidence monitoring became one of loss of mine volume and the equivalent flow of brine out of the mine. Stability of the underground chambers and the total decommissioned facility could be evaluated through the subsidence and the brine outflow. The status of the subsidence at decommissioning is given by the survey results obtained just prior to decommissioning. These data were reported [Bauer and Neal, 1997; Bauer, 1999a, 1999b] as changes in elevation and as subsidence rates, as shown in Figure 4. The subsidence monument locations are shown with respect to footprints of the Weeks Island and Markel Mines. The figure shows the subsidence contours over these mines as determined just before decommissioning in late 1999. In general, the detailed results of Figure 4 indicate clearly the effective centers of the subsidence depressions above both the Weeks Island Mine and the Markel-Morton Mine complex. As one would expect, these centers are roughly at the center of the footprints of each mine or mine complex. There is no indication of abnormal centers of subsidence in the contours, indicating that the subsidence is generally continuous and contiguous. While the contour plots of rates give a great deal of information, the specific results can be examined more readily when only the maximum displacement of the subsidence is extracted and displayed. As shown in Figure 5, the maximum subsidence measurements over both the Weeks Island Mine and Markel-Morton Mine complex at the

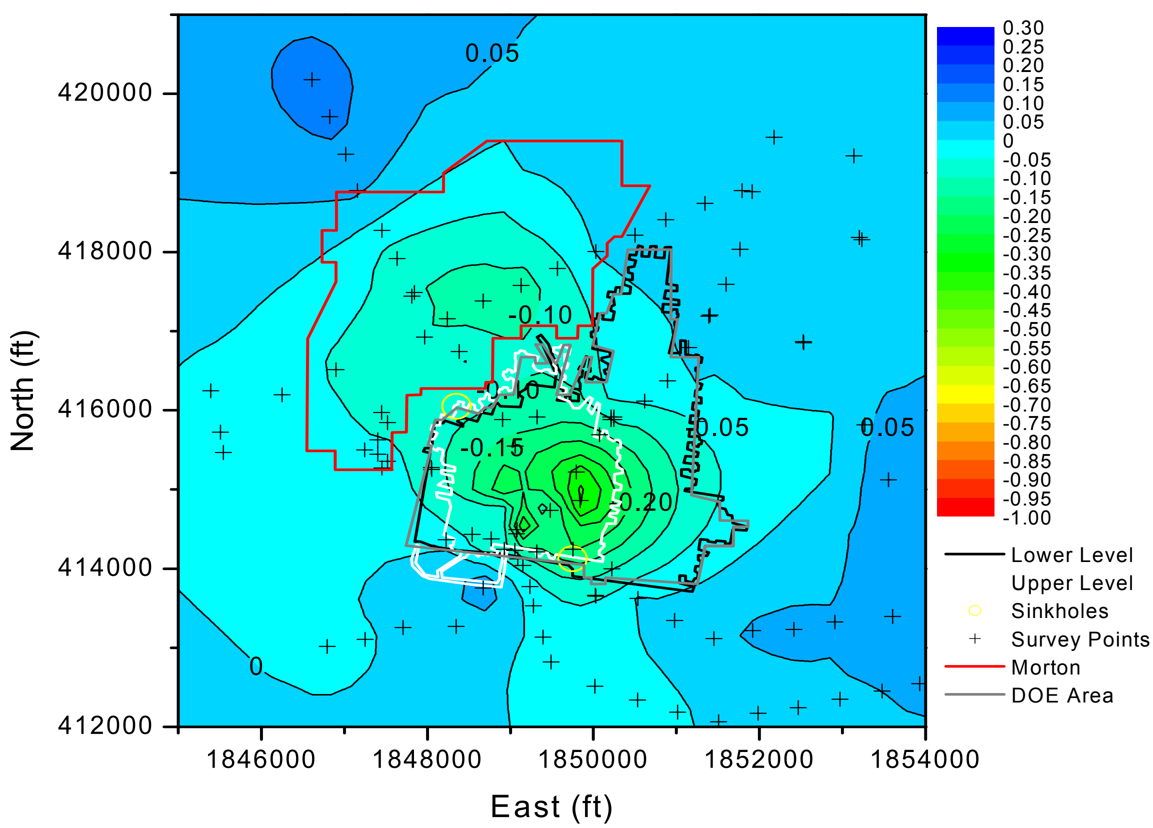

Figure 4. Subsidence Weeks Island and Markel Mines, 3/99 – 10/99 [Bauer, 1999b].

time of decommissioning indicate both are subsiding at nearly the same rate, 0.20 ft/yr for the Weeks Island facility and 0.18 ft/yr for the Morton Complex. During the time of removal of the oil, the subsidence rate of the Weeks Island facility increased sharply to 1.08 ft/yr. However, after the mine was filled with brine, the subsidence rate began to decrease. The subsidence over the Morton Complex during the same period increased slightly to 0.24 ft/yr. These results from late 1999 [Bauer, 1999b] were essentially confirmed in 2003 [Bauer and Ehgartner, 2003]. Although Figure 5 extends beyond the

1999 decommissioning timeframe, the condition in 1999 is clear. Consequently, it is this subsidence condition as defined at that time that became the baseline condition for the Monitoring Phase measurements.

An informative numerical analysis was made by Hoffman and Ehgartner [1996] using a representative three-dimensional finite element model of the Weeks Island and Morton Mine complex to calculate the expected subsidence. Predictions based on this analysis

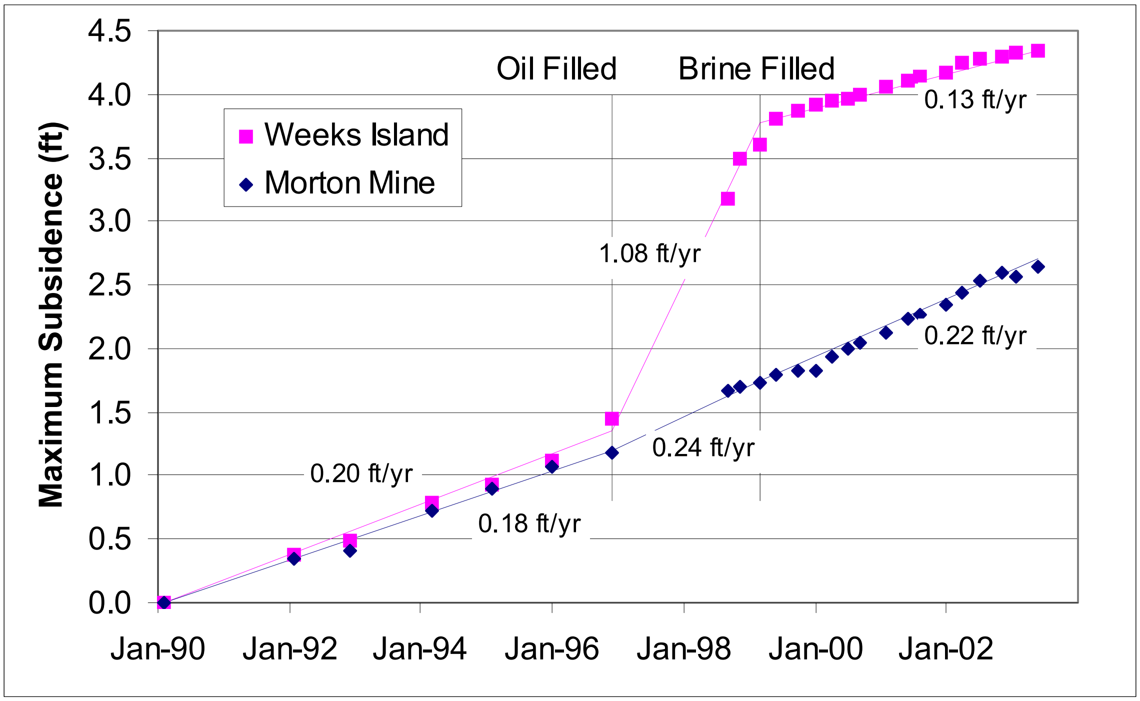

Figure 5. Maximum Subsidence Weeks and Markel-Morton [Bauer and Ehgartner, 2003]

were carried through the decommissioning of the facility. The predicted subsidence rate with oil fill is about 0.07 ft/yr, which decreases markedly after brine fill to approximately 0.002 ft/yr. Clearly, the predicted rate of 0.002 ft/yr is considerably less than the measured rate of 0.13 ft/yr. In fact, both the oil and brine filled predicted rates are markedly less than the measured rates for these conditions. At this point, while numerical calculations may be informative, they do not appear to be an accurate prediction of the actual subsidence behavior.

As is apparent, the footprints of the Markel-Morton Mines complex are in very close proximity to the Weeks Island Mine. Clearly, therefore, the measured subsidence where the edges of the individual subsidence depressions overlap is the sum of individual subsidences from both mines in that location. However, based on subsidence depression shapes, the regions of overlap appear to be relatively small. Upon decommissioning, continued monitoring of the subsidence at regular intervals became part of the Monitoring Phase. Monitoring was initially set at quarterly intervals, but this interval was sometimes extended. A number of reasons caused this modification in schedule including data significance with small displacements and response to contract schedules. Nevertheless, the yearly monitoring State requirement was always met.

One of the consequences of subsidence is that some of the site facilities were damaged to some degree. Observations [Bauer and Ehgartner, 1999] were made of subsidence related deformation of surface structures, especially shaft houses and equipment, together with associated maintenance and repair. The shaft houses and hoisting equipment were particularly susceptible, but other buildings, roadways and surface pipelines also suffered damage. In any location where subsidence occurs, the potential for damage to surface structures nearly always exists. While non-uniform subsidence has produced damage in the surface structures of the Weeks Island facility, all the structures remained in normal operation until the facility was decommissioned.

When a mine, such as the Weeks Island SPR facility, is decommissioned and access to the underground is no longer possible, one of the few methods of monitoring the general response of the mine is through the measured subsidence**.**

Because they may reflect more or less directly the response of the underground chambers, the subsidence measurements are one of the important components of the Monitoring Phase.

5. MONITORING PHASE RESULTS AND ANALYSIS

Four specific areas of data collection and analysis were pursued during the five-year period of the Monitoring Phase. These addressed (1) the sampling of wells to determine hydrocarbon levels in the groundwater and sampling of the East Fill Hole to determine hydrocarbon levels from the mine outflow, (2) the development and long-term behavior of the sinkholes, (3) the long-term subsidence measurements of the ground surface over the Weeks Island Mine and the Markel-Morton Complex, and further visual inspection of the surface footprint above these mines; and (4) the East Fill Hole measurements of brine flow and heads from the underground chambers.

5.1 Monitoring for Hydrocarbons

The monitoring for hydrocarbons will be separated into two distinct areas, the first dealing with the groundwater sampling from the four wells near to Sinkhole #1 and the second dealing with the sampling of the brine from the East Fill Hole. Fundamentally, these different areas of sampling are addressing the same general problem, even though the proximity to the source of contaminant differs considerably.

5.1.1 Groundwater Monitoring of Surface Wells

When the Monitoring Phase started with detection monitoring in November 1999, there remained four open wells (M5, M6, M7, and M8) from the ground surface that span the watertable and extend into or near the top of salt. These wells were to serve as sampling locations to test for the presence of hydrocarbons, which would potentially be an indication of oil escaping from the decommissioned Weeks Island oil storage facility. The schematic of Figure 6 shows the location of the wells with respect to Sinkhole #1, the Morton Service Road, and the local groundwater gradient. As shown in Figure 1, the general location is on the southeastern periphery of the Weeks Island footprint [SPR ER, 2001].

Prior to decommissioning, a program of Long-Term Monitoring of ground water was established. This program not only permitted observation of possible crude oil traces but also the determination of groundwater flow direction and velocity [SPR ER, 2001]. The

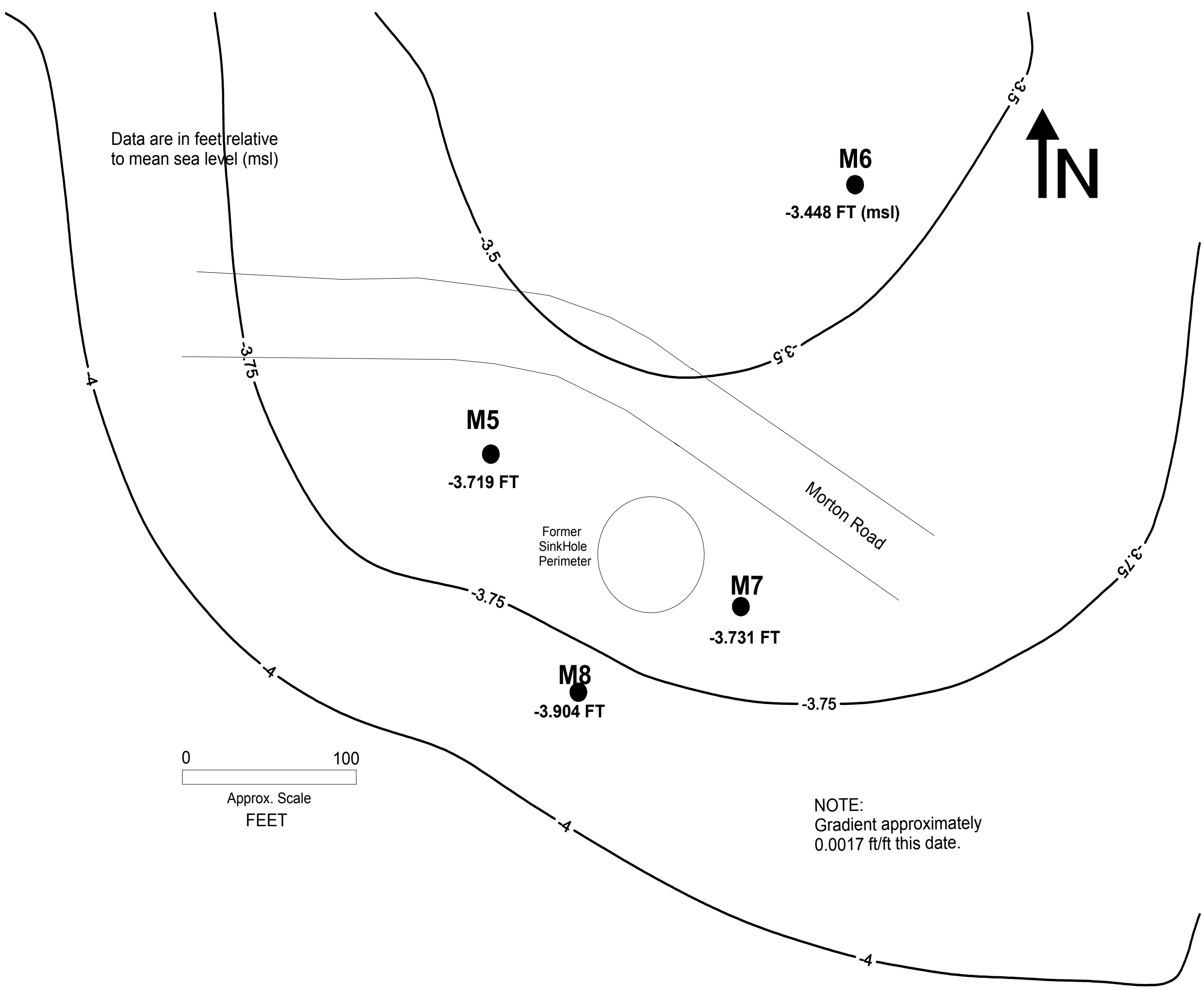

Figure 6. Groundwater Sampling Wells, Sinkhole #1, and Gradient [Westbrook, 2004].

groundwater flow was found to be generally toward the south at a velocity of about 75 ft/yr under the influence of a very small gradient, as shown in Figure 6. Such a small gradient supports that the aquifer potentially has a high permeability, consistent with the measured values and perhaps expected for a relatively unconsolidated dome overburden.

At the time of decommissioning, the results of groundwater monitoring conducted over the several prior years through the Long-Term Monitoring Program confirmed no petroleum hydrocarbon contamination [Molecke, 2000]. However, it was then recognized that subsequent post-decommissioning detection monitoring would be required. Detection of any crude oil, identifiable with the unrecovered, or trapped, oil in the Weeks Island Mine, depending upon amount, would be of potential environmental concern and if necessary a candidate for mitigation measures. As a result, the four monitoring wells, as shown in Figure 6, were used to establish a baseline, or ambient, total petroleum hydrocarbon (TPH) level before decommissioning. Some 10 samples were obtained over a three-year period, with the last sample taken in June 1999. The baseline monitoring established that no TPH levels exceeded the historical limit of detectability of 5.0 mg/l [SPR ER, 2001]. These four wells constitute the basis for quarterly monitoring of TPH through 2004, the period of the Monitoring Phase [Gibson, 1999]. This monitoring phase began in November 1999 with the first "detection" mode sampling. As noted by Molecke [2000], the Environmental Protection Agency Method1664 (IR) infrared screening test defined the procedure at that time. The 1664 (IR) Method utilizes infrared absorption levels to determine a relatively simple TPH level. Two SPR publications, "Revised Routine Sampling For The Purpose Of Detection Monitoring Weeks Island Long-Term (WILT) Ground Water Monitoring Wells, Rev. 2.," and "WILT Data Handling and Management Plan, Rev. 2," prescribe sampling, data handling and reporting procedures.

Essentially by agreement between the DOE/SPR/PMO and the DynMcDermott service contractor, sampling was scheduled on three month intervals, with the first detection monitoring sample taken in November 1999, and the data and results were to be summarized and reported to the Louisiana Department of Natural Resources, Office of Conservation, on a quarterly basis [Westbrook, 2004a]. At that time, the accepted laboratory analysis used as the standard method previous baseline ground water sampling program was reestablished for the monitoring phase using the same infrared EPA 1664 IR method to determine total petroleum hydrocarbon (TPH) content but with a lower limit of detectability of 1.0 mg/l versus the background detection limit of 5.0 mg/l, which was considered an acceptable indication of uncontaminated water. Any TPH detected above this historical limit was taken as an alert point for further action.

Between the November 1999 first "detection" mode sampling and late 2002, when the first alerts were found, none of the groundwater samples tested above the 5.0 mg/l limit. However, during the course of routine monitoring in November of 2002, the TPH level in two of the test wells rose above the 5.0 mg/l limit of detectability. This result was immediately confirmed by retesting the suspect wells in December of that year [SPR ER, 2002]. Interestingly, some of the 1664 IR results suggested extremely high levels of hydrocarbons, which would have been apparent to visual observation. To the contrary, visual observation indicated a potential problem with the test method. Consequently, further testing was pursued using the TPH IR method then in use and a chromatographic method, TPH 8015-Oil GC, using duplicate samples from the wells. A summary of the test results that led to the retesting and the use of the 8015-Oil GC method is given in Table 1. In addition, these samples were analyzed independently, with the assistance of a DM EPA Environmental Advisory Committee (EAC) scientist, using a field portable gas chromatograph. Overall, the 8015 GC test can be more specific to a given fraction of the hydrocarbon spectrum. In fact, the 8015-Oil GC is specific to the signature of crude oil, in contrast to other hydrocarbons. Not only is the GC method more specific, but it is more sensitive, with a limit of detectability of 0.15 mg/l. In a detailed comparison study, all wells were sampled and tested using both the IR method and the 8015-Oil GC method.

Table 1. Test Results in November 2002 (Results in mg/l) [Westbrook, 2004b].

Well				Test Date	
	Nov. 22, 02	Dec. 16, 02	Dec. 16, 02	Feb 3. 03	Feb 3, 03
Test Sample	Original	Retest 1	Retest Dup.	Duplicate	Duplicate
Test Method	1664 IR	1664 IR	1664 RI	1664 RI	8015 GC
M5	6.77	227	ns	4.34	0.750
M6	168	568	10.7	826	0.360
M7	ND 1 mg/l	ns	ns	1.22	0.300
M8	ND 1 mg/l	ns	ns	2.71	ND 0.15 mg/l
EFH	**ND 1 mg/l**	**ns**	**ns**	**ND 1 mg/l**	**ND 0.15 mg/l**

Note: ND is not detectable at the stated level, ns is not sampled.

The definitive conclusion of the retesting was that the fraction results from the TPH 8015-Oil GC method (two separate apparatii) indicated no hydrocarbon levels above the original alarm level of 5.0 mg/l. However, the GC tests, because of the increased sensitivity, did show scattered hydrocarbon indications, but summation of the components of the analyses resulted in a total of 1.0 mg/l hydrocarbon or less. The detail in the GC analysis also suggests the "signature" of the samples were not that of crude oil. Clearly, agreement of both the TPH 8015 GC and the EPA Environmental Advisory Committee scientist GC results are a clear indication of spurious IR results, in this case. It was suspected the IR readings were susceptible to some unknown chemical or biological interference leading to erroneous readings. Based on the comparison study, it was concluded the chromatograph method was the more reliable, and it became the accepted method of sample analysis and replaced the IR method in May 2003 [SPR ER, 2003]. The 8015 GC is now also the accepted EPA method of testing.

As the monitoring sampling continued, occasional results using the newly adopted TPH 8015-Oil GC method have shown values in excess of the detection limit of this method. While each of these occasions is investigated, none have given a level greater than 1.0 mg/l. Consequently, there is no indication of hydrocarbon contamination in the wells, within the initial definition of a detection limit of 5.0 mg/l. It is important to note that while some results using the 1664 IR technology exceeding the detection limit were recorded, these were spurious and ultimately proven to be erroneous. Subsequent to the replacement of the 1664 IR analysis method with the 8015-Oil GC method, no readings exceeded the 5.0 mg/l alarm limit.

It appears reasonable to conclude from the extensive testing of the four surface wells during the Long-Term Monitoring Program prior to the Monitoring Phase and subsequently during the monitoring phase that no credible evidence of groundwater contamination has been found.

5.1.2 East Fill Hole Monitoring

The samples of water taken from the East Fill Hole (EFH) are somewhat unique. These samples are taken from the brine of the decommissioned underground chambers, rather than from surface wells. At one time, crude oil was in direct contact with the casing and underground chamber surfaces. Undoubtedly, the brine itself probably remains in contact with some of the unrecovered oil trapped in the roof irregularities. If any hydrocarbon contamination were to be found, one might certainly expect it to be found in the EFH.

As a part of the water monitoring program, during decommissioning the EFH was adapted to permit water sampling, and these samples were added to the water monitoring base [Levin, 1999]. The adaptation of the EFH consisted of emplacement of a packer in the 30-inch casing through which a smaller diameter tube passed. The smaller tube was sized to accept a flowmeter and fluid level instruments. Just above the plug the smaller diameter tube was perforated to prevent isolation of the fluids. The 30-inch casing was, itself, perforated just above the top of salt at the level of a briny aquifer using shaped charge penetrations. Flow from the underground chambers could then go directly into the briny aquifer. A water sampling system was also installed in the EFH.

Test results of the water samples taken from the EFH have in general shown no contamination within the initial detection limits of 5.0 mg/l. Occasionally, there are some spurious results that fall slightly above the limit of detection. However, when these are investigated, they do not suggest any contamination problem. After the introduction of the new 8015-Oil GC method, there were also a few cases where the 0.15 mg/l detection limit of the 8015-Oil GC method was exceeded. In these cases, the integrated spectrum of the results indicate that the TPH levels are always below 1.0 mg/l, as shown by the limited, but typical, data in Table 1 [Westbook, 2004b].

To date, water sampling of the EFH have shown no creditable instances of levels of TPH exceeding the initial detection limits established at the end of 1999.

5.2 Sinkhole Monitoring

At the time of the decommissioning of the DOE Weeks Island facility in late 1999, Sinkhole #1 was quasi-stable because the freeze wall was effective in stopping flow of groundwater through the fracture into the mine. However, because the Weeks Island Mine was then flooded, it was thought that no further inflow of groundwater into the underground chambers could occur [Molecke, 2000]. And consequently, sinkhole growth would cease. The freezing plant was also turned-off in the late summer 1999 time frame, leading to the eventual thawing of the freeze wall. The sinkhole at this point was filled to grade with sand. Nevertheless, it was realized that the thawing of the unconsolidated geologic materials above the cap rock and the salt dome could result in some additional void creation and potential soil movements and collapse.

An inspection of the Sinkhole #1 area in June 2001 found a rather abrupt and marked change in the condition of the sinkhole. The surface had dropped some 24 ft (288 inches). This was believed to correspond roughly to the time at which the freeze wall plug became completely thawed. Theoretical calculation of the thaw time suggested a relatively long period for thawing [Ehgartner, 1995a] with complete thaw of the freeze wall predicted for April 2003 [Ehgartner, et al., 2002]. The predictions are based on the measured temperatures in the center and monitoring well of the sinkhole. The physical evidence of the thawing was essentially based on the sinkhole response and the very last complete set of hydrological and temperature data from Monitoring Well 4270, located in the freeze wall about 8 ft from the sinkhole center, showing thaw at that location by May 2001[Ehgartner, et al., 2001].

Sand was again added to bring the surface to grade and address safety concerns. In addition, shortly after the observation of the sinkhole activity, two monument stations were emplaced, one station (west) was near the edge of the sinkhole and one (east) was essentially in the center of the sinkhole, to monitor further developments. The measured amount of drop of Sinkhole #1, during the first few months, is shown in Figure 7 [Ehgartner et al., 2001]. Over the first few months, the results are difficult to interpret. The west monument indicated a somewhat episodic response, and eventually showed little deepening. This is perhaps what could be expected from a monument on the edge of the sinkhole, where sand was continually being added to bring the surface to grade and prevent further slumping of the soil. In contrast, the east monument, emplaced somewhat after the west monument, showed a continuous drop at nearly a constant rate, at very nearly 1.07 inches/day. Subsequent to the initial drop of 24 ft, these results show that the sinkhole continued to deepen to the equivalent of approximately 31 ft by mid September 2001. To some extent the behavior was obscured by concurrent sand filling, since this tends to maintain a constant cone of withdrawal, and hence, a constant sinkhole diameter. Even considering this effect, the amount of sand added continued to increase over the early time frame, as shown in Figure 8 [Ehgartner, et al., 2001].

The apparent continued growth of Sinkhole#1 was of concern. Two scenarios for the continued response of the sinkhole were advanced [Ehgartner et al., 2002]. One scenario was based on the potential formation of voids in unconsolidated overburden as the ice thawed and the resultant water no longer supported the soil. The collapse of these voids produced the observed drop of the sinkhole, but continued void formation and collapse would eventually diminish and stop. Thus, the sinkhole would stabilize as the soil again consolidated. In this scenario, the amount of void created by thawing was calculated and predicted the sinkhole would deepen by some 32 ft at the freeze wall boundary [Ehgartner, et al., 2001]. This scenario was expanded to include the initial 24 ft collapse, which was thought to be of a large near surface void, and further indicated that the total

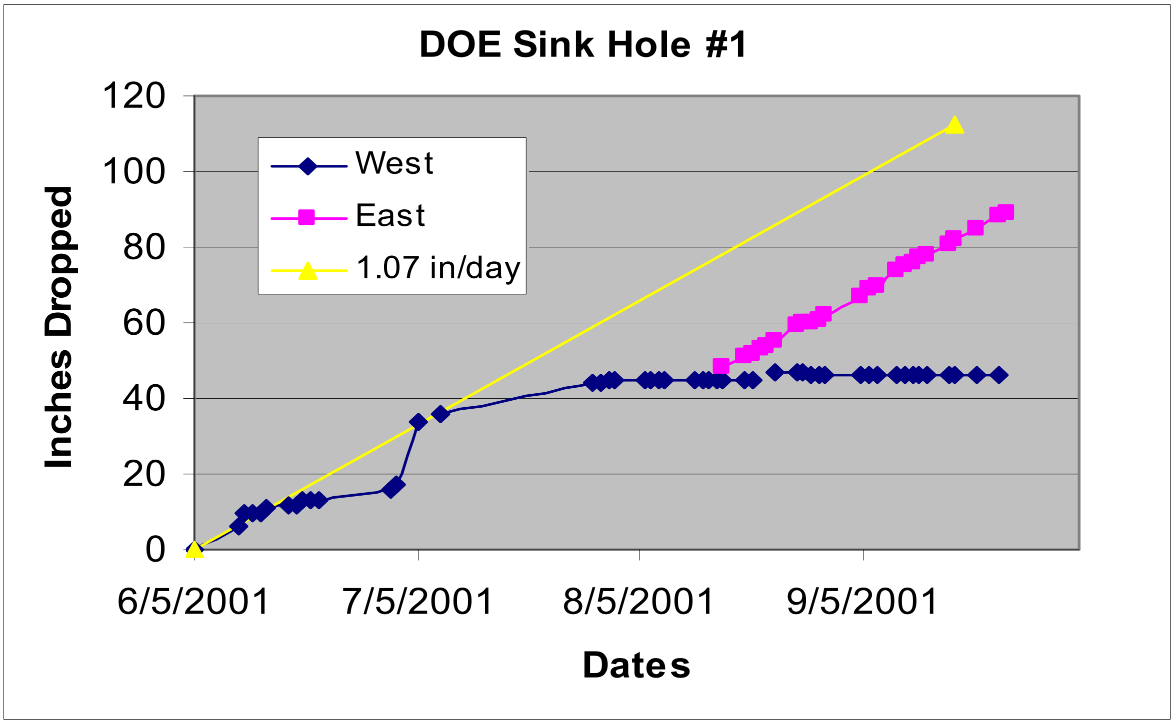

Figure 7. Sinkhole #1 History after June 2001 Abrupt Drop [Ehgartner, et al., 2001].

sinkhole drop could be about 75 ft, upon complete thawing. The other scenario was based on the existence of a continuous open fracture pathway from the sinkhole to mine chambers below. The concept was that the sand would continue to cascade through this pathway to pile up on the chamber floor. While the pile up would eventually plug the pathway, the quantity of sand required would be extremely large, perhaps as much as 25,000 yd^3. Regardless, the time history of the sinkhole would determine which scenario was correct.

In response to the renewed activity of Sinkhole #1, the monitoring and observation was carried out on a weekly basis, but was soon changed to a bi-weekly and then to a monthly schedule. By the end of 2002, the subsidence rate of the sinkhole had stabilized to about 1 inch/week [SPR ER, 2002].

Continued monitoring of the sinkhole showed the sinking rate had slowed significantly, until in 2004, when the rate was informally reported by site workers as 0.5 to 2.0 inch/month [Johnson, 2004]. The diminishing rate of sinking with time suggests the gradual compaction of the voids formed when the freeze wall thawed. This compaction will further diminish with time because of the gradual exhaustion of voids. Under this concept, further sinkhole dropping is expected to virtually cease.

However, it now appears that the configuration of Sinkhole #1 is more complex than the single sinkhole initially suggested. In November 2004, a small, 3 ft diameter by 6 ft deep, subsidiary sinkhole, #1A, appeared some 65 ft from Sinkhole #1. Although the obvious delay in the collapse of this sinkhole to the ground surface is pronounced, it is

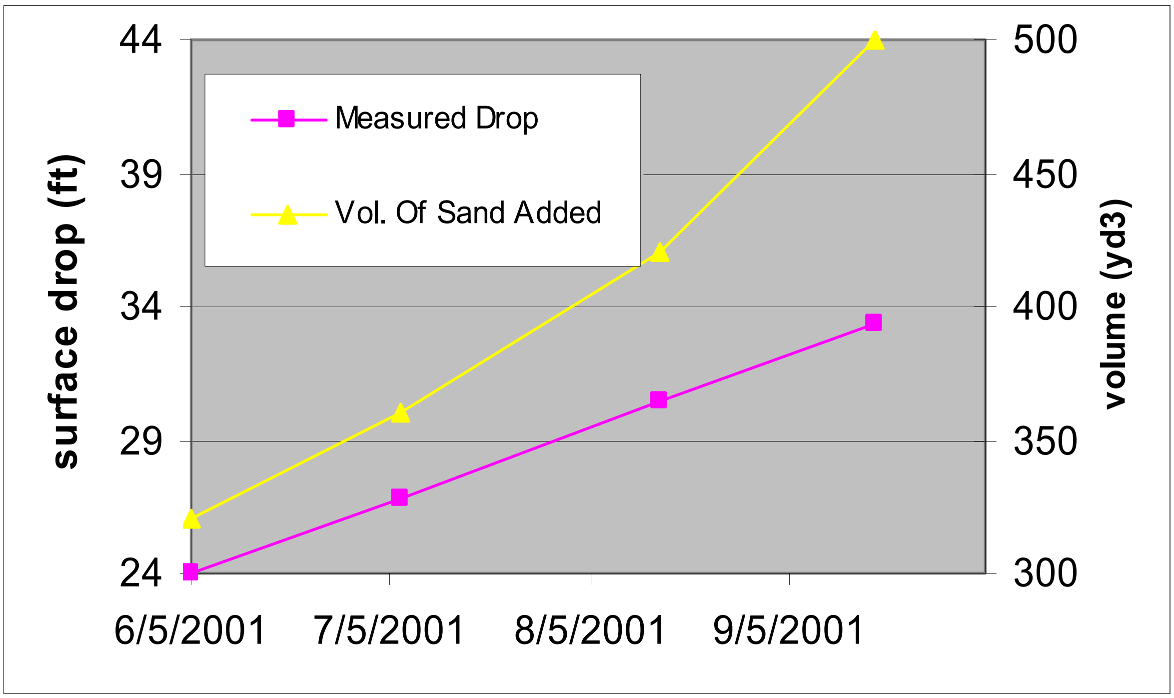

Figure 8. Sinkhole #1 Sand Additions after Abrupt Drop [Ehgartner, et al., 2001].

not difficult to realize that subsidiary effects around the main sinkhole could occur. In fact, this is most likely a manifestation of the reconsolidation collapse of a pre-existing void. While the outermost ring of freezing wells had a diameter of 54 ft, freezing of the ground beyond this diameter obviously took place. However, while the extent of the ground freezing was not determined, it was certainly well beyond the 54 ft freezing ring. Moreover, during the freezing process, Ehgartner [1995b] calculated the stress fields and potential for fracture formation as the salt was cooled to the freezing point of brine. The potential for radial fracture formation during this process extended beyond the freeze wall. Thus, the potential for new, ancillary peripheral groundwater paths into the sinkhole throat could exist during the freeze wall formation. This would give rise to the type of subsidiary sinkhole observed. Although the formation of additional subsidiary sinkholes may be possible, the very long delay in the development of Sinkhole #1A suggests that further sinkholes are unlikely.

The behavior of Sinkhole #2 must also be summarized. The sinkhole was found in 1995, was stable until 1998 when it started to deepen, and then became stable again. At the time of decommissioning, when it was still possible to observe, this sinkhole appeared stable. After decommissioning in 1999, quarterly surface walk-around inspections were no longer possible. These inspections had depended upon periodic removal of the surface vegetation over the perimeter footprint. When the vegetation returned, observation was impossible and personnel safety would be compromised with further walk-around inspections. It was believed the filling of the Weeks Island Mine and the Markel with brine would mitigate any further development of Sinkhole #2, and further would preclude other sinkhole formation by preventing flow of fresh water into the underground chambers.

In conclusion, it can be argued that the two previously known sinkholes along the periphery of the decommissioned Weeks Island facility are stable, and that the new subsidiary sinkhole near Sinkhole #1 will also prove stable. Continued growth in Sinkhole #1 is falling to zero, in accordance with the slow reconsolidation of the thawed soil. Moreover, it is expected that having the entire facility brine filled would severely retard or halt any further development of these sinkholes, or for that matter any as yet undiscovered sinkholes.

5.3 Surface Subsidence (Weeks Island and Markel-Morton Complex)

Surface subsidence is a natural consequence of removal of material during mining, leaving an underground void. Depending upon the amount of material removed, and the depth, subsidence may be more or less pronounced. The measurement of subsidence at Weeks Island has been ongoing since 1931, although the active mining started in 1902. Because Weeks Island has been the site of continuous, and even accelerated, mining activity, the subsidence is expected to continue into the future.

At the time of decommissioning, the dome contained three mines, the Weeks Island mine that had been used as a SPR crude oil storage facility, the interconnected Markel Mine that had acted as a transition commercial mine allowing development of a new mine, and a new Morton Mine that became an independent commercial salt mine in the dome. The Markel and Morton mines since they sit one above the other could be considered as part of the same complex.

It was anticipated initially that surface subsidence level surveys would continue during the Monitoring Phase at quarterly intervals, more frequently than required by the State agreement. However, the actual frequency was between a quarterly and semi-annual depending upon the subsidence activity and magnitude. In some cases, contract interruptions produced delays. Reports documenting the analyses of the surveys have been routinely published beginning in 1999 [for example: Bauer, 1999; Bauer and

Ehgartner, 2004]. On the average, surveys and their analyses have occurred more frequently than semi-annually. As is often the situation with extensive level surveys of this type, spurious individual measurements occur, usually because of monument damage or incorrect reading and recording. A different kind of error may occur when the initial benchmark elevation reading is in error, which causes the entire survey or survey loop to exhibit an erroneous change in elevation. Whenever, these errors occurred, they were noted and rectified, when possible, to give a corrected subsidence behavior. In no case did the initially spurious measurement indicating potential abnormal subsidence at a given monument persist in further surveys. As a result, general subsidence over the mines seems both contiguous and continuous, consistent with a well-behaved process.

At the time of decommissioning, the subsidence reflected the complicated history of the decommissioning process as well as the development of the Markel-Morton complex. A figure presented earlier (Figure 5, Section 4.5) summarizes this history. As the figure indicates, the Weeks Island Mine (DOE) and Morton Mine maximum subsidence were both increasing, nearly linearly with time, at relatively modest rates of 0.2 ft/yr and 0.18

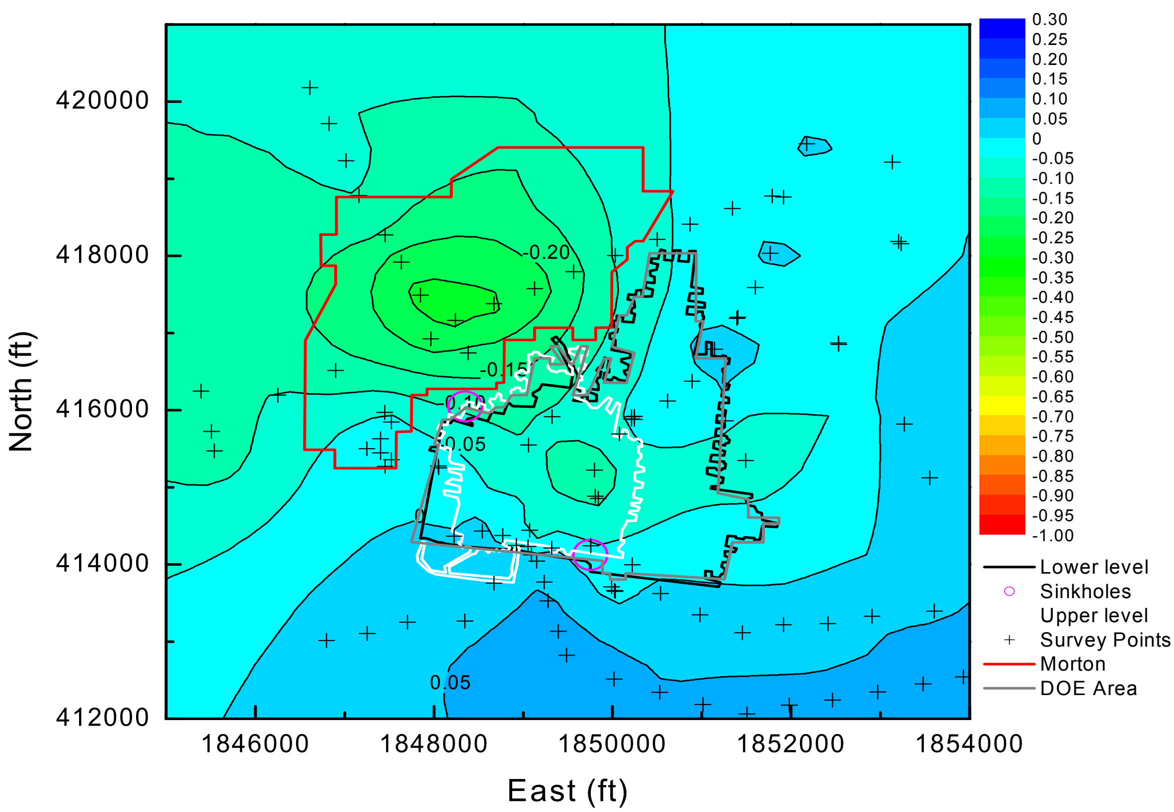

Figure 9. Subsidence Rates 4/00 - 9/00 (ft/yr) [Bauer and Ehgartner, 2004].

ft/yr, respectively. This changed abruptly in 1996, when the Weeks Island subsidence rate increasing markedly to 1.08 ft/yr as the withdrawal of oil from the Weeks Island storage facility was completed (the chambers were empty) and brine filling of the chambers began. This rate was much higher than predicted using geomechanics models. After brine filling and pressurization to hydrostatic pressure, the subsidence rate of the Weeks Island facility decreased markedly to about 0.13 ft/yr [Bauer, 2000]. The subsidence rate after brine filling is about 12 % of the maximum rate measured when the mine was empty and the lower level of the mine was being filled with brine. This is comparable to reduction noted following brine fill of other mines, which were initially empty [van Sambeek, et al., 1994]. The Markel-Morton (Morton) Complex subsidence rate increased only slightly over this time period. However, this was not necessarily solely from the drawdown because mining in the Morton Mine also continued.

While individual subsidence reports are available throughout the Monitoring Phase, the total subsidence situation can be summarized adequately at the beginning and end of the

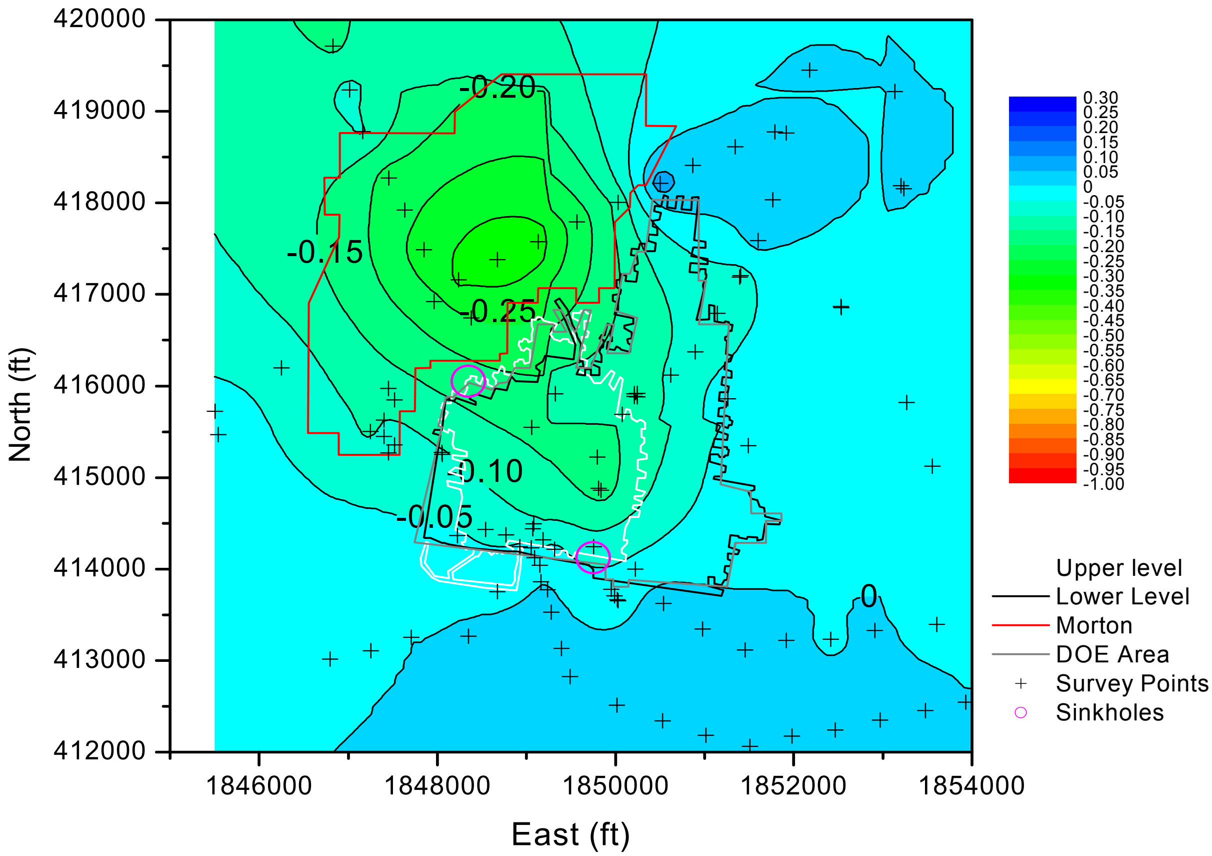

Figure 10. Subsidence Rates 8/03 - 2/04 (ft/yr) [Bauer and Ehgartner, 2004].

period using the subsidence contours over the entirety of the mines. Bauer [2004] gives the 4/00-9/00 subsidence rates, as shown in Figure 9, over the Weeks Island Mine and the Morton Complex. When the rates in this figure are compared to the rates during the time of decommissioning, as shown in Figure 5 (Section 4.5), it is apparent that the maximum subsidence rate contour has moved northwest from over the center of the Weeks Island Mine to over the center of the Morton Complex. Maximum subsidence rates contours over the period 4/00 – 9/00 are approximately –0.10 ft/yr over the Weeks Island and about–0.30 ft/yr over the Morton Complex. These can be compared to the 3/99 - 10/99 contour rates that were -0.30 ft/yr over the Weeks Island Mine and –0.10 ft/yr over the Morton Complex [Bauer, 1999b]. Remember, however, during decommissioning, the subsidence rates over the Weeks Island Mine were accelerated.

As noted previously, these higher rates over the Weeks Island Mine during brine filling were transitory and rapidly decreased when the mine chambers were completely filled with brine and pressurized to hydrostatic.

The rates found in Figure 9 can now be compared to those measured in the 8/03-2/04 timeframe as found in Figure 10, where the rates are approximately -0.15 ft/yr over the Weeks Island and –0.30 ft/yr over the Morton Complex. These are little changed over the five-year Monitoring Period, and the subsidence rates remain consistent. Some of the details of the contours, however, have apparently changed over the five-year period, perhaps because of inherent vagaries in contouring.

While the contour plots of the subsidence depression over the mines are very informative, trends are difficult to discern. As a result, the maximum subsidence rates as a function of time over the Weeks Island and the Markel-Morton Complex were extracted, and plotted for the time period before decommissioning in Figure 11, and after decommissioning in Figure 12. There is considerable variation in the individual results. This is a natural consequence of the relatively small changes in subsidence rates with time, the uncertainty in the individual survey results, and the natural variation in local subsidence response. Regardless, the uncertainties do not obscure the general trend of the subsidence over these mines. In fact an “average” line constructed through the data shows the trend. Before the decommissioning of the Weeks Island facility, and after the Markel mine was closed, but with the Morton Mine fully operational, the subsidence rates over the Weeks Island facility and the Markel-Morton Complex were almost identical. They ranged very close to -0.20 ft/yr, with the Weeks Island subsidence rate essentially constant, and the Markel-Morton Complex subsidence rate increasing by about 1 % per year.

The subsidence behavior changes after the decommissioning of the Weeks Island facility was complete. As shown in Figure 12, the Markel-Morton Complex subsidence rate appears to be a smooth continuation of the pre-decommissioning rate, with a rate of –0.23 ft/yr in 2000 and rising approximately 1.5 % /yr afterward. In contrast, the post-decommissioning rates over the Weeks Island facility decreased from being approximate –0.2 ft/yr in 1995 to –0.11 ft/yr in 2000. The post-decommissioning subsidence rate over the Weeks Island facility is increasing about 1.5 %/yr, essentially identically to that of the Markel-Morton Complex. The subsidence rates seem to be rising in parallel.

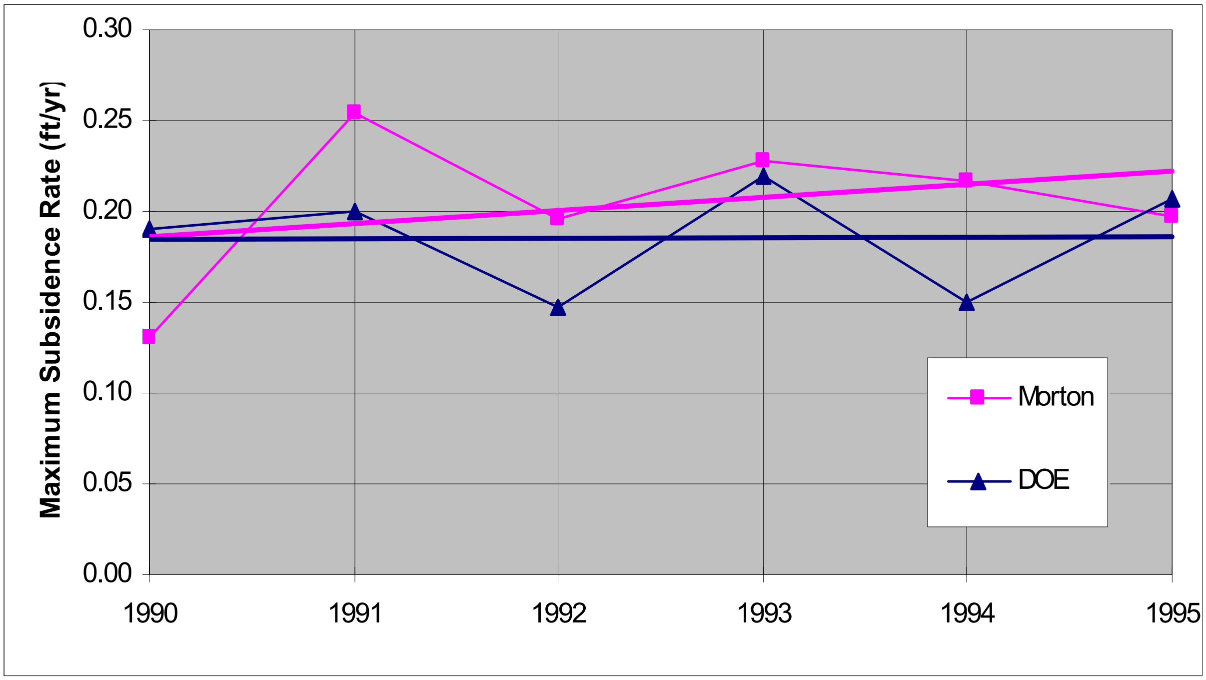

Figure 11. Maximum Subsidence Rates, 1990 - 1995 [Bauer and Ehgartner, 2004].

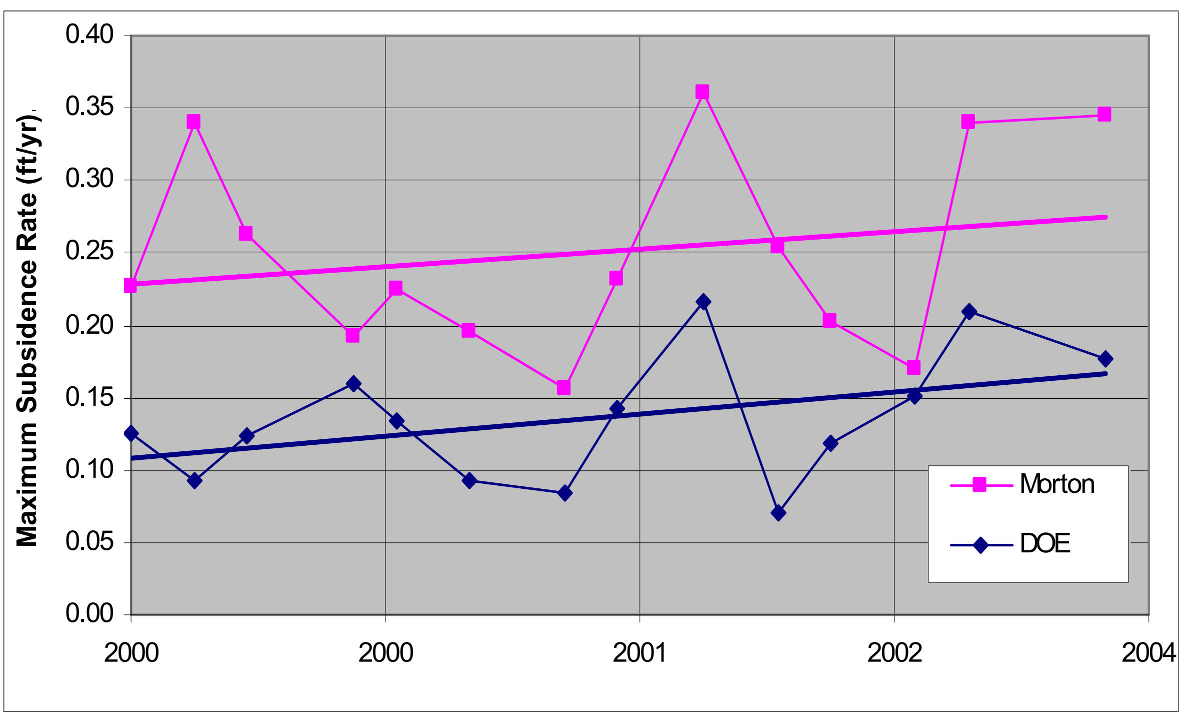

Figure 12. Maximum Subsidence Rates, 2000 – 2004 [Bauer and Ehgartner, 2004].

In the period between 1996 and 1999, during oil drawdown and brine filling of the Weeks Island facility, the subsidence rate reflected the changing condition of the underground. During drawdown, the subsidence rate over the facility increased markedly. The rate then decreased as the facility was filled with brine. The reason is straightforward. In judging the long-term subsidence response, transient effects during drawdown are thought to have little affect. In fact, the transient effects are the result of changes in stress conditions that cause changes in creep closure rate. Whatever the final stress conditions, they will govern the long-term closure rates. Even though some changes in damage levels in the salt must occur during the transition, these will eventually readjust. Thus, it is the subsidence rates that are established over the long-term state of the mine that are important and will be maintained.

Although the subsidence rates are instructive, the total subsidence is perhaps more instructive. While the measured total subsidence over the Weeks Island facility initially exceeded that measured over the Morton Complex, this could not be maintained. It is clear that the total subsidence over the Morton Complex, because it is an active mine, will eventually exceed that of the Weeks Island facility. In fact, as expected, the total subsidence values over the two facilities became just equal in 2004, and will diverge in the future. Rather than show the direct subsidence displacements, the same behavior can be illustrated in a slightly different manner.

As shown in Figure 13, the cumulative subsidence volume, as determined by a piecewise integration over the footprint of the respective mines of a grid multiplied by the local subsidence depth, gives a quantitative representation of the creep closure. Because the integration is only over the footprint of the mine, the volumes calculated will be smaller than the actual volume of the subsidence depression, by perhaps as much as 10 to 30%, as estimated by the areas under two-dimensional calculated subsidence profiles for the configuration of these mines [Hoffman, 1996]. In making such estimates it must be remembered that the spread of the subsidence depression depends upon the material properties used in the calculation, and can give either a broader or narrower depression.

While Figure 13 illustrates most of the subsidence response prior to decommissioning, including the transition during drawdown and brine filling, the post-decommissioning subsidence response is clarified in Figure 14 for the time period from 2000 to 2004. While the uncertainty, or scatter, of the raw survey data is relatively large, it is acceptable considering the difficulty in surveying and the limited number of survey monuments involved. However, once these survey data are integrated over the mine footprint to give subsidence volumes, the result becomes very well behaved, with little apparent scatter.

What makes both Figure 13 and 14 interesting is that the slope of these curves gives the subsidence/year, which can be interpreted as the mine chamber loss of volume/year. The mine chamber loss of volume/year can in turn be taken as the volume of brine out flow from the mine each year, once the mine is filled with brine. Thus, based on a rough differentiation, from Figure 13 we obtain mine volume loss rate of about 140,000 bbl/yr

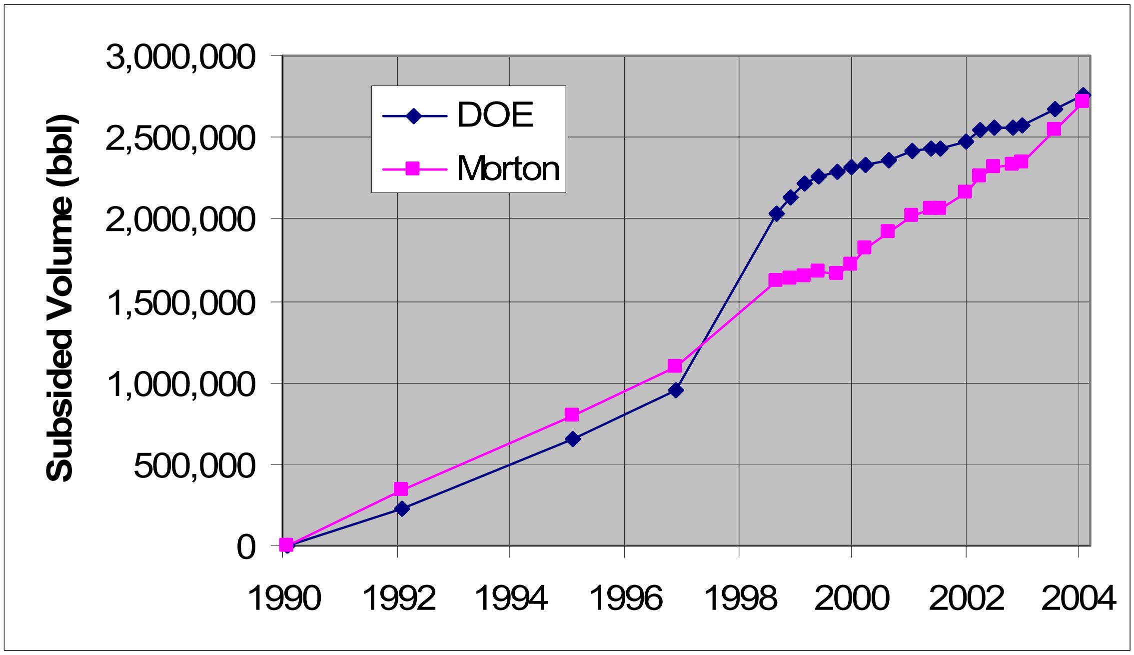

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Figure 13. Cumulative Subsidence Volume [Bauer and Ehgartner, 2004].

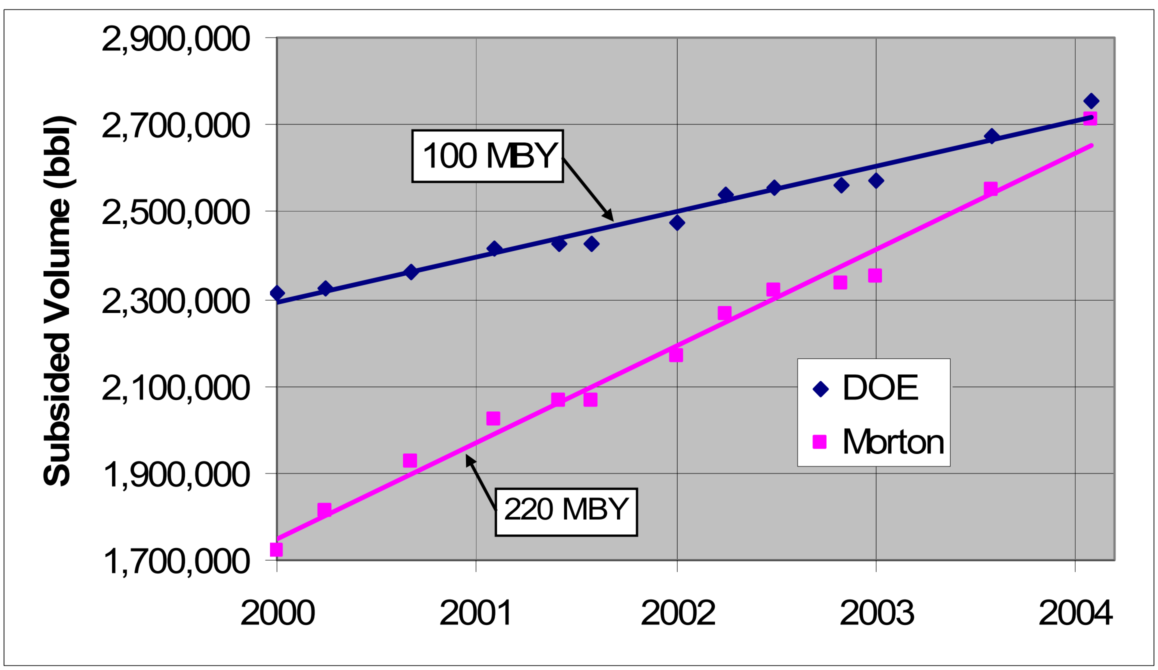

Figure 14. Cumulative Subsidence Volume, 2000-2004 [Bauer and Ehgartner, 2004].

between 1990 and 1997 for the Weeks Island mine. During the transition between 1997 and 1999, the Weeks Island mine loss rate increased to about 650,000 bbl/yr. Over this same time period, between 1990 and 1997, the Morton Complex loss rate was 158,000 bbl/yr, and thereafter gradually increases.

The same type of differentiation from Figure 14 gives a relatively constant volume loss rate for the Weeks Island mine of approximately 100,000 bbl/yr between 2000 and 2004. Over this same 2000 to 2004 time period, the Morton Complex loss rate is roughly 220,000 bbl/yr, and it is also quasi-constant on the scale of the graph. But, a somewhat larger scale shows that the Morton Complex mine volume loss is gradually increasing with time.

While subsidence continues over both the Weeks Island Mine and the Morton Mine Complex, the past and current history indicates the subsidence is stable, without local points of abnormal subsidence or other inconsistent behavior.

5.4 Hydrological Conditions and Brine Outflow

At the time of decommissioning, it was realized that the underground chambers would continue to close from long-term creep even though the chambers were filled with brine. A very direct way to monitor the creep closure is to measure the brine outflow from the mine. As noted previously, toward this end, the 30-inch diameter cased East Fill Hole was fitted a packer just below the top of salt, a 2 7/8- inch diameter tube was placed through the packer, and a tight-fitting flowmeter was inserted into the tube. Any outflow from the underground would have to pass through the flowmeter. Drill hole perforations just above the packer/instrument location assured the larger diameter cased hole was in equilibrium with the smaller tube. Further, the large diameter casing was perforated using shaped charges slightly above the top of salt to provide a flow path into the saline portion of the surface aquifer, considered safe for the disposal of the brine from the underground [Levin, 1999a]. The flowmeters were calibrated prior to installation. Their response was linearly proportional to the laboratory measured flow, with very little scatter of results [Levin, 1998].

Levin [1999b] determined the flow characteristics of the shaped charge perforations and found flows up to 2,500 bbl/yr were reasonable, while the perforations could dissipate 25,000 bbl/yr. However, these flow quantities may be considerably less than the outflow from the mine.

Over the five years of the Monitoring Phase, the response of the EFH flowmeter has been difficult to interpret. While the flowmeter appeared to respond correctly in a laboratory setting, when installed in the field, the flow measurements were not as expected; flows were exceedingly small and could be either out-of or in-to the mine, as shown in Figure 15. The reliability of the flowmeter was questioned and it was subsequently removed and laboratory tested, with emphasis on the response at small flows, but the results indicated the instrument had not changed and was indeed correct [Ehgartner, 2002]. Nevertheless, as the monitoring continued, the reliability of the flowmeter, primarily due to recent electronics failures, continues to be of concern.

Regardless of the problems, if the data are examined closely, only a few data points indicate negative flow. Most of the data indicate a positive flow, even though the quantities are quite small. The flow measurements indicate an outflow rate of only 300 to 400 barrels/yr.

Interestingly, the measured out flow volumes are substantially smaller than the mine closure volumes determined from surface subsidence. After brine filling of the mine, the subsidence volumes are on the order of 100,000 bbl/yr. This means that the brine out flow must be of the same order.

It also must be noted that the hydrologic heads could be determined from the four wells associated with Sinkhole #1. The hydrologic head as measured at the four wells is shown in Figure 16 [Westbrook, 2004c]. These heads change, as would be expected, according

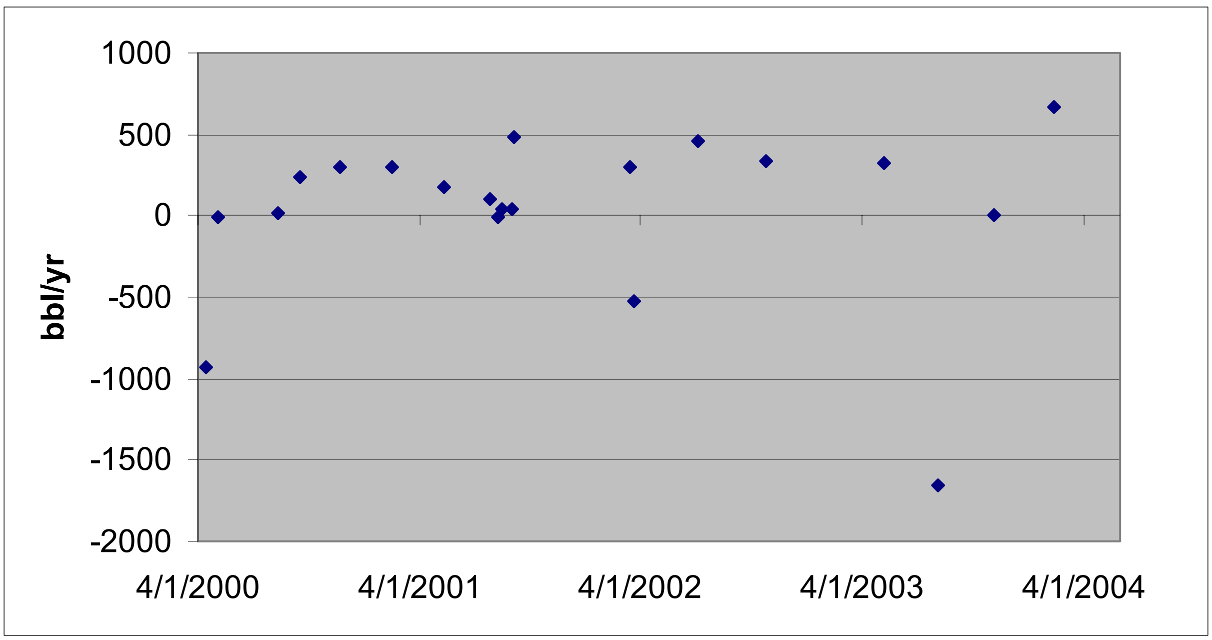

Figure 15. Brine Flow at EFH [Westbrook, 2004c].

to the local changes in precipitation that causes the water table to change. This is a possible explanation for the general decline of the water table beginning in 1999. The general flow remains in the south-southwest direction. There was slight flattening of the head between wells when the freeze plug melted [SPR ER, 2002] in 2001. But, this flattening could be coincidental. Nevertheless, post-decommissioning results seem to be compatible with the behavior prior to decommissioning, as perhaps expected. The groundwater system is a large system, so if flow is occurring out of Sinkhole #1, it is undetectable in terms of the water table. The water table is apparently stable within the local changes of meteoric water.

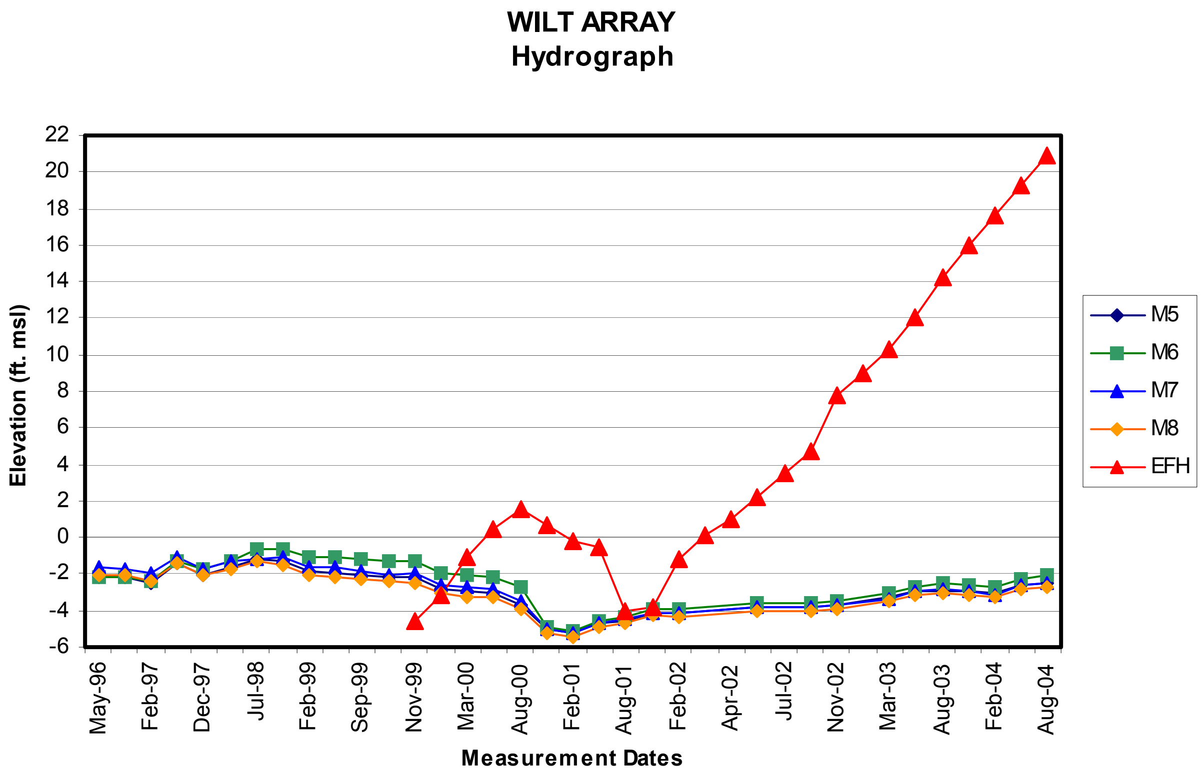

Figure 16. Water Heads at Sampling Wells and at EFH [Westbrook, 2004c].

The head as measured in the EFH possibly seems erratic, rising, falling and rising again over the time period of the Monitoring Phase. The levels measured seem usually to exceed the water table heads measured at the sampling wells. There is one interesting exception. The EFH head fell to become the same as the local water table from the sampling wells apparently coinciding with the complete thawing of the Sinkhole #1 ice plug. The EFH head then again increased markedly, with the most recent measurement at 22 ft above mean sea level (msl).

Currently, there appears to be a significant discrepancy between the out flows measured at the EFH and those volume change calculations by integrating the subsidence depression. The subsidence measurements suggest a volume loss of around 100,000 bbl/yr and that is to be compared to the EFH out flow measurements of 300-400 bbl/yr. Exactly how this apparent discrepancy occurs is unknown, at this time. Fortunately, the database offered by the hydrology measurements represents a relatively minor contribution to the monitoring results during the Monitoring Phase. Although some questions remain about the reliability of the brine flow measurements, and the meaning of these results, they may suggest primarily technical errors in fielding the EFH tests and not a problem with the decommissioned facility.

In summary, the hydrologic response of the groundwater measured at the sampling wells has been essentially unchanged over time, except for expected fluctuations from variations in precipitation. However, clearly, some questions remain on the accuracy and reliability of the flows measured at the EFH.

6. DISCUSSION AND SUMMARY

The Monitoring Phase at Weeks Island involved several rather straightforward objectives based on a series of field measurements and observations. As with any program of field measurements and interpretations, a number of unintentional problems occurred, primarily with the difficulty of measurements and with failures of analytic instruments. By-and-large, these problems were found, analyzed, and corrected. The result was reasonably reliable data and an accurate picture of the status of the decommissioned facility at the end of the five-year period of the Monitoring Phase.

Typically, the monitoring activities were in four areas: the monitoring of the surface groundwater through shallow wells for hydrocarbon contaminant, the monitoring of sinkhole development and growth with time, the measurement of surface subsidence over the Weeks Island Mine and the Markel-Morton Mine Complex, the measurement of the brine outflow from the East Fill Hole caused by creep closure of the underground chambers, and finally, measurement of the fluid levels in the shallow wells and the East Fill Hole.

Ground water contamination monitoring: As initially set forth, the sampling of the four shallow wells in the vicinity of Sinkhole #1 was scheduled on a quarterly basis as agreed upon by the DOE and DynMcDermott, the service contractor. Wells were drilled either slightly into or slightly above the top of salt or screened across the watertable to intercept lighter floating material. Water samples were to be obtained using procedures to assure to their integrity and then to be analyzed using an EPA 1664 IR method, which provided a measure of the Total Petroleum Hydrocarbon (TPH). The stated detection limit for this method is 5.0 mg/l of total hydrocarbon. This detection limit was considered small enough to establish background. Between November 1999 and November 2002 the TPH from the wells was below a 1.0 mg/l detection level, with no indication of contamination. However, in November 2002 sample analysis indicated several spurious readings above the detection limit, some so large, that if true, the sample would have been visually contaminated. Considerable effort was devoted to solving the problem, beginning with duplicate re-test samples and then utilization of a new EPA analysis method based on 8015-Oil gas chromatography (GC) which was more sensitive, more reliable, and interrogated the hydrocarbon spectrum. The sensitivity of the GC method is stated to have a detection limit of 0.15 mg/l. The spectrum could discriminate between crude oil and other hydrocarbons. When side-by-side samples of the wells were tested, the 8015 method test results were consistent and reproducible, with the spectrum integration of the sample always showing less than 1.0 mg/l, well below the action/background level of 5.0 mg/l. The 8015-Oil analysis method replaced the previous 1664 IR method in May 2003. Since that time no groundwater sample from the wells has exceeded the acceptable level.

While the exact reason for the failure of the 1664 IR method is unknown, it is suspected that conditions in the well changed with time to permit algae, or similar materials, or other chemicals to be introduced. This material interfered with the response of the IR instrument and produced erroneous results. The 8015-Oil GC method is specific to the crude oil spectrum, and hence, is not susceptible to interference from other materials.

Throughout the monitoring of the EFH, there were a few spurious results using the 1664 IR analysis method, but investigation indicated there was no contamination. Similarly, occasionally the detection limit of the 8015-Oil GC method was exceeded. However, integration of the spectrum for these tests still yielded less than 1.0 mg/l, and they were considered uncontaminated.

The general conclusion of the groundwater sample testing for TPH is that there was no contamination found within the initial limits of the 1664 IR analysis method. Erratic and incorrect analysis results were found using the 1664 IR method, which upon investigation proved to be the fault of some unknown interference with the method. Replacement of the 1664 IR method with the more accurate and reliable 8015-Oil GC method corrected the analysis problem.

Sinkhole monitoring: The discovery of Sinkhole #1 directly above the superimposed edges of the two Weeks Mine underground excavations in May 1992 was of immediate concern. This sinkhole apparently allowed an inflow of fresh surface water into the storage chambers with the attendant possibility of displacement of the oil to the ground surface. This eminent threat to the facility was initially controlled by the injection of saturated brine directly into the throat of the salt fracture leading into the underground storage chambers. Continued concern led to the construction of a freeze wall, eventually a freeze plug, extending to the top of salt and surrounding the sinkhole. Although the freeze wall and brine injection worked exceedingly well, it was realized sinkholes remained a severe problem and the integrity of the storage facility could not be assured over time. In fact, stress and fracture conditions leading to the existing sinkhole were not unique to that location. The decommission of the facility involved withdrawal of the oil and filling the chambers with brine to hydrostatic pressure. The brine filled facility would preclude further flow of fresh water into the mine through any sinkhole. The decommissioning process was completed in November 1999. Earlier, in August 1999, refrigeration of the freeze plug was stopped and the plug allowed to thaw.

Although brine injection and the freeze wall had stabilized Sinkhole #1 at the time of decommissioning, thawing of the ice plug apparently resulted in a sudden deepening of the sinkhole by 24 ft in June 2001. The concern was the magnitude of the continued deepening and the quantities of sand backfill required to fill the deepening hole. Two concepts were advanced: the sand was flowing directly through the salt fracture into the underground chambers or the ice thawing in the uncompacted overburden created a large volume of voids. Which of these concepts was accurate would be critical in controlling the sinkhole growth. If on the one hand sand was moving into the underground chambers, the quantity of sand to fill the chamber and plug the salt fracture from below would be extremely large. For void consolidation, on the other hand, it was calculated that the total sinkhole depth would be about 75 ft. Fortunately, continued monitoring of the sinkhole would determine the actual process. Just after June 2001, the Sinkhole #1 was deepening at a rate of about 1.0 inch/day. While the sinkhole continued to deepen with time, the rate of deepening subsequently gradually decreased, until at the end of the monitoring period the deepening rate is between 0.5 to 1.0 inch/month. The results “on the ground” support the concept of a diminishing growth of the sinkhole with time as the voids continue to consolidate and be eliminated.

A second sinkhole was found over the northwestern perimeter of the Weeks Island mine in February 1995, directly opposite to the first sinkhole. This sinkhole was initially 10 ft deep and later deepened by 3 ft. It was sand filled, but no further remedial action was taken. It was believed the filling of the facility with brine would prevent further growth, and this was verified on several occasions by observation following brine fill. But, observation eventually stopped because the walk-around surveys ended when vegetation control ceased.

As events would have it, a new, smaller sinkhole closely related to Sinkhole #1 appeared in November 2004 some 65 ft away from Sinkhole #1. Even though the long delay in the collapse of this sinkhole to the ground surface seems unusual, it is thought to be related to the extent of the freeze wall beyond the outer freezing ring and to the potential for the cooling of the salt to form radial cracks and possible ancillary water flow paths around the developing freeze wall. The long delay time suggests this subsidiary sinkhole is unique, and the rate of progression to the ground surface was very slow.

In summary, the ever-diminishing rate of deepening of Sinkhole #1 suggests that the process is self-limiting and will eventually stop. Moreover, the filling of the facility with brine has removed the potential for freshwater inflow and the driving influence for sinkhole formation and growth.

Surface subsidence monitoring: Monitoring of the subsidence over the Weeks Island mine has been ongoing since 1931. With the acquisition of the facility by the DOE, intense surface surveys were emphasized since 1983. The surveys also included the surface subsidence over first the Markel Mine and then over the Markel-Morton Mine Complex. These surveys were maintained throughout the drawdown, brine filling and decommissioning of the facility. During the 1990 to 1995 timeframe, with the Markel Mine abandoned, maximum subsidence rates over the Weeks Island Mine were essentially constant, at about –0.20 ft/yr. Maximum rates over the Markel-Morton Complex stated at about -0.20 ft/yr in 1990 but then increased at about 3 %/yr. From these subsidence rates, the Weeks Island Mine rates underwent a significant transition when the oil was withdrawn, rising to a very high level, and then falling again after filling to an even lower level of 0.10 ft/yr in 2000, rising 1.5 %/yr thereafter. In contrast, the Markel-Morton Complex maximum subsidence rate was about -0.23 ft/yr in 2000, rising 1.5 %/yr thereafter. The Weeks Island and Markel-Morton rates essentially parallel each other in recent years, suggesting the two systems may influence each other.

While maximum subsidence rates are of interest, the subsidence data can be further treated to obtain the subsidence volume through an integration over the area of the subsidence depression. This integration over just the area of the mine footprint, which underestimates the depression area by 10 to 30 %, gives a pre-decommissioning subsidence volume of about 140,000 bbl/yr. With a crude correction for the area discrepancy, this value compares well with a 1994 volume loss field measurement of 160,000 bbl obtained by strapping the oil/gas interface with time [Todd, 1994].

The post-decommissioning values of maximum subsidence rates differ from those expected. While the exact values differ considerably, the Hoffman and Ehgartner [1994] subsidence rates of the brine filled facility were calculated to be just 3.0 % of those of the oil filled pre-decommissioning mine. An actual field measurement of other flooded mines, while exceedingly crude and based on dry mine conditions prior to flooding, puts the brine filled subsidence rate at around 5.0 % of the dry mine subsidence rate, reasonably close to the calculated estimate. However, this is in contrast to the 35 % decrease observed at Weeks Island, where the post-decommissioning integrated subsidence volume is about 100,000 bbl/yr. At this time, there is no explanation of the apparent discrepancy in these estimates among flooded mines. Certainly, the quality and quantity of Weeks Island subsidence data suggest the subsidence volume calculations are accurate.

Interestingly, the apparent reduction in closure rate upon filling of the mine with brine is relatively modest, amounting to only a 35 % reduction. Conventional wisdom would have this as a much larger value, perhaps 90 to 95 %.

Perhaps of even more importance, at a volume loss rate of 100,000 bbl/yr, the Weeks Island Mine is losing only 0.12 % of the initial 89 MMb in volume per year. Together with the other observations on the continuity of the subsidence, this strongly suggests, within reasonable certainty, a relatively stable mine condition.

The subsidence results, when considered in their entirety, show a very stable behavior. There are no spurious results from individual monuments that persist with time to indicate other than consistent and contiguous subsidence. As anticipated, the Weeks Island Mine subsidence experienced a transition behavior during drawdown and brine fill, and then an overall decrease in the maximum subsidence rate. In contrast, the Markel-Morton Complex exhibited a continuous behavior during the same timeframe, eventually equaling and now exceeding the Weeks Island subsidence. Because of the nature of creep closure, subsidence over the Weeks Island facility and the Markel-Morton Complex will continue. In addition, the three-level Morton Mine remains an active operation, and the relative subsidence may increase with time.

Brine out flow and fluid level monitoring: Since the decommissioning process intentionally sealed all shafts and drillholes leading into the mine, it was essentially isolated except for the East Fill Hole, which was left open. For the Monitoring Phase, the EFH was modified to accommodate flowmeters that would measure the outflow of brine. As noted previously, the 30 inch casing was plugged just below top of salt, a 2 7/8-inch diameter tube was placed through the plug to accommodate the flowmeter, and the 30 inch casing was perforated using shaped charges at the level of a saline surface aquifer. Roughly, the measured flow rates were only 300 to 400 bbl/yr. The flowmeters measured a fluid output considerably smaller than anticipated, even registering negative flows in some instances, indicating flow back into the mine. Initial and subsequent calibrations, however, indicated the instruments were accurate. An important question was raised about the cause of the very low flow rates. The measured flows are in marked contrast to those volumes calculated from the subsidence depression integrations. In theory, these two volumes could be expected to be equal. At this time, this discrepancy remains unexplained.

Even though the explanation for the low measured flow rates in the EFH is unresolved, it is trivial to speculate that the EFH is not necessarily the only opening to the underground chambers. The salt fracture beneath the original Sinkhole #1 is believed, from direct tracer evidence, to be connected to the underground, as well. If this is true, then perhaps the two systems accommodate the total outflow of brine and in fact may form a hydraulically linked system through the mine.

The water levels measured at the four sampling wells are very consistent among themselves over time. Although the level fell between 1999 and 2001 by about 2.0 ft, and later remained stable, there is no indication that this is other than a response to local precipitation. However, the timing of the fall in water table does correspond, probably coincidently, with the time of oil withdrawal and brine filling during decommissioning.

The only other measurement of water head was in the EFH. Here, the EFH measured water level behavior was somewhat erratic. It has usually remained above the water table measured in the sampling wells, except for a brief period when they were nearly the same; coincidently, coinciding with the melting of the freeze plug of Sinkhole #1. While the cause of this behavior is unexplained, the limited hydraulic conductivity of the EFH perforations may have some bearing.

In terms of the overall monitoring program, the problematic EFH flow measurements are a relatively minor contribution, even though they are unsatisfying. Sometimes, the desire for unique data causes development of sophisticated measurement systems. The fielding of these systems often leads to unanticipated consequences. This may apply to the EFH flowmeter system. Never the less, the disposition of the quantities of brine from creep induced mine closure remains an open question.

7. CONCLUSION

The status of the decommissioned Weeks Island facility at the completion of the five-year Monitoring Phase is presented in this report. The general databases supporting the monitoring efforts, the problems encountered, and the resolution of these problems point to the diligence of the monitoring efforts. In terms of the preponderance of evidence the reasonable and expected responses from the major components of the Monitoring Phase suggest the decommissioned site is stable and secure. Based on the monitoring results, there is reasonable confidence in the conclusions reached. While the desire would be to fully answer all questions concerning the behavior of the decommissioned mine, the uniqueness of the system and current state of art in technology will always limit our understanding. That being said, the goals of the monitoring program have been met. Ultimately, discussions between the DOE and the State will determine whether or not further effort is necessary.

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