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# MINE-INDUCED SINKHOLES OVER THE U. S. STRATEGIC PETROLEUM RESERVE (SPR) STORAGE FACILITY AT WEEKS ISLAND, LOUISIANA: GEOLOGIC MITIGATION AND ENVIRONMENTAL MONITORING

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ABSTRACT

A sinkhole formed over the former salt mine used for crude oil storage by the U.S. Strategic Petroleum Reserve at Weeks Island, Louisiana. This created a dilemma because in-mine grouting was not possible, and external grouting, although possible, was impractical. However, environmental protection during oil withdrawal and facility decommissioning was considered critical and alternative solutions were essential. Mitigation of the sinkhole growth over the salt mine was accomplished by injecting saturated brine directly into the sinkhole throat, and by constructing a cylindrical freeze curtain around and into the dissolution orifice at the top of the salt dome. These measures vastly reduced the threat of major surface collapse around the sinkhole during oil transfer and subsequent brine backfill.

The greater bulk of the crude oil was removed from the mine during 1995-6. Final skimming operations will remove residual oil trapped in low spots, concurrent with initiating backfill of the mine with saturated brine. Environmental monitoring during 1995-9 will assure that environmental surety is achieved.

## SINKHOLE FORMATION AND ISSUE IDENTIFICATION

The initial sinkhole at the Weeks Island SPR site was first observed in May 1992. It gradually enlarged and deepened, concurrent with the increasing dissolution of salt over the mined oil storage area below (Neal and Myers, 1995). Being small at first, it allowed time for an orderly study and decision process to proceed.

A second and much smaller sinkhole was first noticed in early 1995 on an opposite edge of the SPR mine, but with a very similar geological and mine mechanics setting. Both sinkholes formed where the edges of the upper -152 m (-500 ft) and lower -213 m (-700 ft) storage levels are nearly vertically aligned. The coincidence of vertical alignment maximizes the tensional stress development, leading to fracturing in the salt. Such cracking takes years to develop, perhaps 20 or more (Neal et al., 1996). The cracks then become flowpaths for brine incursion, wherein after time brine seeps into the mined openings. Undersaturated ground water gradually enlarges the cracks in the salt, leading to further dissolution and eventual collapse of the overburden to form sinkholes. Other geologic conditions within the salt and overburden may have been secondary factors in controlling both mining extent and sinkhole location.

Recognition of sinkhole causative processes led the Department of Energy to a decision in December 1994 to decommission the facility and relocate the oil to other storage facilities. During the oil transfer, mitigation was accomplished by two separate but complementary means, either of which may have been effective alone.

## MITIGATION

Beginning in August 1994 and continuing to the present (1997), the injection of saturated brine directly into the sinkhole throat (Fig. 1) some 76 m (250 ft) beneath the surface has practically arrested further dissolution and sinkhole growth, buying time to make adequate preparation for the safe and orderly transfer of crude oil to other storage facilities (Bauer et al., 1996). This mitigation measure marked the first time that such a control procedure had been used in salt mining. Previously, all control had been achieved by in-mine and/or surface grouting. Brine injection will continue through final oil removal and the subsequent backfilling with saturated brine.

Brine injection was planned to keep pace with, or slightly exceed, natural inflow into the mine, as monitored in the fillhole sump (Fig. 2). Injection rates were gradually increased from about 10 to 25 liters per minute (3-7 gpm). The specific source(s) of mine inflow, although believed to be primarily through the sinkholes, was only one of many uncertainties. The borehole access provided by several penetrations into the sinkhole throat afforded multiple approaches for the injection operation. Multiple injection sites

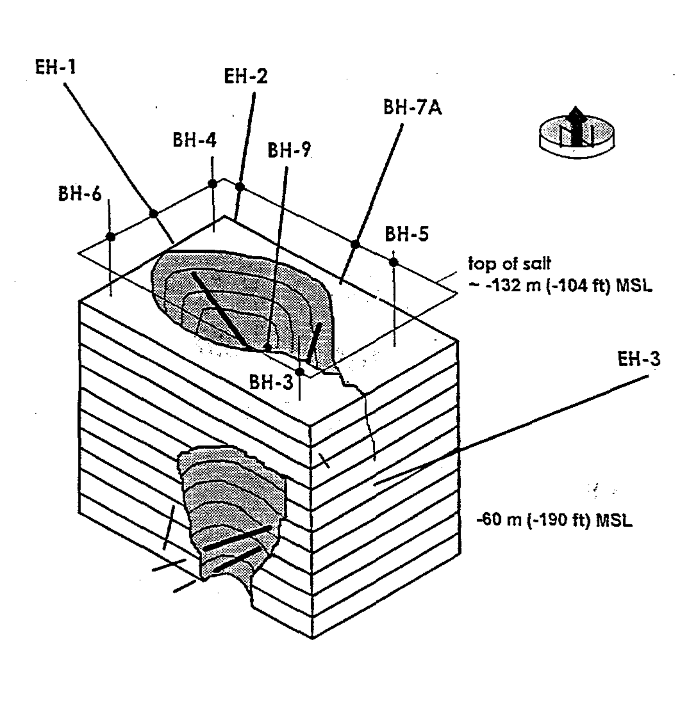


Fig. 1 Diagrammatic representation of exploratory drilling and sinkhole throat. Boreholes BH-3, 4, 5, and 6 were drilled for crosswell seismic tomography; slantholes BH-7A and 9 were drilled for throat definition. EH-1, 2, and 3 further defined the throat and provided decisive information regarding grouting potential. Accented segments are throat penetration.

became necessary because of intermittent interruptions in brine delivery caused by salt crystallization in lines and flowmeters brought on by cold weather. There were also periodic instrumentation problems.

To monitor the hydrologic effect of brine injection, an In Situ Permeable Flow Sensor (Ballard and Gibson, 1995) was placed at the bottom of borehole BH-9 in October 1994. This probe was located within the sand-filled conduit about three meters below the top of salt, and measured the flow rate of brine up and out of the sand-filled conduit (as a result of the excess brine injected below in BH-7A). Flow data from this probe allowed the flow rate of brine down the sand-filled conduit from the brine injection point to the mine to be calculated from the difference between the brine injection rate deep in the sand-filled conduit and the flow rate up and out of the sand-filled conduit at the top of salt. These values were in good agreement with brine inflow rates into the mine measured in the fill hole sump, strengthening the hypothesis that the sinkhole was in fact hydrologically connected to the mine. Both measures of the flow rate down the sand-filled conduit increased steadily during the early part of 1995, from about 7-11 liters per minute and then flattened out during the summer. The injection of brine into the throat and concomitant slowing of dissolution has altered the natural hydrologic environment in significant ways. Had this not been accomplished, the sinkhole growth rates would have progressed significantly (Russo, 1994).

To provide added insurance during oil transfer, a freeze curtain was constructed in 1995 around the principal sinkhole by installing 54 wells, which provided access to freeze the overburden and top of salt to a 67 m depth. Construction began in June 1995 and was completed within five months (Fig. 3). The wall was formed by chilling calcium chloride refrigerant in the wells to an average temperature of -38° C (-36° F) and circulating it in three circumferential rings in and around the sinkhole. Installation of the freeze wells included the innovative use of a movable rig platform straddling the sinkhole and mounted on rails outside the well area. This allowed freezing to commence on the outer ring while the inner ring wells were being drilled and prepared. At times, three drill rigs were operating simultaneously within the relatively small area of the sinkhole. The outer ring of twenty-two wells, with a diameter of 54 ft, was drilled approximately 3 meters into salt (-38 m MSL) to anchor the freeze wall into the salt stock. The middle ring of twenty-two wells, with a diameter of 14.6 m, was drilled at or slightly into the salt (-35 m MSL). The inner ring of 10 wells, with a diameter of 12 m, was placed at the top of the salt. Five of the inner ring of wells did not tag salt and are assumed to be in the area of the sinkhole cavity.

The final configuration of the freeze wall during drawdown was an ice cylinder 6 m thick with a nominal outside diameter of 21 m. Continued freezing formed an essentially cylindrical icewall in the zone of saturated ground water between the ground surface and the top of salt. The brine levels in the freeze wells were modified in April 1996 to concentrate freezing at the lower depths, near the top of salt (-24 to -38 m MSL). The resultant "ice cap" (plug) functions similar to the ice wall cylinder, but requires less energy to maintain. This cap will be maintained until the crude oil storage chambers have been emptied of crude oil and filled with brine, scheduled for June 1998.

A piezometer and flow meter monitoring system has provided the means to balance brine injection and prevent inflow of undersaturated groundwater. The mitigation system has functioned well and by November of 1996 ~~more than 90%~~ about 95% of the oil inventory had been safely removed. Drawdown of the oil was expected to be completed by December 1996. Then, residual oil in the mine will be reclaimed by skimming in conjunction with brine filling. Backfilling of the SPR mine with saturated brine after the oil is removed will help ensure future stability by ~~minimizing~~ greatly reducing further salt creep closure, thereby preventing additional sinkhole formation. Environmental monitoring, to be described, has been conducted throughout the decommissioning process and will continue for at least five years following site abandonment, currently scheduled for mid-1999.

## CONTINUING EFFECTS AND SINKHOLE PROGRESSION

Under conditions of partial oil fill, the processes of subsidence and fracturing caused by continuing salt creep around the mined openings is predicted to continue indefinitely. Additional sinkhole development would likely occur within a few years if the mine

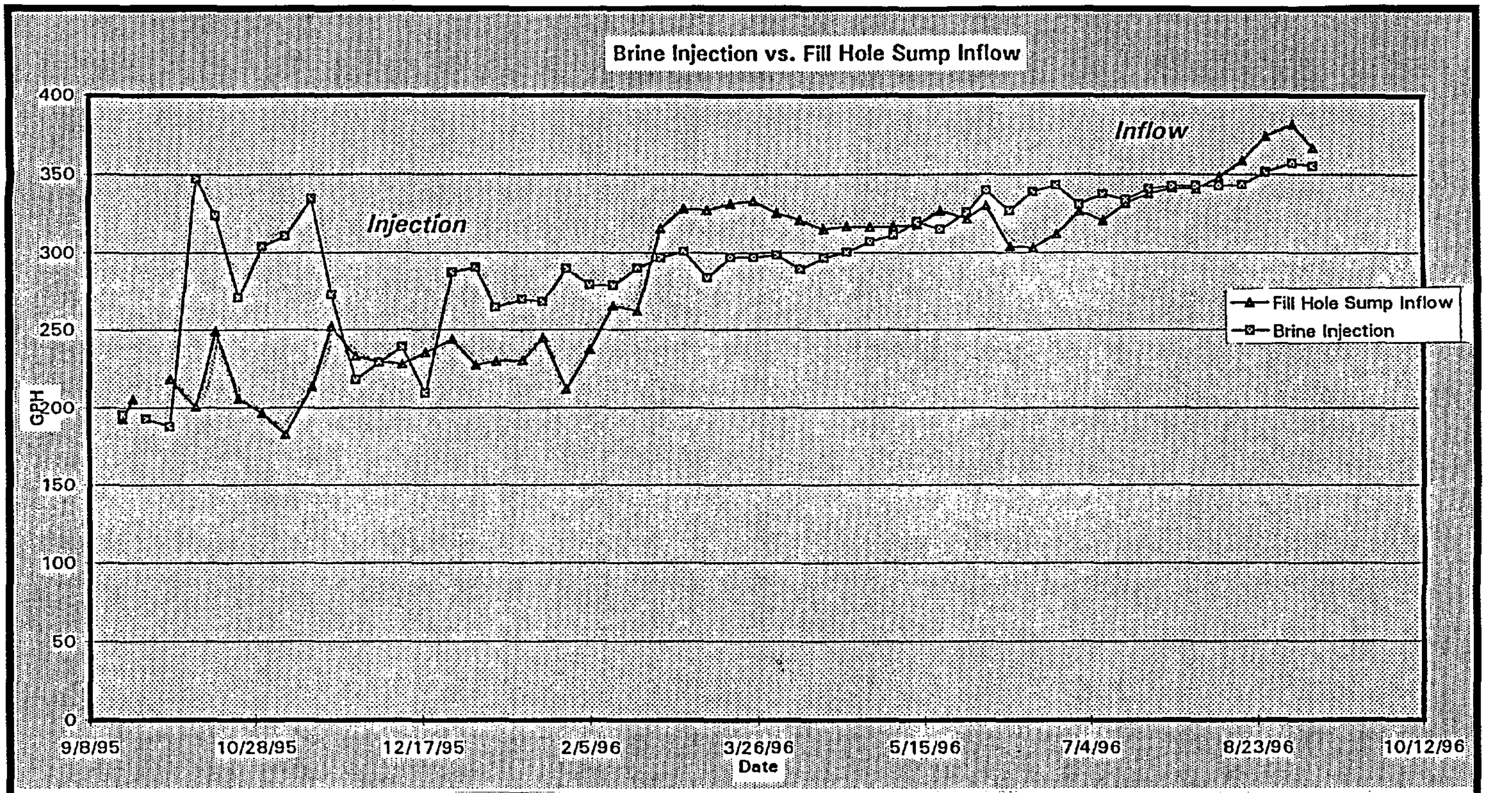


Fig. 2 Comparison of brine inflow rate into the fillhole sump with that injected into the throat of the principal sinkhole. The respective volumes and generally increasing trend are similar, suggesting a common connection.

were left at atmospheric pressure. Once the mine is filled with saturated brine, as mine closure plans now assure, creep and subsidence rates will be considerably reduced, so there will be much less opportunity for further sinkhole development

An earlier leak in late 1978, in an area known as the "Wet Drift" (Acres, 1987), might have been a forewarning of events to come. Although in-mine and surface-based grouting controlled the leak at the time, it could just as easily have become uncontrollable and formed a sinkhole(s) then, had the appropriate mitigation steps not been taken. The location of that occurrence was also near the coincident boundaries of the upper and lower mine levels. However, at the time of the Wet Drift leaks, the technology needed to understand the mine conditions, predict future events, and thus influence management decisions was not considered.

ENVIRONMENTAL MONITORING PLANS

Environmental protection has been a significant concern throughout the construction and operation of the SPR and is the primary reason for decommissioning the Weeks Island site. DOE published an Environmental Assessment with attached Finding of No Significant Impact (FONSI) for decommissioning the oil storage facility (DOE, 1995) Environmental monitoring will provide assurance that the objective of maintaining environmental integrity is being met. Once the oil is removed by the pumping system to the extent possible, subsequent skimming operations will remove ~~all but an estimated 0.03% of the total oil~~ originally stored in the mine. The mine will then be completely filled with saturated brine ~~and will become stabilized~~.

Monitoring efforts which specifically address sinkhole-related concerns commenced in 1994 and will continue through decommissioning. These efforts are summarized as follows:

*Perimeter inspections* were instituted in 1994 and are conducted quarterly for the purpose of identifying new sinkholes or other mine-related subsidence effects. An en echelon alignment of sinkholes over the edges of other mines has been observed. The most likely areas of future occurrence at Weeks Island are adjacent to the existing sinkholes. Surface inspections during oil removal are now concentrated around those locations. Although neither timing nor location is predictable with precision, the study of numerous sinkholes elsewhere shows that progression is inevitable, provided that relevant conditions and enough time exists for development. The second sinkhole was discovered in late February 1995 during a routine inspection. Dense vegetation hindered visibility and accessibility, hence inspection effectiveness. Therefore, the surface over the upper level perimeter was cleared in 1995 and is cleaned periodically along a 30 m (100 ft)-wide swath to remove new growth. These inspections are scheduled to continue through June 1999, at which time the mine should stabilize as a result of the brine backfill, making further sinkhole development highly unlikely.


Fig. 3 A cylindrical freeze curtain was constructed around the sinkhole, extending 6 m into salt, so that groundwater inflow was inhibited, if not stopped. A hydrologic monitoring system consisting of piezometers below the top of salt and brine injection within the the sinkhole throat confirmed the integrity of the mitigation.

*Subsidence monitoring* has been conducted annually since the early 1980s, beginning after the mine was filled with oil. The monitoring system was upgraded in 1990 with the addition of some 80 new monuments, several of which extend into salt. The survey data has provided the most accurate and complete subsidence data over any Gulf coast salt mine. The results define two well developed subsidence fields over the SPR and adjacent Morton Mines (Nieland et al., 1994; 1994; Yeh, 1994).

Computational *mechanical modeling* has shown that once the mine is backfilled with brine, creep closure and consequent subsidence will be reduced to less than 3% of its present value and that the mine will be stable (Hoffman and Ehgartner, 1994; PB-KBB, 1994; Van Sambeek et al., 1994). These calculations are borne out by experience from Jefferson Island and Belle Isle mines, since their flooding and abandonment in 1980. The monitoring of subsidence will continue through April 1999 and is expected to show that the predicted stabilization of salt creep has been achieved. The stabilized mine is predicted to close at a rate that will account for only about 45 l (12 gal)/hr or about 2,500 barrels per year (Hoffman and Ehgartner, 1994).

A *creep closure / brine release* monitoring system is planned for the East Fill Hole, consisting of a low-volume flowmeter and a piezometer to measure hydrostatic pressure. These data will be compared with modeled volumes of brine anticipated for pressure relief to the saline portions of the aquifer, estimated at about 2,500 barrels per year. Additional monitoring for TPH may also be conducted at this location.

*Hydrologic monitoring* will be conducted in four wells near the first sinkhole to test for possible groundwater effects resulting from hydrocarbon leakage, if any, or from brine effusion. Samples will be collected every four months from the monitoring wells through August 1999, and annually thereafter through 2004, testing for total petroleum hydrocarbons (TPH) on 8 m (25 ft) intervals below the water table. Baseline determinations have been made following the initial sampling in April 1996.

## IMPLICATIONS

The principles learned at Weeks Island should provide mine designers and operators knowledge to understand the occurrence of sinkholes, plan for their progression when they occur, and to minimize and mitigate their adverse effects.

## ACKNOWLEDGMENTS

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