

Replenishment of Salt to the Bonneville Salt Flats: Results of the 5-Year Experimental Salt Laydown Project

W.W. White III, P.G., U.S. Bureau of Land Management

Abstract

From November 1997 to May 2002, Reilly Industries, Inc. (Reilly) and Bureau of Land Management (BLM) conducted a Salt Laydown Project in an attempt to increase the salt-crust thickness of Bonneville Salt Flats (BSF). The objective of the 5-year experimental project was to replenish approximately 1.5 million tons of salt and add a 0.4-inch thickness of new salt crust to the existing salt crust each year. The Salt Laydown Project demonstrated that sodium-chloride salt in brine removed from BSF for mineral extraction can be replenished.

During the 5-year period, 6.2 million tons of sodium-chloride salt was transported back to BSF. The average annual 1.2 million tons of salt exceeded an estimated annual salt loss of 0.85 million tons. Over the 5-year experiment, 4.2 million tons of salt removed for mineral extraction was replaced by 6.2 million tons of Laydown salt. The difference resulted in a net addition of about 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system. Before the Laydown Project, some of the brine removed from BSF was replaced by meteoric precipitation, which dissolved salt crust. During the Laydown Project, the removed shallow-aquifer brine was believed to be mostly replaced by Laydown brine, which generally approached halite saturation and consequently minimized salt-crust dissolution.

Satellite imagery shows a 5-square-mile increase in the salt crust from 1997 to 1999. Based on the new salt-crust area and its measured thickness of 0.25 to 1 inch, about 0.6 million tons of salt were added to the existing salt crust. The 2-inch increase to salt-crust thickness expected as a result of the project was not observed in measurements from recent test pits and auger holes excavated in BSF. However, geochemical modeling suggests that 17 to 25 million tons of additional salt could be assimilated into the shallow-brine aquifer beneath BSF. Therefore, excepting contribution to the new salt-crust area, most of the 6.2 million tons of salt transported to BSF was apparently incorporated into the underlying shallow-brine aquifer. This may contribute to additional salt-crust formation in the future.

Introduction

The Bonneville Salt Flats (BSF) are located in the western part of the Great Salt Lake Desert of northwestern Utah. BSF is part of a large playa that occupies one of several enclosed sub-basins that comprise the Great Salt Lake Desert (fig. 1). These sub-basins include the Bonneville Salt Flats, Pilot Valley, and the Newfoundland basin. BSF is roughly divided into a north and south half by the east-west trending Interstate Highway 80 (I-80) and the adjacent Western Pacific Railroad right-of-way. The Western Pacific (now Union

Pacific) Railroad right-of-way is parallel to, and 1,400 feet south of I-80. BSF's north half includes sites of a historical circular race track and the 10- to 12-mile-long International Track, and is dominated by public land managed by U.S. Bureau of Land Management (BLM). Its south half is mainly private and dominated by commercial potash production. Twin cities of Wendover, UT and Wendover, NV are adjacent to I-80 and 4 miles west of BSF's western margin.



Figure 1. A portion of the Great Salt Lake Desert showing sub-basin locations (Bonneville Salt Flats, Pilot Valley, and Newfoundland basin).

Societal Need for the Salt-Laydown Project

Reported depletion of salt-crust thickness has been a concern to the public and land-managing agencies for at least 26 years (McMillan, 1974, p. 1; Lines, 1979, p. 4). This concern is based on changes in salt-crust area and volume reported between 1960 and 1988 that were measured north of the Western Pacific Railroad and I-80. McMillan (1974, p. 3) reported a 9 and 15% respective decrease in salt-crust area and volume during 1960–1974. Brooks (1991, p. 8) calculated 20 and 30.6% respective decreases in salt-crust area and volume during 1960–1988.

Because the BLM, Reilly Industries, Inc. (Reilly), and the racing community (represented by “Save the Salt” - STS) were concerned about the reported deterioration of BSF, they attempted to replenish salt to BSF through cooperative agreements. In 1991, Reilly and STS jointly funded a salt-replenishment feasibility study that resulted in a Salt-Laydown facility plan (Bingham, 1991). According to the plan, sodium chloride (NaCl) brine would be pumped out onto BSF at a rate of 6,000 gallons per minute, 24 hours per day, for 6 months (November–April) during each year of the program. This experimental program was scheduled to operate for 5 years. The Salt-Laydown facility plan suggested that up to 7.5 million tons of salt could be deposited during a 5-year period over a 28-square-mile area. According to Bingham (1991, p.2), the project could result in a 2-inch addition to the existing salt-crust thickness.

Based on the 1991 salt-replenishment feasibility study, BLM and Reilly entered into a Salt-Laydown Agreement in 1995. Under the Laydown Agreement, Reilly financed the installation and operation of a \$1,000,000 Salt-Laydown facility, and BLM and Reilly initiated a cooperative monitoring agreement to measure the amount of salt delivered to BSF each year of the program. The Laydown Project began delivering brine to BSF on November 1, 1997, and completed the 5-year experiment on May 2, 2002. Reilly is currently continuing the Salt Laydown Project on a voluntary basis.

Previous Work

Published pre-1997 studies (i.e., pre-Salt Laydown Project) of the BSF range from investigations conducted from 1925 to 1993 and include work from the following: Nolan (1927), Turk (1969, 1978), Lindenburg (1974), McMillan (1974), Lines (1978, 1979), USGS Conservation Division (1981), Brooks (1991), Mason and others (1995), and Mason and Kipp (1998). Details of these studies and their conclusions are summarized in White (2003).

Objectives

This paper summarizes the results of the 5-year experimental Salt Laydown Project that was initiated on November 1, 1997, and completed on May 2, 2002. Also included is application of the TEQUIL geochemical model to predict possible changes in BSF salt-crust thickness as a result of halite dissolution from specified rainfall events.

This report’s objectives are to: 1) describe components and operation of the Salt Laydown Facility, 2) explain and quantify results from 5 years of Laydown Project operation and compare project data with BSF baseline data, 3) compare pre- and post-Laydown salt-crust thicknesses and areal extent, and 4) evaluate effects of mixing Laydown brine with shallow-aquifer brine using the TEQUIL model, and provide explanation for the fate of the Laydown salt in the BSF solid-liquid system.

Laydown Facility Description

The Laydown facility (fig. 2) is composed of brackish-water supply wells, about 11 miles of transfer ditches and associated pumps, three evaporation ponds comprising about 1,300 acres of bedded salt deposits, and a brine-distribution manifold. Because the ditch system and brine-distribution manifold traverse a 13-mile distance over flat terrain, the biggest challenge is to move water from one end of this flat area to the other. The following description of the Laydown Facility shows how this water movement is accomplished.

Brackish water is obtained from seven alluvial-fan wells on the south flank of the Silver Island Range. Brackish water contains from 6.2 to 8 g/L TDS (total dissolved solids) (Mason and Kipp, 1998, p. 49), compared with the shallow-brine aquifer that averaged 244 to 297 g/L TDS during 1994–2002. Brackish water from the seven wells is pumped into a series of transfer ditches that move water south and under I-80, a distance of 4.5 miles. To keep the brackish water flowing, Brackish-water pump #1 (BW#1) was installed in the transfer ditch south of I-80. A second pump (Brackish-water pump #2 - BW#2) was installed 1.5 miles south of BW#1. With aid of BW#1 and BW#2, brackish water was delivered through a 24-inch-diameter discharge pipe into the northwest corner of Primary Pond #4 North (PP#4N) where the salt dissolution process began.

PP#4N is an old solar-evaporation pond that was used to precipitate NaCl (as the mineral halite) from potassium-bearing brine during the economic mineral-recovery process. The 921-acre halite deposit was estimated to be 3 to 4 feet thick, and to contain about 8 million tons of NaCl. During its residence time in PP#4N (about 15 to 30 days), the brackish water dissolved as much as 2 pounds of salt per gallon, and the density of the resulting brine approached 1.2 g/mL (NaCl saturation). In the first three years of the project, PP#4N supplied 4.6 million tons of salt to the Laydown Project.

At the beginning of the project’s fourth year, the efficiency of salt recovery from PP#4N began to decrease and brine quality dropped below acceptable limits. To resolve this problem, the brackish-water flow was re-routed through existing transfer ditches, and pump BW#2 was moved from PP#4N to the North Ripening Pond. North and South Ripening Ponds (NRP and SRP) then became the primary sources of Laydown salt. Salt-crust thickness measurements obtained from 26 auger holes drilled in NRP and SRP during 2002 averaged slightly more than 4 feet. Based on these measurements, salt tonnage present in NRP and SRP was estimated to be about 4 million tons. Because

NRP and SRP combined acreage was about 400 acres (less than half of PP#4N's 921 acres), less surface area was available for salt dissolution. To ensure a sufficient supply of brine for the project, as brine in NRP and SRP reached a grade of 14% NaCl (or brine density of about 1.12 g/mL) it was transferred from these ponds and stored in PP#4N. This brine transfer allowed for faster cycling of brackish water

through NRP and SRP, provided more storage room for the developing brine, and enabled the 14% brine to dissolve additional salt from PP#4N and increase its grade to a more acceptable level (about 18–20% NaCl, or brine density of about 1.16 g/mL). During the last 2 years of the project, the NRP-SRP-PP#4N pond system supplied nearly 1.6 million tons of Laydown salt to the project.

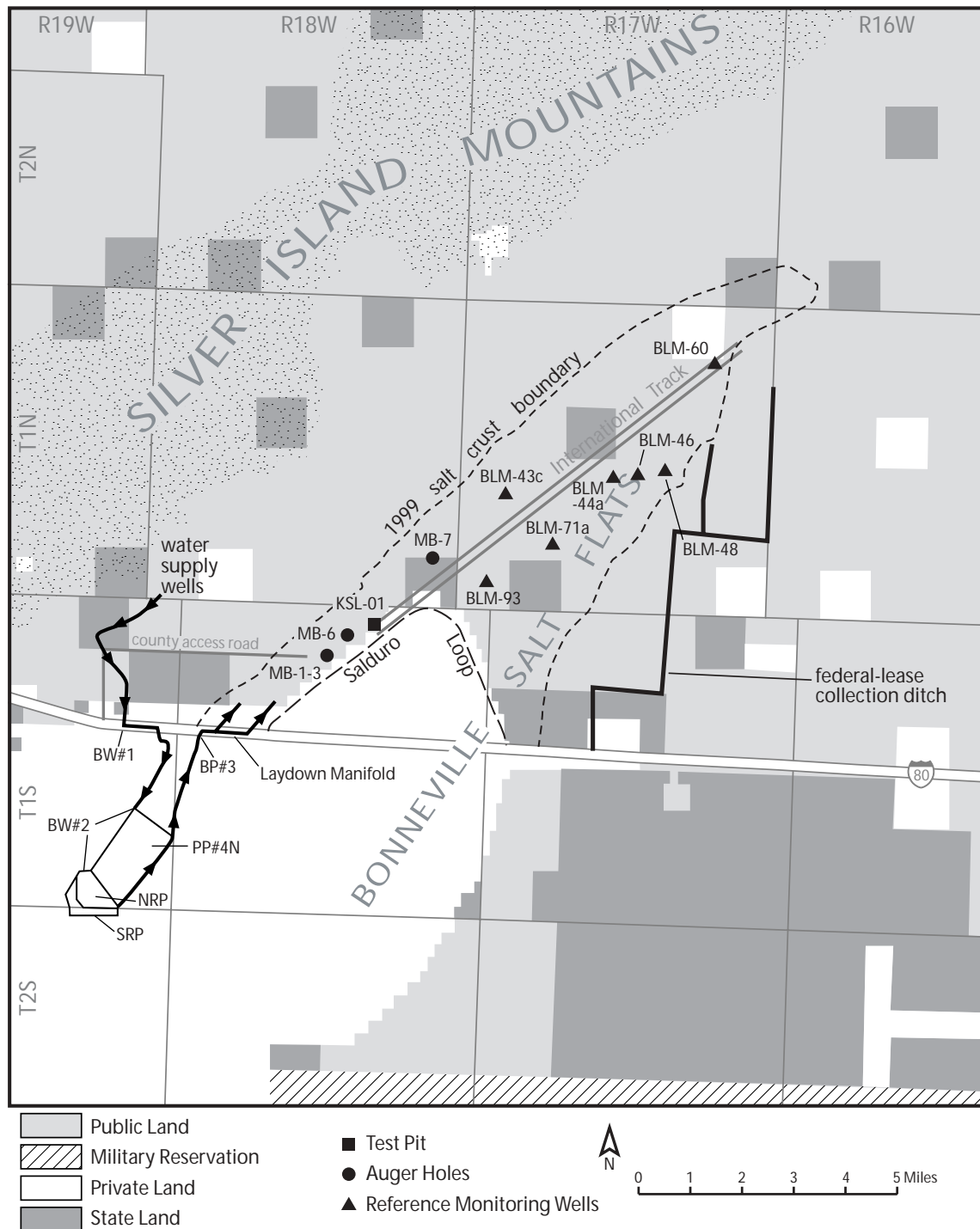


Figure 2. Index map of reference monitoring wells, auger holes, and Reilly Laydown facilities in relation to Interstate 80, and Bonneville Salt Flat features (e.g., Salduro Loop, International Track, and county access road), Arrows on transfer ditches show water-flow direction.

Linking NRP and SRP to PP#4N also allowed for continued use of the original brine discharge head gate in the southeast corner of PP#4N. From the southeast corner of PP#4N, brine flows through a north-trending, 3.3-mile transfer ditch that terminates at Brine pump site #3 (BP#3 - fig. 3). Brine is lifted approximately 11 vertical feet above the transfer ditch by the active pump and discharged into a concrete vault. Pumping the brine into the concrete vault provides sufficient hydraulic head for the brine to flow north for a distance of about 0.4 miles through a 24-inch-diameter discharge pipe. The north-trending discharge pipe passes under I-80 and discharges brine into the west end of a brine-laydown manifold. The laydown manifold is an east-west trending, 1.5-mile-long, 30-foot-wide area between west-bound I-80 and a parallel frontage road. Brine flows north from the manifold and onto BSF through twelve culverts that are uniformly spaced along the manifold's length.

Methods

Methods used to compile data presented in this paper are described by White (2002a, p. 436–444), which summarized the first 3 years of the 5-year experimental Salt Laydown Project. Because this paper summarizes the completed 5-year project, data generated during the last 2 years of the project have been added to an appendix derived from White (2002a) and published on BLM's website (White, 2003).

Results and Discussion

Laydown brine was delivered to BSF for 5 years with the objective of adding salt to the salt crust. The Laydown brine was discharged to the salt crust from November through April where it mixed with the winter transient pond described by Mason and Kipp (1998, p. 33) and White (2002a, p. 444). Because of its source and location (mainly on the salt crust), the transient pond is hydrologically connected with the shallow-brine aquifer.

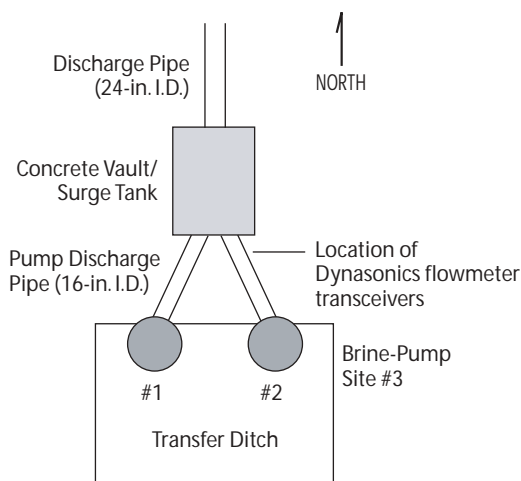


Figure 3. Plan view of Brine-pump site #3; pump #2 is active, and pump #1 is standby.

In the 1991 salt-replacement feasibility study, Bingham (1991, p. 2) estimated that a 0.4-inch thickness of NaCl salt could be added to the total salt-crust thickness each year. However, the effects of adding Laydown brine to the transient pond, and consequently to the shallow-brine aquifer, were unknown. Results focus on the following questions regarding the influence of adding Laydown brine to the transient pond:

- How much dissolved salt was delivered to BSF by the Laydown Project?
- How much salt was added to the salt crust?
- Does shallow-aquifer brine chemistry vary historically, and how does it compare with Laydown brine chemistry?
- How does composition of salt precipitated as a result of the Laydown Project compare with that of pre-Laydown salt crust?
- How much dissolved Laydown salt may be assimilated into the shallow-brine aquifer?
- Has the composition of minerals precipitated from the shallow-brine aquifer changed as a result of the Laydown Project?

Progress of Salt-Crust Restoration

The Laydown experiment was conducted during six-month periods (November through April of the following year) for five successive years. To simplify yearly data reporting in the following tables, fiscal year terminology is used unless otherwise indicated. A fiscal year is defined as the period from October 1 through September 30 of the following year, and is identified with the FY prefix.

Tons of salt delivered to BSF

Over 5 years of operation, the Laydown project delivered to BSF 6.3 billion gallons of brine containing 6.2 million tons of NaCl (table 1), about 83% of the possible salt mass estimated (Bingham, 1991, p. 2). Annual salt delivered averaged 1.2 million tons, and ranged from 0.76 to 1.96 million tons.

The average mass delivered exceeded the estimated salt loss of 0.85 million tons (Mason and Kipp 1998, p. 93). Densities for the delivered brine typically ranged from 1.15 to 1.19 g/mL (table 2). Minimum annual densities usually occurred in January or February, and maximum values usually occurred in November. The mass delivered and the brine densities were low in FY98 because of start-up problems (White 2002a, p. 444). The largest masses of salt delivered and highest brine densities occurred in FY99 and FY00 due to improvements to the Laydown Facility during 1998 (White 2002a, p. 445). Brine density decreased in January and February 2000. In March 2000, the salt-crust surface of PP#4N was ripped by a bulldozer to improve salt dissolution and, in response, the brine density increased (table 2).

At the beginning of FY01, efficiency of salt recovery from PP#4N began to decrease and brine quality dropped below acceptable levels. To resolve the problem, brackish-water flow was re-routed from PP#4N to North and South Ripening Ponds (NRP and SRP), which became the primary sources of Laydown salt for the last 2 years of the 5-year experimental project (see fig. 2). Because of difficulties encountered while making the transfer from PP#4N to NRP and SRP, and the reduced surface area available in the two new ponds, the mass of Laydown salt delivered was reduced.

Two strategies were successfully used to increase salt dissolution into the Laydown brine: 1) brackish-water was pumped for 15 to 20 days per month, rather than the entire month, to allow a specified volume of brackish water greater residence time in NRP and SRP and enhance salt dissolution; 2) brine was transferred from NRP and SRP to PP#4N for storage and additional salt dissolution (PP#4N still contained about 0.5 million tons of salt as of January 2002). Although FY01 and FY02 Laydown tonnages were similar (table 1), the efficacy of using PP#4N as a storage pond to help upgrade the brine from 14 to 18–20% NaCl content (or a brine density of 1.12 to 1.16 g/mL, respectively) may be reflected in slightly improved FY02 brine densities, as compared with those of FY01 (table 2).

Table 1. FY98-02 totals of Laydown NaCl tonnage, acre-feet, gallons, and pump hours.

| Totals | NaCl, million tons (dry) | Pumped Brine | | Hours Pumped Per Year (Nov-Apr) | | |
|-------------------|--------------------------------|--------------|--------------------|------------------------------------|--------------------|------------------|
| | | acre-feet | million gallons | Maximum Possible | Actually Pumped | % of Possible |
| FY98 | 0.825 | 3,161 | 1,030 | 4,344 | 2,567 | 59.1 |
| FY99 | 1.965 | 5,335 | 1,738 | 4,344 | 4,332 | 99.7 |
| FY00 | 1.833 | 5,345 | 1,741 | 4,368 | 4,340 | 99.4 |
| FY01 ¹ | 0.764 | 2,571 | 884 | 4,344 | 2,205 | 50.8 |
| FY02 ² | 0.836 | 2,780 | 906 | 4,344 | 2,413 | 55.5 |
| FY98-02 | 6.229 | 19,192 | 6,300 | 21,744 | 15,857 | 72.9 |

¹ Includes 7 days of pumping from May 1 to 7, 2001.

² Includes 2 days of pumping from May 1 to 2, 2002

Table 2. Average monthly Laydown-brine-density values (expressed in g/mL) for November through April during FY98-02.¹

| Month | Nov | Dec | Jan | Feb | Mar | Apr |
|-------------------|-------|-------|-------|-------|-------|-------|
| FY98 | 1.161 | 1.080 | 1.074 | 1.178 | 1.148 | 1.133 |
| FY99 | 1.194 | 1.192 | 1.183 | 1.187 | 1.186 | 1.189 |
| FY00 | 1.187 | 1.178 | 1.152 | 1.145 | 1.178 | 1.202 |
| FY01 ² | 1.164 | 1.155 | 1.119 | 1.148 | NP | 1.148 |
| FY02 ³ | 1.132 | 1.158 | 1.162 | 1.144 | 1.157 | 1.161 |

NP – No production

¹ Density values based on daily brine-sample measurements conducted in Reilly's Wendover laboratory.

² Average brine density for 7 days of pumping from May 1–7, 2001 was 1.127.

³ Average brine density for 2 days of pumping from May 1–2, 2002 was 1.166.

Yearly production data from the Salt Laydown Project has demonstrated that NaCl salt in brine removed from BSF for mineral extraction can be replenished. During the 5-year experimental project, 6.2 million tons of NaCl salt was transferred to BSF. Using USGS-estimated annual salt loss of 0.85 million tons per year (Mason and Kipp 1998, p. 106), about 4.2 million tons of salt may have been removed from the shallow-brine aquifer via the federal lease-collection ditches north of I-80 during the same 5-year period. This resulted in a net addition of about 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system.

Volume of Laydown brine added to the shallow-brine aquifer

Mason and Kipp (1998, p. 92) modeled fluid and salt inflow and outflow to the shallow-brine aquifer and demonstrated a volumetric balance between annual recharge and discharge that was within 5%. However, the yearly addition of Laydown brine would skew this annual volumetric balance towards additional recharge. Laydown brine volumes during the 5-year experiment ranged from 2,570 to 5,340 acre-feet (values rounded from table 1) and were initially added to the transient winter pond volume. A portion of these annual Laydown volumes contributed to recharge of the shallow brine aquifer during the winter months, while any remaining volume contributed precipitated salt to the salt crust as the residual transient pond evaporated during the spring and summer months.

An obvious question is how this additional volume of Laydown fluid could be accommodated within the system while maintaining the recharge-discharge balance. Several options are possible: 1) the average amount of annual meteoric precipitation decreased (reducing water levels in the shallow-brine aquifer), 2) the area covered by the transient pond increased, or 3) a combination of the previous two conditions occurred. Review of available weather data and recent field observations suggest a combination of the listed conditions. For example, average meteoric precipitation for BSF and vicinity was less during the 1997–2002 Laydown project compared to historical records. Specifically, the sum of monthly average meteoric precipitation for November–April and May–October periods recorded at the Wendover airport weather station was about 30% less than that of its 1934–2002 period of record (table 3).

Table 3. Meteoric precipitation data from Wendover, UT Airport weather station: 1997–2002 sum of monthly averages for Nov-Apr and May-Oct periods are compared with those of the station's 1934–2002 period of record (Western Regional Climate Center 2003).

| Calendar year | Nov-Apr Avg. | May-Oct Avg. |
|------------------------|--------------|--------------|
| 1997 | 0.52 | 2.04 |
| 1998 | 1.76 | 5.68 |
| 1999 | 0.92 | 1.35 |
| 2000 | 1.71 | 0.76 |
| 2001 | 1.89 | 0.78 |
| 2002 | 1.09 | 0.86 |
| 1997–2002 Avg (n = 6) | 1.32 | 1.91 |
| 1934–2002 Avg (n = 69) | 2.03 | 2.70 |
| Percent difference | 35 | 29 |

Decrease in meteoric precipitation over the 5-year period would result in less recharge, consequently increasing storage in the shallow-brine aquifer. Additional available storage is also suggested by October 2000 and 2001 field observations (White 2002b). In October 2000, the shallow-brine aquifer water level was at the surface of the salt crust. During October 2001, sparse water level data from measurements of auger holes drilled in the center of the salt crust along a 2-mile stretch of the International Track recorded shallow-brine aquifer static water levels that averaged about 1.3 feet below ground level. Assuming that this depth to the shallow-brine aquifer applied to the 31 square miles of salt crust existing in the fall of 1999, and porosity was 45%, a volume of approximately 11,600 acre-feet of additional storage would become available, which would easily accommodate the yearly Laydown brine volume.

Evidence of increase in transient pond area coverage was also observed during an October 2001 field examination; 1-inch thick salt crust extended from the east margin of the 1999 salt-crust boundary and thinned to a feathered edge at the lease-collection ditch system shown in figure 2 (White 2002b). Presence of this thin salt crust shows that the 2000–2001 transient winter pond extended beyond the 1999 salt-crust boundary.

Based on the forgoing, the added Laydown volume can be assimilated into the shallow-brine aquifer, and has potential to help maintain salt-crust mass balance. Specifically, before the Laydown Project, some of the brine discharged from BSF through the lease collection ditch was replaced by meteoric precipitation, which dissolved salt crust (Mason and Kipp, 1998, p. 45). During the Laydown Project, the shallow-aquifer brine discharged through the lease collection ditch was believed to be mostly replaced by Laydown brine that approached halite saturation and consequently minimized salt-crust dissolution.

Amount of salt added to the salt crust

Area measurements—Using measurements from Landsat 5 imagery, White (2002a, p. 445–447) estimated that the salt crust area increased by about 5 square miles during a 2-year period (September 1997 to October 1999). BSF salt-crust areas measured from fall 1997, 1998, and 1999 Landsat 5 scenes were approximately 26, 29, and 31 square miles, respectively (fig. 4). The new 5-square-mile area was added to the eastern margin of the salt crust (as it existed in the fall of 1997), and the following measurements apply to the 5-square-mile addition. Based on salt-crust density (110 lbs/ft³ - rounded from Mason and Kipp, 1998, p. 54) and thickness measurements (0.25 to 1.0 inches), the 5-square-mile increase may represent about 0.16 to 0.64 million tons of salt, which could represent about 23% of the 2.8 million tons of NaCl salt delivered by the Laydown Project during FY98 and FY99. Salt-crust thickness studies and geochemical modeling of the effects of mixing Laydown brine with the shallow-aquifer brine (described in the following sections) suggest that most of the Laydown salt tonnage not included in the 5-square-mile area was probably assimilated into the shallow-brine aquifer.

Salt-crust thickness measurements—The salt-replenishment feasibility study (Bingham, 1991, p. 2) estimated that the Laydown Project could add 0.4 inches of additional salt per year to the surface of the salt crust. In an attempt to verify this predicted increase of salt-crust thickness, BLM measured salt-crust thicknesses during the life of the Laydown Project and compared these measurements with two different types of historical salt-crust measurements: 1) total salt-crust thickness (i.e., from the surface of the salt-crust to its interface with underlying carbonate mud), and 2) thicknesses of individual halite and gypsum strata that make up the total salt crust.

Total salt-crust thickness—Historical measurements of total salt-crust thickness were made by the Utah State Department of Highways (UDOT) in 1960 and 1974, and by BLM in 1988 (McMillan 1974; Brooks 1991). UDOT and BLM each augered more than 100 holes in the salt crust during their respective studies. Because the 1988 BLM auger-holes locations were surveyed (Brooks 1991, p. 4) and their salt-crust thicknesses were the most recent historical record available, the 1988 measurements were compared with BLM total salt-crust measurements made during the Laydown Project so that any measurable changes could be documented.

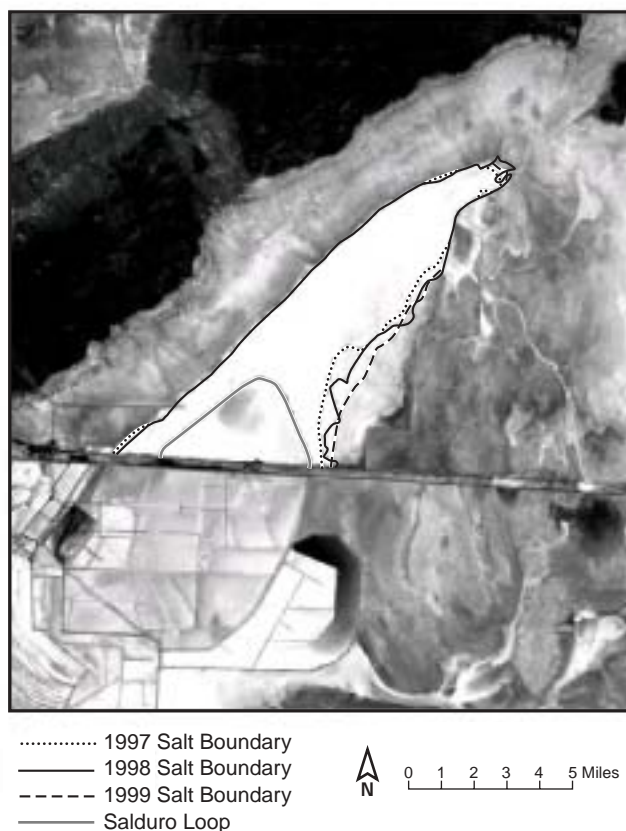


Figure 4. 1999 Landsat 5 image showing progressive increase in salt-crust area from September 1997 through October 1999.

From 1998 through 2002, BLM measured total salt-crust thicknesses at 13 selected BSF monitoring locations (see fig. 2 and table 4). The 1988 thickness values for these 13 locations were extrapolated from BLM's 1988 data (Brooks 1991; White 2002a, p. 443). Comparisons were made between the 1988 thickness measurements and 20 recent measurements made from 16 auger holes and 4 test pits distributed among the same 13 locations during the 1998–2002 period. Total salt-crust thickness values from the 20 measurements averaged 27 inches, and ranged from 12 inches at MB-2 to 42 inches at BLM-93. Extrapolated 1988 total salt-crust thickness values for the 13 locations also averaged 27 inches, and ranged from 12.2 inches at MB-2 to 46.8 inches at BLM-93.

When 1998–2002 total salt-crust thickness measurements were compared with their correlative 1988 thickness measurements, nine locations exhibited thickness decreases (from 0.2 to 5.2 inches), while four locations showed thickness increases (from 0.5 to 3.2 inches). However, when 1998–2002 measurements were compared among themselves, locations where multiple total salt-crust measurements were taken either exhibited the same thickness from year to year (i.e., BLM-46, BLM-60, and BLM-93), or showed substantial thickness increases (i.e., 4+ inches for BLM-43C and BLM-44A). Generally, greater variability of total salt-crust thickness was observed between 1988 and 1998–2002 measurements, rather than among those of 1998–2002.

This range of change in total salt-crust thickness between the 1988 and 1998–2002 measurements may be due not only to seasonal and spatial variation in the salt-crust thickness (see “Salt crust strata thickness”), but may also be a function of historical weather events and difficulty with replicating salt-crust thickness measurements.

For example, Mason and Kipp (1998, p. 55) estimated 10 to 14 million tons of salt were dissolved from the salt crust just north of I-80 during the winter of 1993. This

transfer of solid-phase salt from the salt crust to the shallow-brine aquifer was due to greater than normal precipitation in January, and unseasonably cool temperatures in January and February. Mason has suggested that this 1993 winter flooding was a significant event that had potential to markedly affect salt-crust thickness, and may be one of several important mechanisms responsible for the variation observed in total salt crust thickness between 1988 and 1998–2002 (J.L. Mason, Hydrologist, USGS, written commun., October 3, 2003).

Difficulties replicating total salt-crust measurements were reported by Kohler (1994–95). Brooks (1991, p. 3) measured 1988 total salt-crust thicknesses from each auger hole using a method similar to that used by UDOT (see White 2002a, p. 449) and reported difficulty in replicating measurements within the same hole. Kohler (1994–1995) also attempted to replicate total salt-crust thickness measurements within the same hole and among multiple, closely spaced holes using the UDOT method. He drilled three holes along a 27-foot line that was located approximately 125 feet northwest of monitoring well BLM-93. The holes were located at both ends and in the center of the line, and the center hole was spaced about equidistant (13 and 14 feet) from each end. Kohler reported that three independent measurements of total salt-crust thickness within the same hole varied by ± 1.2 inches (or ± 0.1 foot), and measurements among the three holes varied by as much as 6 inches over a 27-foot lateral distance. This reported variation could easily mask the reported change in total salt-crust thickness summarized in table 4. Additionally, variability of total salt-crust thickness measurements within individual holes and among closely spaced holes, along with the imprecise UDOT measurement method suggest that using the 1988 total thickness values as an absolute baseline for comparison with recent thickness measurements to determine gain or loss of salt crust may introduce significant error. These comparisons are probably qualitative at best.

This preliminary comparison with 1988 thickness measurements is based on a small population of data from 16 auger-hole and 4 test-pit locations collected from 1998 through 2002. To more accurately assess effects of the Laydown Project on total salt-crust thickness, thickness measurements from a larger population of drill holes need to be collected on a yearly schedule (White 2002a, p. 449).

Salt crust strata thickness—Pre-Laydown Project thickness measurements of individual halite and gypsum strata were made from 10 test pits excavated in the salt crust by BLM during 1994–1997. These test pits were located adjacent to six reference-monitoring wells whose locations were surveyed (BLM-42A, BLM-43C, BLM-46, BLM-60, BLM-71A, and BLM-93 - see fig. 2). Based on halite and gypsum strata thickness measurements from these test pits, it was determined that at least five distinct strata comprised the salt crust (White 2002, p. 447). These five strata were consistent in sequence and composition among the 10 test-pit locations (table 5). The 1994–1997 salt-crust strata

Table 4. Total salt-crust thickness measurements taken at 13 locations during 1998–2002, compared with correlative 1988 thicknesses (thickness and change expressed in inches).

| Location ¹ | 1988 ² | 1998 ³ | 2000 ³ | 2001 ³ | 2002 ⁴ | Change ⁵ |
|-----------------------|-------------------|-------------------|-------------------|-------------------|-------------------|---------------------|
| MB-1 | 14.8 | 12.5 | | | | -2.3 |
| MB-2 | 12.2 | 12.0 | | | | -0.2 |
| MB-3 | 20.8 | 19.0 | | | | -1.8 |
| MB-6 | 22.7 | 22.0 | | | | -0.7 |
| MB-7 | 33.4 | 36.0 | | | | +2.6 |
| BLM-43C | 34.7 | | 31.8 | 36.0 | | +1.3 |
| BLM-44A | 30.7 | | | 26.4 | 31.2 | +0.5 |
| BLM-46 | 26.2 | | 24.0 | 24.0 | | -2.2 |
| BLM-48 | 18.4 | | | 13.2 | | -5.2 |
| BLM-60 | 20.2 | | 19.5 | 19.5 | 19.2 | -1.0 |
| BLM-71A | 35.8 | | | 32.4 | | -3.4 |
| BLM-93 | 46.8 | | 42.0 | 42.0 | 42.0 | -4.8 |
| KSL-01 | 32.8 | | | | 36.0 | +3.2 |

¹ Auger holes MB-1-MB-7 drilled along the International Track; auger holes and test pits associated with BLM-43C, etc. placed adjacent to these reference wells; test pit KSL-01 near International Track near mile-post 3 (see figure 2).

² Values extrapolated from Brooks (1991) using Radian CPS/PC v. 4.2.

³ Auger holes (n = 16).

⁴ Test pits (n = 4).

⁵ Change between 1988 and 1998, 2001, or 2002 measurements.

thickness measurements were used as baseline thickness values for comparison with later salt-crust strata measurements performed during the Laydown Project.

Because Bingham (1991, p. 2) predicted that the 5-year Laydown experiment could add up to 2 inches of thickness to the existing salt crust, it was originally thought that annual measurements of the salt-crust strata during the Laydown Project would show a gradual thickness increase in the surface stratum (dense-cemented halite). Therefore, multiple-year thickness measurements of the salt-crust strata sequence were made from seven test pits and ten auger holes excavated adjacent to six monitoring-well locations during 1998-2002 (BLM-43C, BLM-44A, BLM-46, BLM-60, BLM-71A, and BLM-93-five of these six locations were also used for the baseline 1994-1997 measurements). The datum selected as a horizon from which to reference all thickness measurements was the top surface of the first uncemented gypsum stratum beneath the surface salt-crust stratum (see table 5). This gypsum stratum was consistently present as the next stratum beneath the surface salt-crust stratum (dense-cemented halite).

Twenty-two dense-cemented-halite stratum thickness measurements were made from these six monitoring-well locations. The 22 measurements averaged 2.3 inches with a standard deviation of 0.6 inches. Of the 22 measurements, 18 were within the thickness range of 1.7 to 2.9 inches, and 4 were outside this range (4.2, 3.5, 1.5, and 1.5 inches). BLM-44A (adjacent to the International Track and thickest portion of the salt crust) exhibited maximum thicknesses of 3.5 and 4.2 inches, while BLM-60 (which lies at the extreme northeast margin of the salt crust) had minimum thicknesses of 1.5 inches.

Although 1994 and 1998-2002 thickness measurements from these reference locations were compared, none of these locations showed the predicted 2-inch thickness increase in dense-cemented halite stratum thickness at the end of the 5-year experiment (table 6). In fact, between 1994 and 2001, dense-cemented halite stratum thicknesses actually decreased at BLM-46, BLM-43C, and BLM-60 by 0.2, 0.5, and 0.8 inches, respectively, and only increased at BLM-93 and BLM-71A by 0.7 inches each. Thickness decreases at three locations and additions of less than 1 inch at two

Table 5. Salt-crust stratum sequence and thickness ranges from 10 BLM test pits (Kohler, 1994-95, and Kohler and White, 1997). See White (2003, Appendix A6) for detailed descriptions of each stratum.

| Stratum | Thickness, inches |
|---|---------------------------|
| Dense-cemented halite (surface stratum of the salt crust) | 1.3 to 2.9 |
| First uncemented gypsum mixed with carbonate clay | 0.5 to 1.2 |
| Cemented-coarse-porous halite | 1.4 to 7.7 |
| Secnd uncemented gypsum mixed with carbonate clay | 0.4 to 1.8 |
| Uncemented-coarse halite | 18.0 to 24.0 ¹ |
| Carbonate clay | ND |

¹Thickness range is based on one test pit that was excavated to the salt/mud interface.
 ND Not determined.

locations were despite an addition of 6.2 million tons of NaCl salt to BSF during the Laydown Project.

Several factors may have contributed to the measured decreases and variability in dense-cemented halite stratum thickness:

- Annual and/or seasonal variations in weather.
- Laydown salt contributions to other salt-crust strata.
- Laydown salt contributions to the shallow-brine aquifer.

Depending upon the amount of halite dissolved from the surface stratum, an apparent thinning (or thickening) of the dense-cemented halite stratum could occur during unseasonably wet (or dry) years in spite of increased salt tonnage added to BSF by the Laydown Project (White 2002a, p. 448). A possible example of seasonal weather variation influencing salt-crust thickness is illustrated in Table 6. The 2002 thickness measurements of dense-cemented halite stratum were taken in March, and without exception were all less than the fall 2001 measurements. Comparing spring 2002 thickness measurements with those of fall 2001, BLM-43C and BLM-44A had 0.6 and 0.7-inch decreases, BLM-46, BLM-60, and BLM-71A each showed 0.5-inch decreases, and BLM-93 had a 0.2-inch decrease. Empirical data and TEQUIL modeling suggest that a 1-inch rain event would dissolve about 0.14 inches from a 1-inch thickness of dense-cemented halite stratum (see "Prediction of BSF Salt-Crust Dissolution from One-Inch Rainfall Event"). It would take a single rainfall event equivalent to 4.8 inches to dissolve between 0.6 and 0.7 inches of salt-crust thickness. The average annual precipitation recorded at the Wendover, UT airport during the period 1924-2001 was 4.8 inches, and the average precipitation for March during the same period of record was 0.4 inches (Western Regional Climate Center, 2003 - Note, March was the month 2002 thicknesses were measured). Based on the aforementioned meteorological data, it seems unlikely that the observed thickness differences are due solely to rainfall, especially since a year's worth of rainfall would be required to achieve the observed decrease in 2002 thicknesses.

Table 6. 1994-2002 thickness comparisons of the dense-cemented halite stratum from test-pit and auger-hole locations placed adjacent to BSF reference monitoring wells during the year listed. Measurements taken in late summer-autumn unless otherwise indicated (thickness expressed in inches).

| Location | | | | | | Thickness change |
|----------|------|------|-------------------|-------------------|-------------------|------------------------------------|
| | 1994 | 1998 | 2000 ¹ | 2001 ¹ | 2002 ² | between 1994 and 2001 ³ |
| BLM-44A | ND | ND | ND | 4.2 | 3.5 | ND |
| BLM-46 | 2.8 | ND | 2.2 | 2.6 | 2.1 | -0.2 |
| BLM-93 | 1.8 | 2.4 | 2.3 | 2.5 | 2.3 | +0.7 |
| BLM-71A | 1.7 | ND | ND | 2.4 | 1.9 | +0.7 |
| BLM-43C | 2.9 | ND | 2.0 | 2.4 | 1.8 | -0.5 |
| BLM-60 | 2.8 | ND | 1.5 | 2.0 | 1.5 | -0.8 |

¹Auger holes

²Spring measurements

³Maximum thickness measured during Laydown Project
 ND Not determined

With regard to contributions to other salt-crust strata, examination of table 7 reveals thickness variation not only of dense-cemented halite, but also of cemented-coarse-porous halite and uncemented-coarse halite strata in seven closely spaced test pits at BLM-93.

However, when respective thicknesses of these three halite strata were added together for each of the last three consecutive years (2000–2002), the average sum was 39.1 inches, and range of summed halite thickness was relatively narrow (i.e., from 37.3 to 40.5 inches). This suggests a possible interrelationship between the three different halite strata in the salt-crust stratigraphic sequence. The shallow-brine aquifer, which maintains the salt crust and governs its strata morphology, is in contact continuously with the uncemented-coarse halite stratum, and seasonally with cemented-coarse-porous and dense-cemented halite strata as the level of the shallow-brine aquifer fluctuates seasonally. These fluctuations in the water table combined with seasonal changes in brine concentration may help facilitate mass transfer of salt from one stratum to another. Furthermore, this mass transfer may be reflected by the undulating top and bottom surfaces observed in the dense-cemented halite and cemented-coarse-porous halite strata. This observed undulation resulted in significant salt-crust strata thickness differences within a short lateral distance (i.e., 2 feet or less). For example, yearly dense-cemented halite thicknesses measured from 18-inch-wide by 24-inch-long test pits excavated at BLM-93 from 2000 to 2002 varied by as much as 0.5 to 1.5 inches over a 24-inch distance. Coarse-porous halite thicknesses measured from the same test pits at BLM-93 varied more dramatically by 1 to 2.5 inches over the same lateral distance (White 2002b). Perhaps the most critical observation is that reported lateral variation of dense-cemented halite stratum thickness measurements exceeds

reported thickness changes measured from the same stratum during the Laydown Project (see table 6).

Lack of progressive salt-crust thickness increases in the surface stratum at reference monitoring-well locations (see table 6) strongly suggest that 1) most of the Laydown salt is initially incorporated into the shallow-brine aquifer, while 2) some is distributed to increased salt-crust area and other subsurface salt-crust strata (e.g., cemented-coarse-porous halite). Additional TEQUIL modeling calculations indicate that between 17 and 25 million tons of Laydown-brine NaCl could be assimilated into the shallow brine aquifer (see “Fate of Laydown-brine NaCl...”). Whereas this salt would eventually be incorporated into the salt crust as halite, there may be a lag time between the period of Laydown-brine delivery and this incorporation. Consequently the effects of this salt addition would not be measured until some time in the future.

In summary, the seasonal and spatial variation of surface stratum and underlying halite strata thicknesses not only make individual salt-crust strata thickness measurements difficult, but also help mask any progressive increases in salt crust thickness that may be contributed by the Laydown Project.

Brine Composition

Comparison of 1994–2002 shallow-aquifer brine samples with historical data

Seven years of recent BLM samples of shallow-aquifer brine were compared with 186 USGS samples collected from 1976 to 1993 (table 8), and 18 samples of shallow-aquifer brine collected by USGS in 1925 (Nolan 1927, Plate 3; see White, 2003, Appendix A1). Sodium and chloride ions dominated both groups of samples. Sodium made up about 91% of cation content, and chloride made up 97% of anion content in both BLM and USGS samples. Magnesium and potassium jointly made up about 8% of cation content in both sample groups, with magnesium and potassium averaging 3 and 5%, respectively. The 1925 potassium and magnesium concentrations (0.131 and 0.126 moles/L) were nearly identical to the average concentrations of the 1976–2002 samples (0.131 and 0.129 moles/L). TDS ranged from 244 to 297 g/L between 1976 and 2002, but peaked to 309 g/L in FY92.

A closer examination of table 8 shows that the data can be separated into two groups based on comparison of ion concentrations (i.e., 1976–1996 and 1997–2002). Molar concentrations of sodium, magnesium, and chloride in the 1976–1996 group are generally high relative to the same species in the 1997–2002 group. For example, the sodium ranges for 1976–1996 versus 1997–2002 are 4.11–4.51 and 3.74–3.95 moles/L respectively. Assuming no errors were introduced during the 1997–2002 sample collection and analyses, and recognizing the sparseness of the data (i.e., multiple-year gaps between sampling periods of record), mechanisms causing the sodium, magnesium, and chloride concentration differences between 1976–1996 and 1997–2002 sample groups are currently unknown.

Table 7. Salt-crust stratum sequence and thickness measurements from seven BLM test pits excavated adjacent to monitoring well BLM-93 (one test pit was excavated at the site during each year listed).

| Stratum | Stratum Thickness, inches | | | | | | |
|--|---------------------------|-------------------|------|------|-------------------|-------------------|-------------------|
| | 1994 ¹ | 1995 ¹ | 1997 | 1998 | 2000 | 2001 | 2002 ² |
| Dense-cemented halite | 1.8 | 1.9 | 1.9 | 2.4 | 2.3 | 2.5 | 2.3 |
| First uncemented gypsum mixed with carbonate clay | 1.0 | 0.7 | 0.6 | 1.1 | 1.0 | 0.5 | 0.6 |
| Cemented-coarse-porous halite | 2.9 | 2.4 | 2.8 | 1.6 | 6.0 | 3.5 | 2.3 |
| Second uncemented gypsum mixed with carbonate clay | 0.6 | 0.6 | 0.6 | 1.5 | 0.5 | 1.0 | ND |
| Uncemented-coarse halite | ND | ND | ND | ND | 29.0 ³ | 34.5 ³ | 34.8 ³ |

ND Not determined

¹Kohler, 1994–1995 unpublished field notes.

²Pit excavated in spring; previous pits (1994–2001) excavated in late summer or early fall.

³Total thickness of uncemented-coarse halite (depth to salt-carbonate mud interface measured).

By contrast, potassium, calcium, and sulfate are relatively unchanged in 1997–2002 compared to 1976–1996 concentrations, and this consistency may be due to buffering by associated solids (i.e., aqueous calcium and sulfate in equilibrium with gypsum in near-surface sediments, and aqueous potassium by adsorption and desorption on clays in the subsurface - B.F. Jones, Research Geochemist, USGS, written commun., July 31, 2003).

However, the FY81-B, K, and L members of the 1976–1996 group are an exception, in that they exhibit potassium concentrations (0.085, 0.095, and 0.114 moles/L) that are markedly below the average potassium concentrations for both 1976–1996 and 1997–2002 groups (0.151 and 0.133 moles/L, respectively). Magnesium concentrations (0.120–0.141 moles/L) for FY81-B, K, and L are also below the 1976–1996 group’s average concentration (0.161 moles/L). These samples were collected in the spring (May) rather than in late summer (time of peak evaporation). Consequently, any spring storm precipitation would dissolve salt crust and maintain sodium and chloride concentrations at a constant level in the shallow-brine aquifer (see FY81 sodium and chloride values in table 8). The lower potassium and magnesium concentrations are more difficult to explain, although they could have been affected by spring storm dilution; however: 1) potassium concentrations are inconsistent with conservative levels achieved by solids buffering mentioned above, and 2) reduced magnesium concentrations may be due to incorporation of aqueous magnesium and silica in the formation of magnesium-silicate interstratifications in fine clay minerals (Jones and Spencer 1999, p. 297).

Comparison of Laydown brine with shallow-aquifer brine

During the 5-year project, overall composition of the Laydown brine was generally similar to that of the BSF shallow-aquifer brine in that sodium and chloride were the dominant ions in both brines. On average sodium, made up 97% of the cation content in the Laydown brine and 90% of that in the shallow-aquifer brine. Chloride made up nearly 98% of the anions in both brines. Four additional ions (magnesium, potassium, calcium, and sulfate) were also present in both brines, although present as traces in the Laydown brine.

Due to initial startup problems, the FY98 Laydown brine contained about 15 to 64% less salt (as indicated by solution density) than the FY00 BSF shallow-aquifer brine. Improvements to the Laydown facility resulted in FY99 and FY00 Laydown-brine concentrations that exceeded those of the shallow-aquifer brine (table 9). Specifically, concentrations of sodium and chloride in the FY00 Laydown brine were 16 and 8% higher than those in the FY00 shallow-aquifer brine, and TDS were 7% higher. The slightly elevated values are not unexpected because NaCl (halite) was the main salt present in Primary Pond #4N. However, sodium and chloride concentrations in the FY01 and FY02 Laydown brines were less than their respective shallow-aquifer brine concentrations. Sodium was nearly 9 and 2% less, chloride was 12 and 6% less, and TDS were 14 and 8% less for FY01 and FY02, respectively. The cause of this decrease in concentration during FY01–02 was depletion of the easily recoverable salt supply in PP#4N, and the subsequent necessity of having to move to two smaller evaporation ponds (NRP and SRP).

Table 8. Comparison of recent (BLM) samples with historical (USGS) samples of the BSF shallow-aquifer brine (samples usually collected during August and September unless otherwise indicated).

| Sample Suite | n | Density | Average Major Ion Concentrations, moles/L | | | | | | | Avg Mole Balance ¹ |
|---------------------------|----|---------|---|-------|-------|-------|------|-----------------|-----|-------------------------------|
| | | | Na | Mg | K | Ca | Cl | SO ₄ | TDS | |
| BLM: | | | | | | | | | | |
| FY02 | 19 | 1.180 | 3.91 | 0.119 | 0.136 | 0.031 | 4.30 | 0.056 | 257 | 0.003766 |
| FY01 | 20 | 1.172 | 3.89 | 0.107 | 0.130 | 0.030 | 4.24 | 0.050 | 254 | 0.003476 |
| FY00 | 10 | 1.173 | 3.74 | 0.102 | 0.110 | 0.033 | 4.09 | 0.051 | 244 | 0.003183 |
| FY97 | 20 | 1.185 | 3.95 | 0.109 | 0.134 | 0.028 | 4.24 | 0.058 | 256 | 0.001462 |
| FY96 | 16 | 1.182 | 4.11 | 0.140 | 0.155 | 0.021 | 4.56 | 0.051 | 282 | 0.003822 |
| FY95 | 13 | 1.196 | 4.47 | 0.189 | 0.152 | 0.026 | 4.71 | 0.052 | 286 | 0.010115 |
| FY94 | 19 | 1.192 | 4.47 | 0.224 | 0.162 | 0.022 | 5.00 | 0.055 | 297 | 0.002707 |
| USGS: | | | | | | | | | | |
| FY93 | 20 | 1.181 | 4.31 | 0.154 | 0.139 | 0.028 | 4.37 | 0.060 | 297 | 0.013832 |
| FY92 | 26 | 1.185 | 4.44 | 0.162 | 0.170 | 0.028 | 4.50 | 0.070 | 309 | 0.014853 |
| FY81- B ² | 34 | 1.185 | 4.22 | 0.120 | 0.095 | 0.031 | 4.70 | 0.053 | 276 | 0.007897 |
| FY81- K ^{2,3} | 17 | 1.188 | 4.37 | 0.141 | 0.085 | 0.032 | 4.77 | 0.055 | 283 | 0.003655 |
| FY81- L ² | 18 | 1.189 | 4.23 | 0.134 | 0.114 | 0.030 | 4.80 | 0.053 | 281 | 0.009904 |
| FY76-78- K ³ | 10 | 1.167 | 3.88 | 0.114 | 0.120 | 0.030 | 4.23 | 0.055 | 253 | 0.002155 |
| FY76-78-USGS ⁴ | 43 | 1.189 | 4.51 | 0.148 | 0.159 | 0.031 | 4.86 | 0.056 | 293 | 0.002053 |
| 1925 | 18 | ND | ND | 0.126 | 0.131 | ND | ND | ND | ND | ND |

TDS Total dissolved solids, g/L

ND Not determined

¹Acceptable limits are ± 0.0055 moles (calculated using method of Sturm and others 1980, p. 175).

²Samples collected by Conservation Division in May; “B” and “L” well numbers were 10-foot-deep auger holes.

³“K” monitoring wells were hand-augered to depths of 19 to 23 feet by Turk (1969, p. 64–65) and subsequently sampled by Lines (1978) and Conservation Division (1981).

⁴“USGS” represent monitoring wells 25 feet deep or less, sampled by Lines (1978).

Compared to sodium and chloride, magnesium, potassium, calcium and sulfate were present in relatively low concentrations in both shallow-aquifer and Laydown brines. Potassium and magnesium made up 5 and 3 to 4%, respectively, of the average cation content for the FY94-02 shallow-aquifer brines.

However, potassium and magnesium concentrations in the FY98-FY02 Laydown brines were as much as an order of magnitude less than those in the shallow-aquifer brine. Calcium concentrations in the Laydown and shallow-aquifer brines were similar, while sulfate concentrations in the Laydown brine were about 30 to 50% of those in the shallow-aquifer brine.

Traces of potassium and magnesium in the Laydown brine may have been contributed from microscopic volumes of shallow-aquifer brine entrapped as fluid inclusions in the precipitated halite in PP#4N, and possibly entrained in the pore spaces between halite crystals (recent microscopic examination of similar halite salt-crust samples from the Newfoundland basin revealed presence of fluid inclusions - B.F. Jones, Research Geochemist, USGS, personal commun., September 5, 2000). This mechanism may account for elevated potassium and magnesium concentrations observed in FY01 and FY02 Laydown brines that were 5 to 6 times that of FY98-FY00 Laydown brines. The elevated concentrations are probably due to contribution from precipitated halite in NRP and SRP, which were the sources of Laydown brine during FY01-FY02. NRP and SRP are used during the summer months to concentrate production brine from about 4 to 7.5% KCl as part of the potash-production process. Some of this enriched brine remains entrapped in newly precipitated halite crystals and in intergranular pore spaces within the 4-foot thick-bedded

halite floors of these ponds. Brackish water used to dissolve bedded salt for the Laydown brine accumulates traces of potassium and magnesium from any fluid inclusions in the new salt it dissolves and from any mixing with residual process brine (table 9).

Predicted Mineral Precipitation from Transient-Pond Brine

The BSF transient pond currently receives input from the shallow-brine aquifer, meteoric precipitation and the Laydown Project. To identify which minerals could precipitate from the transient-pond brine, its chemistry was simulated using a range of compositions as input for TEQUIL modeling. The compositions used were those of 1) pre-Laydown shallow-aquifer brine, 2) mixtures of pre-Laydown shallow-aquifer brine and Laydown brine, and 3) post Laydown shallow-aquifer brine. Effects of a simulated rainfall event on the dissolution of salt crust were also examined.

Simulation of mixing Laydown brine with the transient pond

The shallow-aquifer brine and the Laydown brine represent the two compositional extremes possible for mixtures used to simulate effects of mixing Laydown brine with the transient pond. Simulated transient pond compositions were based solely on contributions from shallow-aquifer and Laydown brines (input from rainfall was ignored). Two different mixtures of the two compositional extremes were simulated for modeling purposes. They include a 90% + 10% and a 50% + 50% mixture of shallow-aquifer and Laydown brines. The 90% + 10% mixture simulates a condition in

Table 9. Seven years of shallow-aquifer brine analyses from selected BSF monitoring wells (MW) compared with 5 years of Laydown-brine analyses; samples collected by BLM and Reilly.

| Sample Suite | n | Density | Average Major Ion Concentrations, moles/L | | | | | | | Avg Mole Balance ¹ |
|-----------------------------|-----|---------|---|-------|-------|-------|------|-----------------|-----|-------------------------------|
| | | | Na | Mg | K | Ca | Cl | SO ₄ | TDS | |
| BSF MW Brine: ² | | | | | | | | | | |
| FY02 | 19 | 1.180 | 3.91 | 0.119 | 0.136 | 0.031 | 4.30 | 0.056 | 257 | 0.003766 |
| FY01 | 20 | 1.172 | 3.89 | 0.107 | 0.130 | 0.030 | 4.24 | 0.050 | 254 | 0.003476 |
| FY00 | 10 | 1.173 | 3.74 | 0.102 | 0.110 | 0.033 | 4.09 | 0.051 | 244 | 0.003183 |
| FY97 | 20 | 1.185 | 3.95 | 0.109 | 0.134 | 0.028 | 4.24 | 0.058 | 256 | 0.001462 |
| FY96 | 16 | 1.182 | 4.11 | 0.140 | 0.155 | 0.021 | 4.56 | 0.051 | 282 | 0.003822 |
| FY95 | 13 | 1.196 | 4.47 | 0.189 | 0.152 | 0.026 | 4.71 | 0.052 | 286 | 0.010115 |
| FY94 | 19 | 1.192 | 4.47 | 0.224 | 0.162 | 0.022 | 5.00 | 0.055 | 297 | 0.002707 |
| Laydown Brine: ³ | | | | | | | | | | |
| FY02 ⁴ | 112 | 1.154 | 3.81 | 0.069 | 0.056 | 0.015 | 4.04 | 0.015 | 237 | 0.000013 |
| FY01 ⁴ | 99 | 1.144 | 3.55 | 0.059 | 0.033 | 0.015 | 3.73 | 0.015 | 219 | 0.000013 |
| FY00 | 30 | 1.164 | 4.33 | 0.012 | 0.014 | 0.033 | 4.43 | 0.031 | 262 | 0.004198 |
| FY99 | 27 | 1.185 | 4.29 | 0.013 | 0.009 | 0.034 | 4.45 | 0.031 | 261 | 0.004801 |
| FY98A | 9 | 1.058 | 1.34 | 0.005 | 0.005 | 0.016 | 1.32 | 0.016 | 80 | 0.001891 |
| FY98B | 8 | 1.130 | 3.16 | 0.008 | 0.008 | 0.025 | 3.33 | 0.026 | 195 | 0.006570 |

TDS Total Dissolved Solids, g/L

¹Calculated using method of Sturm and others, 1980, p. 175; acceptable limits are ± 0.0055 moles.

²Samples collected in August and/or September from selected BSF monitoring wells in a 27-well suite.

³With exception of FY98A and B and FY01-02, average sampling frequency was two times per month (Nov through April); FY98A and B were collected in January and March-April 1998, respectively.

⁴Daily samples collected and analyzed by Reilly.

which the transient pond interacts with the shallow brine aquifer as a well-mixed system. The 50% + 50% mixing ratio simulates a condition in which the transient-pond volume does not mix with the shallow brine aquifer, and only the transient-pond volume is considered. Although it is known that the transient pond and shallow brine aquifer are hydrologically connected, this simulation provides a case in which the Laydown-brine component is larger than in the previous case. Details of and rationale for these two simulations are reported in White (2002a, p. 452–453).

Chemical analyses from FY94 and FY97 samples of the shallow-brine aquifer were selected as the end members that represent the compositional range for the shallow-brine aquifer. Pre-Laydown transient pond composition was assumed to be similar to that of the shallow-brine aquifer. To simulate mixing the Laydown brine with the transient pond, the two end members were combined with the FY00 Laydown-brine composition (highest of annual Laydown concentrations) to make two different brine mixtures (i.e., FY94 shallow-aquifer + FY00 Laydown brine, and FY97 shallow-aquifer + FY00 Laydown brine). Each of the two brine mixtures was subdivided into a 90% + 10% and a 50% + 50% mixing ratio to make four different mixing combinations. To calculate new cation and anion molar concentrations for the four mixing combinations, the FY94 and FY97 shallow-aquifer and FY00 Laydown brine analyses were run through the mixing function of AquaChem v. 3.7 software (Waterloo Hydrogeologic, Inc., 1998). Calculated molar concentrations from these four mixing combinations and an excess amount of halite were used as inputs to the TEQUIL 25°C version. Ten moles of halite were input to 1) simulate placing each brine mixture on the surface of halite-dominated salt crust, and 2) determine capacity of the four different brine mixing combinations to assimilate additional salt.

TEQUIL modeling

Description—TEQUIL is based on Pitzer electrolyte equations and calculates liquid-solid-gas equilibria in complex brine systems (Moller and others, 1997). The TEQUIL 25°C version for the Na-K-Ca-Mg-H-Cl-OH-SO₄-HCO₃-CO₂-H₂O system (Harvie and others, 1984) was selected for use in this study.

Parameters and Output—To simulate brine evaporation in a closed system, TEQUIL was constrained to reduce the original water mass of the brine by 10% in the first evaporation step, and then reduce the resulting new water mass by 10% in the second evaporation step, and so on. After 45 evaporation steps, more than 99% of the original water mass was depleted (the simulation evaporated the brine to dryness without replenishment from an outside source such as rainfall). The original water mass was 1000 g or 55.508 moles.

Output from the model lists the new brine volume and resulting composition from each evaporation step, and

identifies the mineral species that precipitate at each step. Brine composition (i.e., water, major ions, and precipitated mineral species) from each evaporation step is expressed in moles. TEQUIL uses the brine composition from the previous evaporation step as input to calculate the brine composition for the next evaporation step. This step-wise process continues until brine compositions have been calculated for all 45 evaporation steps. New molar concentrations of the brine at any step in the simulated evaporation sequence can be obtained for additional modeling simulations (see “Prediction of BSF Salt-Crust Dissolution from One-Inch Rainfall Event”).

TEQUIL-generated plots for simulations presented in this paper are reported as mineral mass precipitated versus percent water remaining as evaporation progresses. Because halite mole values far exceed those of all other predicted mineral precipitates, halite is plotted on the primary Y axis, and the other predicted mineral precipitates are plotted on the secondary Y axis.

Mineral precipitation from pre-Laydown transient pond

TEQUIL modeling was used to predict mineral precipitation from the transient pond. Because chemical composition of the transient pond was assumed to be similar to that of the BSF shallow-brine aquifer, pre-Laydown shallow-brine aquifer composition was represented by annual chemical analyses of monitoring-well samples collected during a 6-year period (FY92–FY97) (table 10). Average molar concentrations (of six major ions) from each year of the 6-year sample period were the input to TEQUIL, which then produced six modeled simulations of precipitated mineral suites.

The minerals predicted to precipitate from the FY92–93 and FY96–97 brine compositions were nearly identical, while the FY94 and FY95 results were slightly different. Predicted mineral-species plots for FY92, FY94, and FY97 are shown in figures 5–7, and plots for FY93, FY95, and FY96 are in White (2003, Appendix A8).

Table 10. Pre-Laydown average molar concentrations of the shallow-brine aquifer from four years of BLM monitoring-well samples and two years of USGS monitoring-well samples

| Sample | n | Density | Na | Mg | K | Ca | Cl | SO ₄ |
|-------------------|----|---------|------|-------|-------|-------|------|-----------------|
| BLM Samples: | | | | | | | | |
| FY97 | 20 | 1.185 | 3.95 | 0.109 | 0.134 | 0.028 | 4.24 | 0.058 |
| FY96 | 16 | 1.182 | 4.11 | 0.140 | 0.155 | 0.021 | 4.56 | 0.051 |
| FY95 | 13 | 1.196 | 4.47 | 0.189 | 0.152 | 0.026 | 4.71 | 0.052 |
| FY94 | 19 | 1.192 | 4.47 | 0.224 | 0.162 | 0.022 | 5.00 | 0.055 |
| USGS Samples: | | | | | | | | |
| FY93 ¹ | 9 | 1.186 | 4.38 | 0.160 | 0.163 | 0.029 | 4.65 | 0.063 |
| FY92 ¹ | 9 | 1.194 | 4.44 | 0.195 | 0.193 | 0.028 | 4.67 | 0.068 |

¹These 9 samples are from 9 of 26 BSF monitoring wells sampled by Mason and others (1995, p. 50, table 4) in 1992–93; these same 9 wells were also sampled by BLM during 1994–97 (see White, 2003, Appendix A1, tables A1.9-A1.10).

The order of mineral precipitation for the various years was as follows (See White 2003, Appendix A9 for mineral species chemical formulas and their respective gram-molecular weights):

- FY92–93 and FY96–97: anhydrite-halite-syngenite-sylvite-polyhalite-carnallite-kainite.
- FY94: anhydrite-halite-polyhalite-sylvite-carnallite-kainite-kieserite-bischofite.
- FY95: anhydrite-halite-polyhalite-sylvite-carnallite-kieserite.

The predicted potassium and magnesium mineral precipitates only occurred after 85 to 90% of the water was evaporated and about 90% of the halite was precipitated. One should

also note that as evaporation progressed, new salt species were precipitated at the expense of some previously precipitated salts, which were simultaneously resorbed into solution. This resorption was in response to reaction of the solid-phase salt with residual brine to form another salt. For example, anhydrite began to resorb as polyhalite and sylvite precipitated; subsequently, carnallite formed at the expense of sylvite, and polyhalite resorbed as kainite and kieserite to precipitate (see figs. 6 and 7; B.F. Jones, Research Geochemist, USGS, written commun., July 31, 2003).

To simplify modeling of mixing the transient pond with Laydown brine, FY94 and FY97 monitoring-well sample analyses were chosen to represent the compositional range of the transient pond. FY94 was selected because its predicted mineral precipitates differed the most from the 6

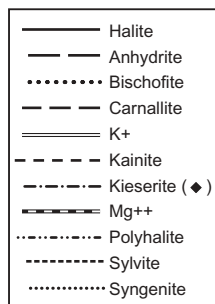
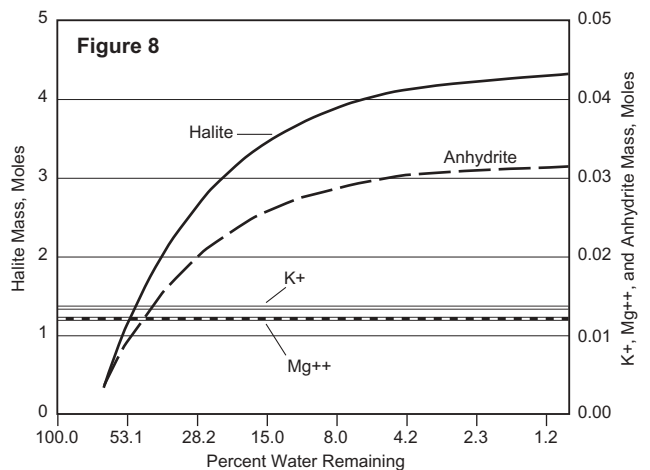
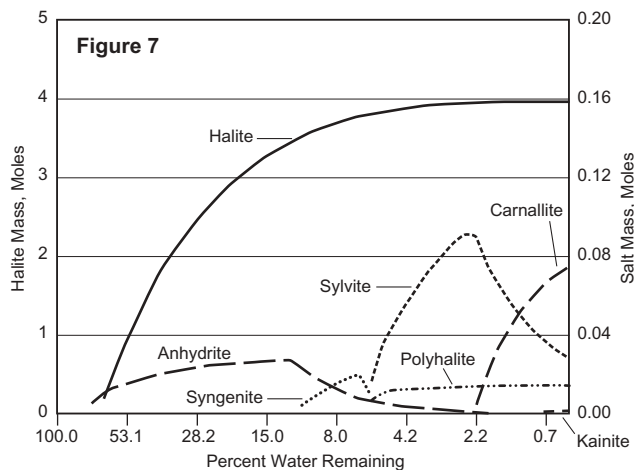
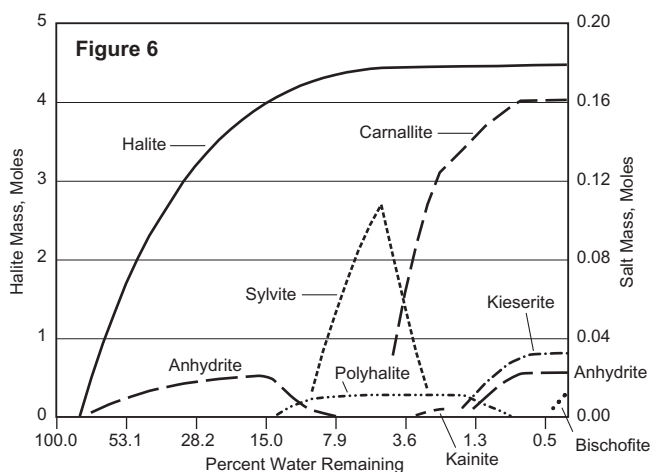
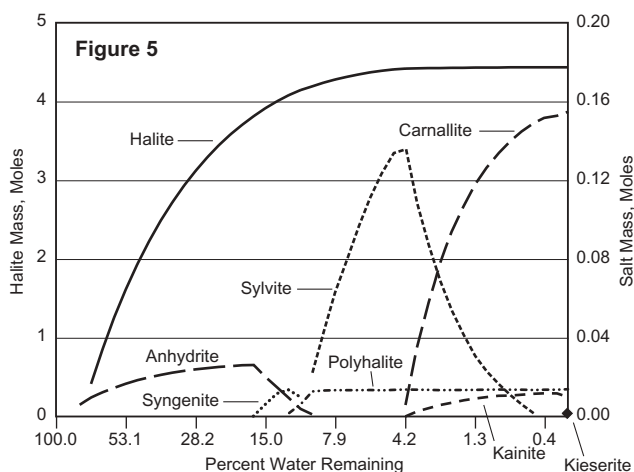


Figure 5. TEQUIL-predicted mineral precipitation plots from average analyses of USGS FY92 monitoring-well samples (n=9).

Figure 6. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY94 monitoring-well samples (n=19).

Figure 7. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY97 monitoring-well samples (n=20).

Figure 8. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY00 Laydown-brine samples (n=30).

years of monitoring-well samples examined. FY97 was selected because its average chemical composition was closest to shallow-brine aquifer and subsequent transient pond composition just prior to the first delivery of Laydown brine to BSF on November 1, 1997.

Mineral precipitation from Laydown brine

In contrast with the seven or eight minerals predicted to precipitate from the two transient-pond end members, only anhydrite and halite were predicted to precipitate from the FY99 and FY00 Laydown brines. Because of their very low concentrations, all potassium and magnesium contained in these brines remained in solution after 99% of the water was removed (fig. 8).

Mineral precipitation from mixtures of transient pond and Laydown brines

The TEQUIL-predicted mineral precipitations from the four brine-mixing combinations were essentially the same as those predicted for their end-member components (i.e., FY94 and FY97 monitoring-well brines—see figs. 6 and 7). However, as the mixing ratios were changed from 90% + 10% to 50% + 50%, the first appearances of individual mineral precipitates were delayed by a period of five evaporation steps, and corresponding mineral masses precipitated were reduced proportionately depending upon the mixing ratio.

Although both sets of mixing ratios approached halite saturation, they were able to dissolve additional halite (halite saturation is equivalent to a brine density of 1.2 g/mL; average densities for FY94 and FY97 monitoring-well samples and FY00 Laydown samples were 1.192, 1.185 and 1.164 g/mL, respectively.). TEQUIL output for both mixing ratios showed that from 1.2 to 1.9 moles (or 12 to 19 %) of halite from the 10 moles used to simulate contact with the halite-dominated salt crust were dissolved during the first evaporation step (figs. 9–12). The model predicted that the portion of the 10 moles dissolved in the first evaporation step would be reprecipitated by the fourth or fifth evaporation step. After reprecipitation restored the halite 10-mole mass, halite in excess of 10 moles was contributed by Na⁺ and Cl⁻ originally contained in the 90% + 10% and 50% + 50% mixing combinations prior to their contact with 10 moles of halite.

As was previously mentioned, the FY00 Laydown brine was enriched in sodium and chloride, and depleted in potassium and magnesium. TEQUIL output at evaporation step #1 showed that mixing Laydown brine with the two transient-pond end members resulted in increased concentrations of NaCl (see “Fate of Laydown—Brine NaCl...”), and a dilution of potassium and magnesium concentrations. Consequently, a larger reduction of original water mass was required to initiate precipitation of carnallite and sylvite. For example, the first occurrence of sylvite in the FY94 monitoring-well plot (fig. 6) coincided with a 90% reduction in original water mass; however, the first

occurrence of sylvite in the FY94 monitoring-well + FY00 Laydown plot (50% + 50% mixing ratio) coincided with a 95% reduction in water mass (fig. 10).

In summary, TEQUIL simulation of mineral precipitation from the four brine-mixing combinations showed the following:

- No new mineral precipitate species were introduced as a result of mixing Laydown brine with transient-pond brine, and subsequently evaporating the brine mixture.
- Anhydrite and halite were the first mineral species to precipitate and were the only minerals present until the original water mass was reduced by 87 and 93%, respectively (figs. 9–12).
- Potassium and magnesium mineral precipitates (sylvite and carnallite) did not appear until the original water mass was reduced by 91 to 97%, and 96 to 98% of the halite was precipitated.
- When compared with the two transient-pond end members (FY94 and FY97), the 90% + 10% and 50% + 50% mixing ratios usually had first occurrences of their mineral precipitates shifted to later evaporation steps, and the maximum predicted mass of precipitated carnallite and sylvite decreased by about 10 to 70% depending upon the mixing ratio (compare figs. 6 and 7 with figs. 9–12).

Mineral precipitation from shallow-brine aquifer: pre- and post-Laydown

TEQUIL model simulations were also used to compare predicted mineral precipitation between pre- and post-Laydown samples from the BSF shallow-brine aquifer. FY97 monitoring-well samples collected one month prior to the start of Laydown brine delivery were selected for comparison with FY00 and FY02 monitoring-well samples. FY00 and FY02 samples were collected about one month prior to the start of the 3rd and 5th year of Laydown brine delivery to BSF. Predicted mineral-precipitate plots for FY97, FY00, and FY02 monitoring-well samples were nearly identical (figs. 7, 13, and 14):

- Predicted mineral precipitates were the same for all three monitoring-well samples; halite and gypsum were first minerals to precipitate and were the only minerals present until 90% of the original water mass was evaporated.
- Relative positions of first occurrences of precipitated sylvite and carnallite were the same for the three samples; sylvite and carnallite first appeared when evaporation reduced the original water mass by 94 and 98%, respectively, and 96% of the halite precipitated.
- Maximum predicted masses for carnallite were identical for FY97, FY00, and FY02 (0.075 moles).
- Maximum predicted masses for sylvite were nearly the same for FY97 and FY02 (0.091 and 0.093 moles) and slightly less for FY00 (0.079 moles).

These results are not unexpected for several reasons: 1) ionic species comprising both shallow-aquifer and Laydown brines were identical and relative concentrations of their dominant species were similar (see table 9), so one would reasonably expect a similar mineral species assemblage upon evaporation of a mixture of the two brines; 2) contribution of Laydown-salt tonnage to dissolved salts contained in the shallow-aquifer brine is a small percentage of the total resource present, so a massive change to the shallow-aquifer brine chemistry would be unlikely. Using parameters of Mason and Kipp (1998, p. 54) about 60 and 175 million tons of salt were estimated

to be present in portions of shallow-brine aquifer covered by respective 28- and 80-square-mile areas of BSF salt crust and adjacent mudflat. These areas were selected because the 28-square-mile area was expected to be affected by the Laydown project (Bingham 1991), and the 80-square-mile area of BSF playa north of I-80 was where the shallow-aquifer brine was identified as being most concentrated (Mason and Kipp 1998, p. 54). The 6.2 million tons of Laydown salt transferred to BSF during the 5-year experiment represents 10 and 4%, respectively, of the brine resource estimated to be contained within these two areas.

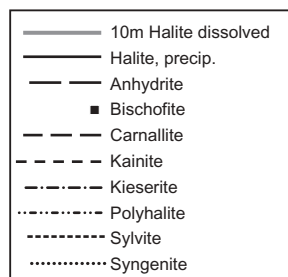
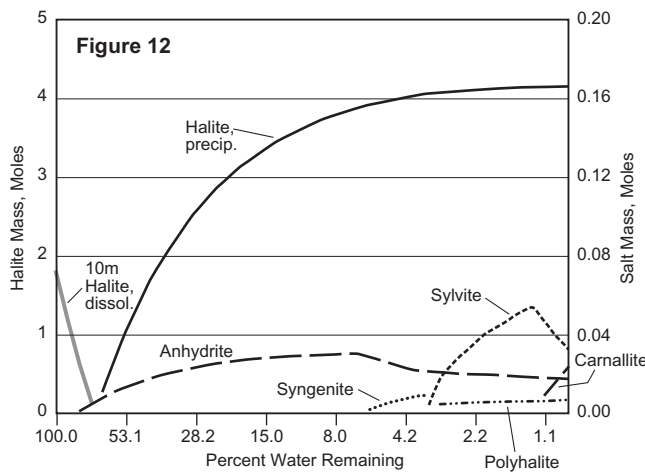
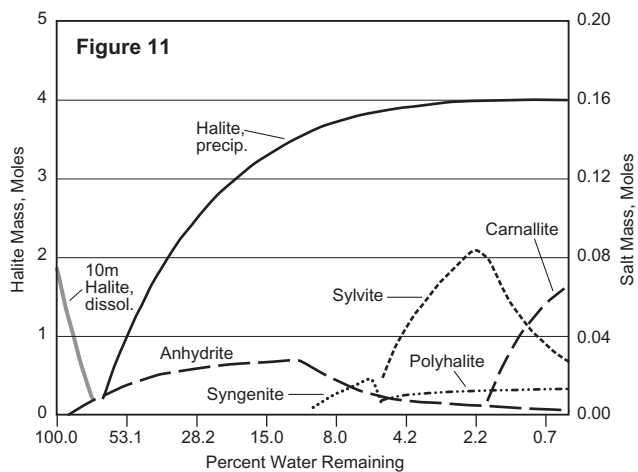
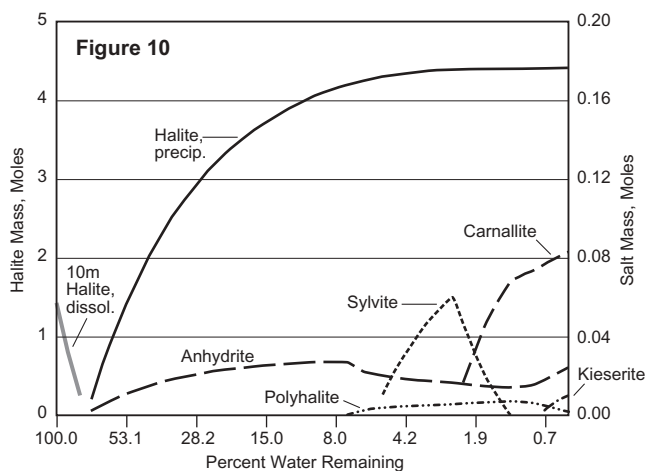
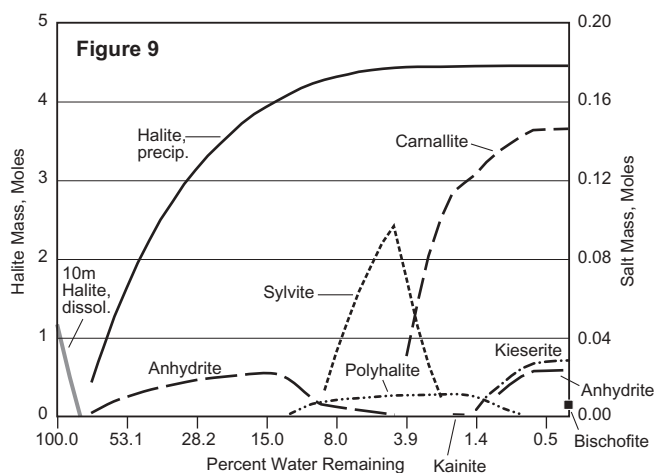


Figure 9. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY94 monitoring-well + FY00 Laydown brines (90% + 10% mixing ratio).

Figure 10. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY94 monitoring-well + FY00 Laydown brines (50% + 50% mixing ratio).

Figure 11. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY97 monitoring-well + FY00 Laydown brines (90% + 10% mixing ratio).

Figure 12. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY97 monitoring-well + FY00 Laydown brines (50% + 50% mixing ratio).

Fate of Laydown-Brine NaCl when Mixed with The Shallow-Brine Aquifer

During 5 years of Laydown Project, 6.2 million tons of NaCl were delivered to BSF. However, tons of Laydown NaCl precipitated as salt crust and tons of NaCl that remained in solution in the shallow-brine aquifer were unknown. TEQUIL outputs from previously described simulations were examined to see if fate of Laydown NaCl could be quantitatively described.

TEQUIL output from 90% + 10% and 50% + 50% mixing ratios that were contacted with an excess of halite (10 moles) showed that the simulated solutions could dissolve additional NaCl. Based on this output, TEQUIL was used to determine how much of the 6.2 million tons could be assimilated by the shallow-brine aquifer within the 28 square-mile area of BSF affected by the Laydown Project. Model output from each of the following brines and brine-mixture simulations was examined: 1) pre-Laydown transient pond end members (FY94 and FY97 MW samples), 2) Laydown brine (FY00 LD), and 3) 90% + 10% and 50% + 50% mixing ratios of the FY94 MW + FY00 LD and FY97 MW + FY00 LD simulations. TEQUIL-calculated moles of sodium from the first evaporation step of these simulations were converted to pounds and tons of NaCl dissolved per gallon (table 11).

Based on the TEQUIL output at the first evaporation step (table 11), the transient-pond end members (FY94 MW and FY97 MW) contained 2.179 lbs/gal (pounds/gallon) and 1.926 lbs/gal of dissolved NaCl. When FY94 MW and FY97 MW were compared to their corresponding 50-50 mixtures, the dissolved NaCl weight increased to 2.842 lbs/gal and 2.896 lbs/gal, respectively. Subtracting the weight of dissolved NaCl in the 50-50 mix from the weight of

dissolved NaCl in the transient-pond end member results in an increased capacity of 0.663 lbs/gal and 0.97 lbs/gal for FY94 MW and FY97 MW. When the increased capacity is multiplied by the 52.5 billion-gallon volume of the shallow-brine aquifer within the 28-square-mile area affected by the Laydown Project, the FY94 MW and FY97 MW end members could accommodate 17 and 25 million tons of additional NaCl. This is about three to four times the 6.2 million tons delivered to BSF by the Laydown Project. These calculations suggest that the 6.2 million tons could initially be assimilated into the shallow-brine aquifer as NaCl in solution. The capability of the shallow-brine aquifer to accept additional NaCl is significant, because it is the shallow-brine aquifer that regulates the distribution of NaCl mass to the BSF salt crust. If the Laydown NaCl mass is assimilated by the shallow-brine aquifer, then: 1) one would anticipate an increase of NaCl concentration in the affected area of the shallow-brine aquifer, and 2) it would not be unreasonable to expect that more halite mass would be added to the existing salt crust as a result of this increased NaCl concentration.

Table 11. TEQUIL-calculated moles of Na at the first evaporation step converted to pounds and tons of NaCl dissolved per gallon of brine.

| Sample | Na moles | NaCl lbs/gal | NaCl tons/gal (*10 ⁻³) |
|--------------------------------|----------|--------------|------------------------------------|
| FY94 MW (n=19) | 4.473 | 2.179 | 1.089 |
| FY97 MW (n=20) | 3.954 | 1.926 | 0.963 |
| FY00 LD (n=30) | 4.328 | 2.108 | 1.054 |
| 90% + 10% 94 + 2K ¹ | 5.666 | 2.760 | 1.380 |
| 50% + 50% 94 + 2K ¹ | 5.835 | 2.842 | 1.421 |
| 90% + 10% 97 + 2K ¹ | 5.866 | 2.857 | 1.428 |
| 50% + 50% 97 + 2K ¹ | 5.947 | 2.896 | 1.448 |

¹Includes 10 moles of halite to simulate contact with salt crust.

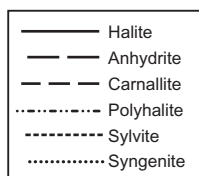
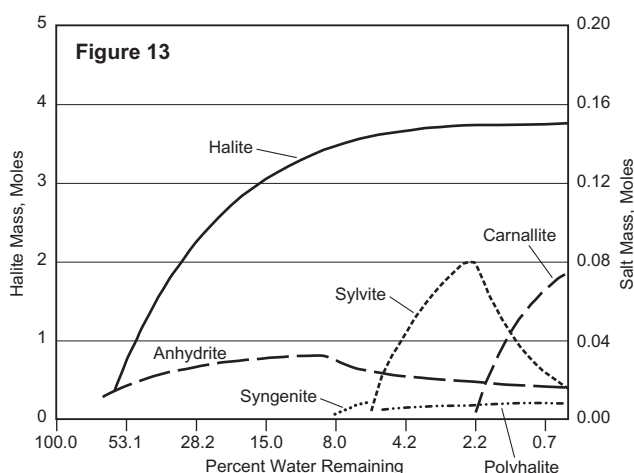


Figure 13. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY00 monitoring-well samples (n=10).

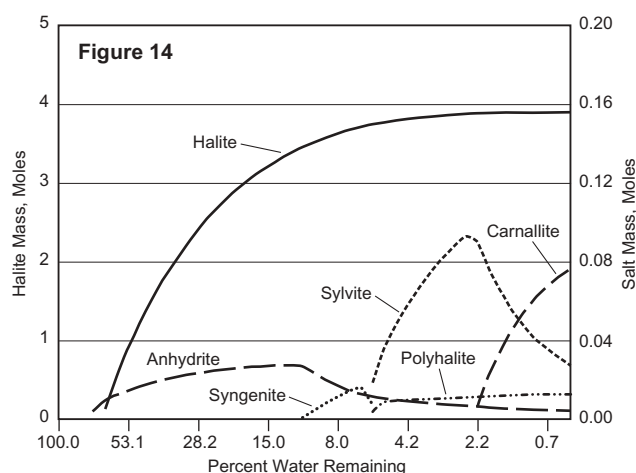


Figure 14. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY02 monitoring-well samples (n=19).

Based on salt-crust monitoring using Landsat 5 imagery, thickness measurements, and geochemical modeling, new halite deposition from five years of brine delivery by the Laydown Project is probably distributed into:

- New salt-crust area (5-square-mile increase since 1997);
- Shallow-brine aquifer (with NaCl assimilation capacity of 17 to 25 million tons); and
- Halite strata (i.e., dense-cemented halite, cemented-coarse-porous halite, and uncemented-coarse halite strata) that comprise the 26-square-mile area of salt crust existing as of 1997.

Prediction of BSF salt-crust dissolution from one-inch rainfall event

As was previously mentioned, annual and seasonal variations in weather have potential to cause changes in salt-crust stratum thickness. To help quantify this possibility, TEQUIL was used to model a 1-inch rainfall event on BSF to determine how much salt-crust mass would be dissolved and consequently, how much thickness would be removed. The 1-inch rainfall was selected because it exceeds the average monthly rainfall measured at Wendover, UT airport during the 1924–2001 period of record (Western Regional Climate Center, 2003). It should be noted that rainfall is not evenly distributed between Wendover airport and BSF during any single event (e.g., compared with average March precipitation of 0.4 inches at Wendover airport, Reilly recorded 0.2 inches during March 2003 at its potash-producing facility, which is 4 miles east of the airport - R. Draper, Mill Superintendent, Reilly Industries, Inc., written communication, March 30, 2003). Therefore, a single event 1-inch rainfall covering BSF would be a significant occurrence.

A 50% + 50% mixture of transient pond and rainwater was used in the modeled simulation. The 50% + 50% mixture simulates a condition where a 1-inch rain event falls on a 1-inch deep transient pond that covers BSF. Complete mixing of rainwater with the transient pond was assumed, resulting

in a new composition for the 1-inch deep pond (pond expands its area from mixing with rain).

Because they are hydrologically connected, the transient-pond composition was assumed to be the same as shallow-aquifer brine composition. The shallow-aquifer brine composition was represented by average chemical analyses of the FY97 monitoring-well brine, and rainwater composition was taken from Hem (1989). The mixing function of AquaChem v.3.7 (Waterloo Hydrogeologic, Inc., 1998) was used to calculate new cation and anion molar concentrations from mixing transient pond with rainwater (table 12). The resulting 50% transient pond (TP) + 50% rainwater (RW) mixture plus 10 moles of halite were input to TEQUIL to simulate contact of the new pond composition with the BSF salt crust.

TEQUIL-calculated moles of sodium (3.996 moles) from the first evaporation step of this simulation were converted to pounds NaCl dissolved per cubic foot of brine (15.9 lbs/ft³). To calculate the thickness of salt crust removed, the following assumptions were made:

- 1 cubic foot of salt crust has a density of 110 lbs/ft³ (after Mason and Kipp 1998; rounded from 109.8 lbs/ft³).
- Salt crust mass per inch of crust in the cubic foot is 110 lbs/12 in. = 9.17 lbs/in.
- Salt mass dissolved into 1 inch of water is 15.7 lbs NaCl/ft³/(12) = 1.31 lbs.
- Depth of salt crust dissolved by a 1-inch rain event is 1.31 lbs/(9.17lbs/in.) = 0.143 in.

The natural spatial variability in the thickness of dense-cemented halite stratum was ±0.6 inches for 82% of 22 measurements (see table 6). Therefore, the salt-crust dissolution predicted as a result of a 1-inch rainfall event (a significant event on BSF) cannot solely account for this natural variability in the dense-cemented halite stratum thickness. Other factors must also be operative.

Table 12. Molar concentrations used as input for TEQUIL simulations of transient pond mixed with rainwater.

| Sample | Na | Mg | K | Ca | Cl | SO ₄ | Density |
|-----------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|---------|
| Transient Pond ¹ | 3.954 | 0.109 | 0.134 | 0.028 | 4.239 | 0.058 | 1.185 |
| Rainwater ² | 2.4x10 ⁻⁵ | 6.0x10 ⁻⁶ | 3.0x10 ⁻⁶ | 1.6x10 ⁻⁵ | 1.6x10 ⁻⁵ | 2.3x10 ⁻⁵ | 1.000 |
| 50% TP + 50% RW | 1.977 | 0.054 | 0.067 | 0.014 | 2.119 | 0.029 | 1.092 |

¹FY97 monitoring-well average (n = 20); FY97 was selected because it was pre-Laydown Project.

² From Hem, 1989, p. 36, Table 6, item #2; 7.0 x 10⁻⁶ moles of bicarbonate were added to achieve charge balance required by TEQUIL

Conclusions

The Salt Laydown-Project demonstrated that sodium-chloride salt in brine removed from BSF for mineral extraction can be replenished. The average annual 1.2 million tons of salt exceeded an estimated annual salt loss of 0.85 million tons:

- Salt-mass balance during the 5-year experiment was maintained in quasi-steady state because the 4.2 million tons of salt removed was replaced by 6.2 million tons of Laydown salt.
- The difference between 6.2 and 4.2 million tons resulted in a net addition of about 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system.
- Before the Laydown Project, some of the brine removed from BSF was thought to be replaced by meteoric precipitation, which dissolved salt crust.
- During the Laydown Project, the removed shallow-aquifer brine was believed to be mostly replaced by Laydown brine that approached halite saturation and consequently minimized salt-crust dissolution.
- The salt addition appears to be distributed between the shallow-brine aquifer, new salt-crust area, and various salt-crust strata.

Monitoring during the project produced the following conclusions regarding changes in salt crust thickness, areal extent and mass:

- Five different strata comprise the salt-crust; thickness measurements of the dense-cemented halite stratum (surface stratum of the salt crust) and underlying cemented-coarse-porous halite stratum showed substantial variation in thickness from 1994 to 2002, while in comparison, minimal change in total salt-crust thickness was observed at 13 monitoring locations from 1988 to 2002.
- None of the monitoring sites where multiple-year thickness measurements were taken showed the expected +2-inch increase in dense-cemented halite stratum thickness at the end of the 5-year experiment (i.e., from 1997 to 2002).
- An unusually wet (or dry) year could measurably decrease (or increase) the thickness of the dense-cemented halite stratum from year to year despite increased salt tonnage added to BSF by the Laydown Project.
- Although the yearly Laydown tonnage would maintain or increase the current mass of NaCl in the salt-crust deposit and shallow-brine aquifer, observed annual and spatial variation in dense-cemented halite stratum masked the annual 0.4-inch increase in salt-crust thickness predicted by the Laydown feasibility study.

- An estimated 5-square-mile increase in salt-crust areal extent was observed between September 1997 and October 1999. This added area represents an estimated 0.2 to 0.6 millions tons of salt that may have been contributed by the Laydown Project.

Geochemical (TEQUIL) modeling of brine compositions determined during the project produced the following conclusions regarding salt addition to the shallow-brine aquifer:

- The model showed that the shallow-brine aquifer within the 28-square-mile Laydown area has the capacity to accept 17 to 25 million tons of NaCl; this tonnage is three to four times the 6.2 million tons of Laydown salt delivered to BSF during the five years of the Laydown Project.
- The ability of the shallow-brine aquifer to assimilate additional salt suggests that most of the 6.2 million tons of Laydown-delivered salt currently resides in the shallow-brine aquifer; furthermore, only 0.6 million tons of Laydown salt could be accounted for in the 5 square miles of new salt crust, and the expected +2 inches of thickness addition to the salt crust was not observed at any of the monitoring locations upon conclusion of the 5-year experiment.
- The Laydown NaCl mass assimilated into the shallow-brine aquifer is eventually redistributed in the salt crust as part of new surface and additional subsurface halite crystal growth.
- The addition of Laydown brine to the shallow-brine aquifer does not change the salt-crust mineral assemblages; anhydrite and halite were the only minerals predicted to precipitate from two different mixing ratios of Laydown brine and shallow-aquifer brine in an open system such as BSF.
- The model predicted a 1-inch rainfall event would dissolve no more than a 0.14-inch thickness of salt crust; however, recorded natural spatial variability in thickness was ± 0.6 inches from a 2.3-inch mean thickness obtained with 22 measurements of dense-cemented halite stratum; consequently, salt-crust dissolution predicted as a result of a 1-inch rainfall event cannot solely account for this natural variability in the dense-cemented halite stratum thickness. Other factors must also be operative.

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