measurements suggested that the ground shook more than the two reactors were designed to handle. The damage detected so far has been minimal and the NRC said the additional inspection should not be interpreted to mean the plant is less safe.[43][44]

In Charlottesville, about 27 mi (43 km) from the epicenter, a gas leak closed several streets, including West Main Street.[45]

In Spotsylvania County, the August 24 opening of public schools was delayed while damage to buildings was assessed.[46] Six patients were treated at the Spotsylvania Regional Medical Center for minor injuries resulting from the earthquake.[56]

Several buildings in Culpeper, about 37 mi (60 km) from the epicenter, sustained structural damage. The brick façade of the Levy Building, built in 1848, collapsed and the building was condemned and demolished.[38][47][48] The walls of St. Stephen's Episcopal Church, constructed in 1821, buckled and were deemed unstable by town officials. Another church, Culpeper Baptist Church, built in 1894, lost its chimney. Schools in Culpeper County delayed their scheduled August 24 opening to assess damage to buildings.[46] Two minor earthquake injuries were reported by the Culpeper Regional Hospital.[47] Damage in Culpeper was estimated at $10 million.[40]

In Fredericksburg, about 37 mi (60 km) from the epicenter, the Dickinson Building on the campus of Germanna Community College was deemed unusable for the rest of the semester, and classes were canceled indefinitely until alternative classrooms could be found.[49] Also in Fredericksburg, a gas leak led to the evacuation of homes and businesses in a two-block radius. [36] Officials estimate the damage total at around $711,000.[40]

In Arlington County, a burst pipe flooded two corridors at the Pentagon. Employees, many of whom left the building when the earthquake was felt, were alerted to the flooding by an alarm system that was installed after the September 11 attacks.[50] Nearby Alexandria also reported structural damages though no injuries.[51]

Washington, D.C.

The White House,[52] the Capitol, and various other buildings were evacuated. The afternoon rush hour was affected, as many workers left early,[53] and the Washington Metro system's trains ran at reduced speeds while tracks and tunnels were inspected.[54]

A National Park Service spokesperson reported that surveys revealed cracks near the top of the Washington Monument, the world's tallest stone structure, which was closed indefinitely.[55][56] The quake damaged three of the four pinnacles (corner spires) on the central tower of the Washington National Cathedral, cracked some of its flying buttresses, and caused additional damage.[57][58][59] As the cathedral's insurance policy did not cover earthquake damage, cathedral officials stated that they would need to raise millions of dollars to fully evaluate the damage and to stabilize and repair its limestone exterior.[59]

The Smithsonian Castle incurred damage to five decorative turrets, and fifty jars of preserved specimens fell
Staff at the National Zoo reported that the behavior of some of the animals in the park suggested that they anticipated the quake seconds or even minutes before they felt it. The earthquake was felt at the great ape exhibits during afternoon feeding time. About three to 10 seconds before the quake, many of the apes abandoned their food and climbed to the top of a tree-like structure in the exhibit. The red-ruffed lemurs sounded an alarm call about 15 minutes before the quake, and the flock of 64 flamingos rushed about and grouped themselves together just before the quake. During the quake, some animals made sounds, some ran or dove for cover, and some stood up and stared at the walls of their enclosures. Some of the animals remained agitated for the rest of the day, while others calmed quickly.\[63\][64]

Maryland, Delaware, and West Virginia

**Maryland:** In Temple Hills, residents were evacuated from two damaged apartment buildings.\[65\] In Kensington, the tops of four spires on the Washington D.C. Temple of The Church of Jesus Christ of Latter-day Saints fell to the ground along with several pieces of marble from the façade.\[66\] Near Brunswick, the quake caused "significant discoloration and a reduction in the quality of the water" of a spring, leading officials to warn against using the water until further notice.\[67\] In the Fells Point neighborhood of Baltimore, St. Patrick Catholic Church was deemed unsafe and will be closed for weeks for repairs.\[68\] In Salisbury, the City Police station endured damage above doorways and in concrete block walls,\[69\] and there was also minor cracking in classroom walls at Salisbury University.\[70\] In Annapolis, several buildings at the United States Naval Academy were damaged.\[71\] In Suitland, eight jars of preserved fish specimens fell from shelves at a Smithsonian Institution storage facility.\[60\] The 1740 Mt. Calvert mansion, historic site, and museum on the Patuxent River in Upper Marlboro received substantial structural damage and was closed indefinitely to the public.\[72\]

**Delaware:** In Wilmington, blocks fell to the street from the steeple of St. Thomas the Apostle Church, and the New Castle County Courthouse was evacuated, as was the air traffic control tower of the New Castle County Airport in nearby Wilmington Manor. In Dover, fire marshals and building inspectors were called to assess structures throughout the capital city, where the city hall was evacuated. In Georgetown, numerous buildings in the county seat were evacuated while crews checked for damage; the Emergency Operations Center there reported 200 calls to 911. Delaware Department of Transportation crews were dispatched statewide to inspect interstate highways, the under-construction replacement Indian River Inlet Bridge, the Delaware Memorial Bridge on I-295, and other bridges and roads.\[73\]
West Virginia: In Martinsburg, several government buildings were evacuated, and multiple citizens reported feeling their homes shaking violently enough to rattle picture frames off the walls. In Charleston, the Kanawha County Courthouse, the West Virginia State Capitol campus, and several other downtown buildings were evacuated; Kanawha County dispatchers received more than 350 calls in 45 minutes, but there were no reports of damage to buildings and infrastructure other than minor plaster cracking in the old courthouse. In Philippi, part of a chimney collapsed at the Barbour County courthouse. The West Virginia Office of Miners' Health, Safety and Training stated that West Virginia coal mines were safe following the tremors.[74][75] A roof collapse in Patriot Coal Company’s Big Mountain Complex forced the closure of the mine.[76]

Pennsylvania, New Jersey, and New York

Pennsylvania: Trembling was felt in buildings in Philadelphia and Pittsburgh and across the state. In Center City Philadelphia, a window shattered on a lower floor at the Independence Blue Cross building, and the company sent its 3,000 employees home for the day.[77] Other office buildings in Center City Philadelphia were also evacuated following the earthquake.[78] Workers at the PPL Corporation in Allentown evacuated the building.[77] The Three Mile Island nuclear plant south of Harrisburg continued to operate during the earthquake.[77] The Bucks County Courthouse in Doylestown was evacuated following the earthquake.[79] In Philadelphia, SEPTA Regional Rail trains were restricted to a speed of 25 miles per hour (40 km/h) while tracks were inspected for damage, and PATCO Speedline trains were briefly suspended, with no damage reported. The Pennsylvania Department of Transportation conducted inspections on bridges across the state to check for possible damage. The Delaware River Port Authority reported no damage to its four bridges across the Delaware River.[80]

New Jersey: Damage in New Jersey was minor. The state Emergency Management office reported two gas leaks in Gloucester County.[81][82] In Burlington, Temple B’hai Israel’s 1801 synagogue building sustained some water damage, and about 20 bricks fell off, damaging a congregant’s car.[82] In Camden, a vacant house partially collapsed, and government buildings were evacuated, with city workers given the option of returning home for the day.[82] Due to damage done by the quake, the municipal government of Woodbury is seeking to raze the historic Colonel George Gill Green Opera House, which was built in 1880.[83] No infrastructure damage was reported in the state.[82]

New York: Tremors were felt to varying degrees throughout New York State. Physical damage was seen in Brooklyn.[24] There were some disruptions, including building evacuations and delays at airports.[84] Amtrak train service at Penn Station was also delayed.[84]

New England

The earthquake was felt throughout much of the six New England states.[85]

Connecticut: In New Haven, play at the 2011 New Haven Open at Yale tennis tournament was stopped for two hours and the main stadium was evacuated while the fire department checked it for damage. No damage or injuries were reported.[86]
Massachusetts: In Boston, the Massachusetts Emergency Management Agency reported tremors and swaying buildings but no damage. The U.S. District Court in South Boston was evacuated and the University of Massachusetts Boston closed early. [87]

Maine: In Maine, the earthquake was felt as far north as Augusta and Portland, but no damage was reported in the state. [88]

Midwestern states

The earthquake was felt in the Midwestern states as far west as eastern Illinois and Wisconsin. [85]

Ohio: In Columbus, the Huntington Center was briefly evacuated and occupants on the upper floors of the Rhodes State Office Tower and the Vern Riffe State Office Tower reported feeling strong shaking. Evacuations also occurred in Canton and Akron. In Cleveland, the press box at Progressive Field shook during the third inning of a Cleveland Indians baseball game. [92]

Michigan: Tremors from the earthquake were felt in Detroit as far north as Saginaw and as far west as communities on Lake Michigan. There were no reports of damage in the state. [93]

Southern states

The earthquake was felt in several southern states as far from the epicenter as Alabama, but no damage was reported.

Canada

Tremors from the earthquake were also felt in eastern Canada, mostly in Southern Ontario, as well as in parts of southern Quebec and the Maritime provinces. In Ontario, a few buildings in Toronto were evacuated, and precautionary measures were taken in Sudbury and Windsor. [85]

2011 is the second consecutive year in which an earthquake was widely felt in Southern Ontario and Quebec, the previous being the June 2010 Central Canada Earthquake that also affected that region.

Aftershocks

Numerous aftershocks followed the main tremor. The first four (of moment magnitude 2.8, 2.2, 4.2 and 3.4) occurred within 12 hours of the main shock. A 2.5-magnitude shock occurred just after midnight on August 25, followed at 1:08 am EST by the strongest: a magnitude-4.5 aftershock that woke many residents in Northern Virginia and Washington, D.C. and was felt as far away as New England, Georgia, and Illinois. [4][100][101][102]

Internet activity and social media

The United States Geological Survey "Did you feel it?" citizen-based earthquake-intensity web site received about 60,000 reports in the first two hours after the quake, and over 100,000 responses within four hours. [103]
According to Facebook, the word "earthquake" appeared in the status updates of 3 million users within four minutes of the quake. Twitter said users were sending up to 5,500 messages (tweets) per second, which tops the peak rate immediately following the 2011 death of Osama bin Laden and was "on par with" the rate after the 2011 Tohoku earthquake and tsunami.[104]

Due to the significantly slower propagation of seismic waves compared to the near-speed-of-light transmission of internet traffic, some Twitter users read about the earthquake seconds before feeling the tremors. For example, Twitter users in such cities as New York City and Boston reported reading tweets about the quake from users in Washington, D.C., or Richmond, Virginia, 15 to 30 seconds before feeling the quake itself.[105]

Wikipedia had an article dedicated to the earthquake by 2:03 PM, 12 minutes after the event, and it was mentioned in two other Wikipedia articles even earlier.[106]

See also

- List of earthquakes in the United States

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52. "US earthquake


67. ^ "Washington County residents warned not to drink water from Yourtee Spring line" (http://www.herald-mail.com/breakingnews...


2011 Virginia earthquake - Wikipedia, the free encyclopedia


2011 Virginia earthquake - Wikipedia, the free encyclopedia


External links

- Louisa County High School security camera footage of the quake and evacuation (http://www.nbc29.com/story/15371474/earthquake-video-from-louisa-county-high-school-security-camera)


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USGS Community Internet Intensity Map
VIRGINIA
Aug 23 2011 01:51:04 PM local 37.936N 77.933W M5.8 Depth: 6 km ID:se082311a

148279 responses in 8682 ZIP codes and 174 cities (Max CDI = VII) 200 km

INTENSITY
I  II-III  IV  V  VI  VII  VIII  IX  X+
SHAKING
Not felt  Weak  Light  Moderate  Strong  Very strong  Severe  Violent  Extreme
DAMAGE
none  none  none  Very light  Light  Moderate  Moderate/Heavy  Heavy  V. Heavy

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Link between natural gas 'fracking,' earthquakes to be probed

The province's energy regulator says it will investigate a link between hydraulic fracturing and new earthquake activity in the extreme northeastern corner of B.C.

BY VANCOUVER SUN   SEPTEMBER 30, 2011

The province's energy regulator says it will investigate a link between hydraulic fracturing and new earthquake activity in the extreme northeastern corner of B.C.

Hydraulic fracturing, commonly called fracking, is a controversial natural gas extraction technique in which water and chemicals are forced underground at high pressure, fracturing the rock to release gas.

B.C. Oil and Gas Commission spokesman Hardy Friedrich said a recent examination of seismic survey data in northeastern B.C. showed the Horn River Basin area near Fort Nelson warranted a closer look.

Since 2009, there have been 31 earthquakes in the Horn River Basin, an active natural gas extraction area. Before 2009, the area had not experienced any recorded earthquake activity, said Friedrich. The earthquakes ranged in size from 2.5 to 3.5 on the Richter scale, which typically means they can be felt but rarely cause damage.

Three of the earthquakes took place at the same time as hydraulic fracturing was underway, said Friedrich.

"There hasn't been a link between the hydraulic fracturing and anomalous seismic activity, but we wanted to take a proactive approach," Friedrich said.

The plan is for the oil and gas commission to work with the Pacific Geoscience Centre, which monitors and researches earthquakes.

The issue of whether hydraulic fracturing can trigger earthquake activity is part of a larger concern about the technique, which uses large volumes of water and some toxic material.

In some cases, this waste is forced back into empty reservoirs under pressure. Concerns focus on groundwater contamination and the migration of gases to the surface.

No harm to groundwater has been reported in B.C., but the practice has already been banned in France and in the state of New York. Moratoriums have also been placed on fracking in Quebec and New Jersey.
Simon Fraser University geologist John Clague said he believes the earthquakes in northeastern B.C. are clearly related to the natural gas activity in the region. It's either happening through fracking or high-pressure fluid injections, Clague said in an email.

While the oil and gas commission's survey of seismic activity only found a concern in the Horn River basin area, 300 kilometres south, residents in the Halfway River area have also been experiencing new, small earthquakes. It's also an area of active natural gas exploration and drilling.

Deryl Simpson had lived for decades in the Halfway River area, when she started feeling small earthquakes - sometimes as often as four a month and sometimes none - in about 2007. "It was really quite alarming," she said, adding she tried to get the province's attention, but there appeared to be little interest.

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Intrusion of saline groundwater into Seneca and Cayuga Lakes, New York

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Abstract
Seneca and Cayuga Lakes have chloride levels 2–10 times higher than the other Finger Lakes. Approximately 170 × 10⁶ kg of salt appear to be added to Seneca Lake from within the basin each year. The region is underlain by Silurian beds of commercial-grade rock salt ~450–600 m below the surface. It has been proposed that Seneca and Cayuga Lakes are saltier than the others because their basins intersect some of these beds.

Fieldwork supports this hypothesis. A deep water mass up to 10% saltier than the rest of Seneca Lake was observed to expand and partially fill the hypolimnion from the bottom up during summer 1991 and 1992. The saltier water was mixed into the rest of the lake in early winter, only to reappear after the thermocline was established. Sediment interstitial water profiles in both lakes reveal large regions of saline groundwater several meters below the sediment surface, and NaCl concentrations as high as 30% have been found.

New York’s Finger Lakes occupy 11 north–south trending basins thought to be preglacial river valleys gouged by Pleistocene glaciation and dammed by moraines (von Engel 1961). The basins are extremely deep for their surface area (max depths: Seneca, 188 m; Cayuga, 132 m) and intersect a thick sequence of Paleozoic marine sedimentary rocks that dips gently to the south–southwest with little structural deformation. Seneca and Cayuga Lakes exhibit much higher concentrations of dissolved sodium and chloride than the smaller Finger Lakes do, in spite of similar patterns of land use throughout the region.

Berg (1963) has noted that salt strata underlie the entire area and that beds of commercial-grade rock salt 450–600 m below ground level are mined at the southern end of both lakes. Because the mines are dry and lie well below the lake floors, he did not consider it probable that groundwater from these depths leaches upward into the lakes. He also considered and rejected the washings from the commercial salt processing plants themselves as the cause, because no point-sources for chlorides were indicated by the salinity distributions in the lakes, and mass balance considerations seemed to preclude it; a source for chlorides much greater than the mines could provide was necessary to maintain the sodium and chloride concentrations at their 1950s levels. However, Berg did observe that noncommercial-grade salt deposits overlie the ores being exploited commercially and that Seneca and Cayuga Lakes, because of their much greater depths, might intersect salt strata or seepages of saline connate water from which the shallower lakes are isolated.

Such a hypothesis would account for Seneca Lake being saltier than Cayuga (because it is more deeply eroded). The regional dip of the bedrock would cause the salt-bearing strata to outcrop near the north end of both lakes, and saline groundwater is in fact found in some near-surface wells and springs near the north end of Cayuga Lake (Berg 1963).

In their chapter on Finger Lakes limnology, Schaffner and Oglesby (1978) noted that the principal sources of sodium and chloride to Seneca and Cayuga Lakes still had not been identified. Berg’s (1963) hypothesis was considered the most likely one, but Schaffner and Oglesby (1978, p. 349) cautioned that “... the location and quantity of any such inflows directly to the lake remain to be verified.” Their data showed significant increases in sodium and chloride concentrations over Berg’s (1963) values in nearly all the Finger Lakes, but the increases were proportionately much greater in the smaller lakes (up to 100%) than in Seneca Lake (up 37%) or Cayuga Lake, which dropped slightly (see Fig. 1).

Neither Schaffner and Oglesby (1978) nor Berg (1963) knew the extent of the bedrock erosion beneath the floors of the lakes, but Mullins and Hitchway’s (1989) data showed that it extends as far as 304 m below sea level in Seneca Lake (or 440 m below lake level). This finding has obvious significance to the salt question because the commercial-grade salt strata considered by Berg are only slightly deeper, even at the southern ends of the lakes. Mullins and Hitchway’s (1989) data show that as a general rule, the Finger Lakes are underlain by at least their own depths of glacial and lacustrine sediments. In the case of Seneca Lake, a maximum sediment thickness of 270 m underlies 188 m of water.

Acknowledgments
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We thank Bud Rago and Anthony Compese, masters of the HWS Explorer, and John Abbot, first mate, for their professional service. We thank Pradep Jangbari, Tom Pearson, and Dave Persson for helpful conversations and access to NYSDEC files, as well as Dave Weller for water chemistry records spanning several decades. We thank Adam Polcheck and Chih-Wei Tsai for preliminary bathymetric work on Seneca Lake. Don Woodrow provided many insights and conversations.

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Finally, it is noteworthy that Onondaga Lake, near Syracuse, New York, is a brackish lake which has long been known to have salt springs along its shores (Murphy 1978). The same salt-bearing strata which underlie the Finger Lakes region (in the upper Silurian Syracuse Formation of the Salina Group) outcrop near Syracuse, as their name implies. Indeed, salt mining was important to the early economic history of the Syracuse area; the city was once named "Salina" and today continues to be known as "salt city." Any discussion of chlorides in Onondaga Lake today is complicated by the fact that the lake has been heavily polluted by nearby chemical plants. Probably less than half of Onondaga's chlorides enter the lake in naturally occurring seeps and springs (Murphy 1978).

Since the paper by Schaffner and Oglesby (1978), little progress has been made on the question of the origin of Seneca and Cayuga Lakes' dissolved salts. Our study assesses the changes that the last two decades have brought and examines the possibility that significant quantities of chlorides are added to Seneca and Cayuga Lakes by non-point-sources within the lakes' basins. Our efforts were focused on Seneca Lake because it is the deeper and saltier of the two and because it is more easily accessed by our research vessel.

Methods

Surface water samples from streams and lakes were collected in 500-ml Nalgene plastic bottles which had been rinsed three times with sample before filling. Samples were refrigerated unfiltered and analyzed within 3 d. Deep water samples from Seneca Lake were collected in 4-liter Niskin bottles and processed in the same manner.

Water samples of 25-100-ml volume were titrated for chloride with a solution of 0.0282 N silver nitrate to an orange endpoint with potassium chromate indicator solution. Analytical error for titrations was generally ±2 ppm. Water samples were titrated for total alkalinity with 0.02 N sulfuric acid to a pink end point with phenolphthalein and bromocresol green/methyl red indicator solutions, as given by Wetzel and Likens (1991). Sediment pore-water samples were titrated in a similar manner, except that aliquots were smaller (usually 1 ml), and analytical error ran as high as ±100 ppm. Such an analytical error was judged insignificant in solutions that approached 20,000 ppm chloride.

Sodium, potassium, calcium, and magnesium in sediment pore-water solutions and lake-water samples were determined directly against appropriate blanks and stan-
Results and discussion

Chloride concentrations in the Finger Lakes—Our measurements of chloride in surface samples from the nine smaller Finger Lakes collected in fall 1992 (Fig. 1) all show significant increases over the values of Schaffner and Oglesby (1978), while the chloride concentrations of Seneca and Cayuga Lakes appear to have declined by ~10 and 30%, respectively. An increase in the use of chloride salts for de-icing roads across the region may be the cause for the observed chloride enrichment in the smaller lakes. Another process must account for the decline in chloride concentrations in Seneca and Cayuga Lakes.

Although direct wastewater input from salt companies could not account for the lakes’ chloride levels in the 1960s, there were several years in the early 1970s when direct dumping of salt into the lakes had clear and significant impacts on chloride concentrations (Ahmbrak 1975). Thus, Likens (1974) found that in 1970–1971, twice as much chloride was discharged from Cayuga Lake as entered it through tributaries. Effler et al. (1989) have modeled the decline of chloride levels in Cayuga Lake after the cessation of large-scale dumping by salt-mining plants and purport to show that no groundwater source of salt input into Cayuga Lake is necessary to balance the lake’s salt budget. Their model relies on estimates of the...
lake's water retention time, the value of which can vary widely from year to year (Oglesby 1978), and they do not neglect to take this into account. Whether the model by Effler et al. accurately describes the behavior of Cayuga Lake, we find it instructive to apply the same model to Seneca Lake to determine whether that lake's salt budget can be balanced without significant input from saline groundwater.

*Modeling chloride concentration in Seneca Lake*—Eight medium-sized and large tributaries of Seneca Lake and its outlet were sampled and analyzed for chloride four times in 1992 to determine whether chloride loading by tributaries could account for the high chloride levels of the lake (Fig. 2). Figure 3 shows the locations of the tributaries, the locations of the three salt-mining plants, and the three largest municipalities in the lake's watershed, as well as the drainage relationships of Keuka, Seneca, and Cayuga Lakes. Keuka Lake drains directly into Seneca Lake, which is the only instance under normal flow regimes of one Finger Lake draining into another. The outlet of Seneca Lake flows through a wetland area to the
Salt in the Finger Lakes

Fig. 4. Time series of chloride concentrations in Seneca Lake surface water. Data symbols: ▲—from Berg 1963; X—from Schaffner and Oglesby 1978; ■—from the City of Geneva water treatment plant records; +—from this study.

north of Cayuga Lake and rarely flows into Cayuga Lake (Effler et al. 1989). However, during periods of very high hydraulic loading, such as the floods of April 1993 and June 1972 (Oglesby 1978), the Seneca outlet can flow into Cayuga Lake.

The eight tributaries shown in Fig. 2 collectively drain more than half of Seneca Lake’s watershed. Indeed, the Keuka outlet alone drains ~25% of the Seneca/Keuka watershed. The two tributaries with the highest chloride levels (Wilson and Kashong) are two of the smallest sampled. A good estimate of the average tributary water chloride concentration entering the lake is 30 ppm, while that of the water leaving the lake is 150 ppm. Seneca Lake has an estimated water retention time of 18 yr (Schaffner and Oglesby 1978), and the volume is 15.54 x 10^6 m^3. If the salinity of Seneca Lake has been in a steady state over the last two decades, a simple mass balance calculation shows that ~170 x 10^6 kg of NaCl would have to be added to the lake each year from within its basin: (15.54 x 10^6 m^3 water) x (1/18 yr) x (10^3 kg water/m^3 water) x (120 kg Cl/10^6 kg water) x (58.5 kg NaCl/35.5 kg Cl) = 170 x 10^6 kg yr^-1 NaCl.

In fact, the lake has undergone a decline in chloride levels of 10-15% in two decades, as shown by historical data from Berg (1963), Schaffner and Oglesby (1978), annual records from the City of Geneva water treatment plant, and this study. Figure 4 shows a rise to 175 ppm by the early 1970s followed by a modest decline since then, a decline that cannot be accounted for by simple flushing of the 175-ppm lake water with 30-ppm tributary water in the absence of other significant inputs. Following the model of Effler et al. (1989) for chloride loading and lake flushing in Cayuga Lake, we have

$$[\text{Cl}]_t = \Sigma W/Q(1 - \exp(-Qt/V)) + [\text{Cl}]_0 \exp(-Qt/V).$$

[Cl]_t is Cl concentration at time t, [Cl]_0 is initial Cl concentration at t = 0, V is lake volume, Q is annual discharge flow to the lake’s outlet, ΣW is the sum of all Cl loads, and t is time.

For Seneca Lake, Q/V = 1/18 yr^-1. If the lake had experienced no chloride loading other than that from tributary water in the past two decades (ΣW/Q = 30 ppm), its chloride concentration would be ~78 ppm today, not the 150 ppm that we observed. Indeed, an application of this model to the observed decline in chloride concentrations (~175-150 ppm in 20 yr) results in a ΣW/Q of 138 ppm. Interestingly, this value is consistent with the

Fig. 5. Schematic latitudinal bedrock profile of Seneca Lake at 42°35’N.
pre-1970s' value of 110–125 ppm reported by Berg (1963), Schaffner and Oglesby (1978), and the City of Geneva records, if a modest allowance is made for the increased use of road salts in the watershed. No aspect of this model and no historical data available to us suggest that Seneca Lake ever had or ever could have had chloride concentrations <100 ppm. Thus, the contention by Effler et al. (1989) that Cayuga Lake lacks significant saline groundwater input cannot be generalized to its saltier neighbor.

The bedrock geology of Seneca Lake—The two salt-mining concerns at the south end of Seneca Lake (A and B, Fig. 3) operate today. Their discharges of chlorides into the lake are monitored by the New York State Department of Environmental Conservation (DEC). DEC records show that their combined daily discharge is <3,600 kg of chloride per day—a few percent of the amount needed to maintain the lake at its current salinity level. The Morton Salt plant near Himrod (C, Fig. 3), no longer operates. However, DEC records show that in the mid- and late-1970s, Morton Salt pumped ~1 × 10^6 kg of waste salt as brine down a deep disposal well on its property. The disposal zone lies well below the lake floor, but not below the depth of bedrock erosion found by Mullins and Hinchey (1989). Knowledge of the depths and thicknesses of bedrock units near Himrod (Subsurface, Inc. unpubl. rep.), of the locations of outcrops of the same formations (Rickard and Fisher 1970), and of the bedrock profiles of Mullins and Hinchey (1989) permits the construction of the schematic latitudinal and longitudinal bedrock profiles shown as Figs. 5 and 6. The profiles leave little doubt that the bedrock basin of Seneca Lake penetrates the salt-bearing Syracuse formation and
Salt in the Finger Lakes

Fig. 9. East–west sections of specific conductance (µhos cm⁻¹) in Seneca Lake (42°35'N) on 8 July 1991.

Fig. 10. Depth-time distribution of isopleths of specific conductance (µhos cm⁻¹) in Seneca Lake (deepest station) in 1991 and 1992.

Fig. 11. Chloride concentration in interstitial water samples of sediment core Seneca E.

the disposal zone of Morton Salt. The regional dip places them into contact with the lake's basin for tens of kilometers. Deep saline seepage from these rock units through the sediments and into the water column is thus likely.

Fig. 12. Locations of sediment cores in Seneca and Cayuga Lakes. Interstitial chloride concentration >4% within 2.5 m of the sediment–water interface—•; interstitial chloride concentration <4% within 2.5 m of the sediment–water interface—O.

Water-column conductivity profiles in Seneca Lake—Evidence for such a seepage process can be seen in water-column conductivity profiles during summer/autumn months when the lake is thermally stratified. A typical summer vertical conductivity profile (Fig. 7) shows a steady increase in conductivity with depth below the thermocline. Water samples collected simultaneously with the CTD cast are found to have chloride concentrations that also increase with depth. The higher conductivity is entirely accounted for by the increase in chloride concentration. Vertical conductivity profiles thus can serve as a proxy for chloride concentrations in the hypolimnion of Seneca Lake. Oglesby (1978) observed a similar pattern in Cayuga Lake.

If either of the salt-mining operations at the extreme southern end of Seneca Lake represents a significant point-source for dissolved chlorides, one might expect conductivity values at the south end of the lake to be highest.
Instead, the deep conductivity sections seem to follow the contours of the lake floor (Fig. 8). Not once in four north–south transects of the lake (10 July, 10 September, and 7 November 1991 and 29 April 1992) did we observe any significant excess in water-column conductivity at the southern end. In fact, water-column conductivity at this end was lower than the lake average in spring, presumably due to input from Catherine Creek, Seneca Lake's second largest tributary. It is surprising that in a lake so long and narrow (56 × 4 km) a slight east–west gradient in conductivity sections was repeatedly observed (8 July 1991 and 30 June and 29 October 1992; Fig. 9). On each occasion, conductivities appeared to be slightly greater on the west side than on the east. It is noteworthy that the Morton Salt Company's installation in Himrod is located 3 km west of the lake at 42°35′N—the latitude along which the east–west transects were made.

Seneca Lake is classified as a warm monomictic lake (Berg 1963). It rarely develops ice cover and circulates freely all winter. Thus, the deep chloride enrichment in the hypolimnion which accumulates in summer and autumn is mixed into the overlying water and homogenized in winter. Figure 10 shows the depth-time distribution of water-column conductivity for the last 6 months of 1991 and all of 1992. In both years, the epilimnion conductivities declined during the period of summer–autumn stratification, while the hypolimnion conductivities steadily increased. The fresher epilimnion can be attributed to mixing with warm and relatively low-salinity input from tributaries. The increasing salinity in the hypolimnion is indicative of saline input from some other source.

### Sediment interstitial water profiles in Seneca and Cayuga Lakes

Seventeen sediment cores were collected from Seneca Lake and four from Cayuga Lake. Four to eight subsamples from each were centrifuged, and the interstitial fluids were analyzed for chloride. Selected cores were also analyzed for total alkalinity and major cations. Table 1 lists the locations of selected sediment cores, and Table 2 gives the chloride results. The interstitial water chloride gradient in a representative sediment core is shown in Fig. 11. Groundwater with chloride nearly that of seawater is present 2–3 m below the sediment–water interface in many locations in Seneca and Cayuga Lakes, and the sharp chloride gradients near the interface strongly suggest the vertical diffusion of saline water. Although considerable spatial variability in near-surface chloride gradients can be seen, a map of core locations (Fig. 12) shows that broad regions at the north end of both lakes exhibit uniformly high near-surface chloride gradients. Only one sediment core south of 42°44′N (Seneca 9) exhibited pore-water chlorides 4% within 2.5 m of the sediment–water interface, although a number of others in this region were in the range of 1–3%. Seneca 9 is adjacent to the Morton Salt plant and might reflect a localized source. However, we consider it unlikely that Morton Salt’s disposal well could be responsible for all of the saline groundwater under the north ends of the lakes. A bed of lake sediment 60 km² in area and 50 m thick that has a water content of 25% at 16% chloride would contain 20 × 10^8 kg of NaCl, and this does not take into account any of the saline groundwater in the 20–30 km of rock

### Table 1. Locations and water depths of selected sediment cores in Seneca and Cayuga Lakes.

<table>
<thead>
<tr>
<th>Core</th>
<th>Landmark</th>
<th>N lat, W long</th>
<th>Water depth (m)</th>
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</tr>
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<td>Kashong Pt. west</td>
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<td>61</td>
</tr>
<tr>
<td>Seneca 7</td>
<td>Belhurst Castle</td>
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</tr>
<tr>
<td>Seneca 8</td>
<td>Plum Pt. west</td>
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<td>163</td>
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*Source: Wing et al.*
Salt in the Finger Lakes

Table 2. Chloride concentrations (\%) in interstitial water samples of selected sediment cores listed in Table 1.

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<td>4.1</td>
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<td>Cl-</td>
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</table>

between Morton Salt and the north ends of the lakes. A billion kilograms would hardly suffice.

Saline groundwater under Seneca and Cayuga Lakes has not previously been reported in the literature, although Harriss (1967) found an increasing chloride gradient with depth in near-surface Seneca Lake sediments (max [Cl], 152 ppm). He seems not to have understood the significance of his finding to the question of high salinity in the lake and attributed his results to evaporation of rainwater solutions in soils in the watershed. Sediment pore-water chloride concentrations very similar to ours were obtained by Grotzinger (1979).

Table 3 lists interstitial water concentrations of sodium, calcium, magnesium, and potassium as well as total alkalinity and chloride for three Seneca Lake cores. Sodium concentrations increase proportionately with chloride in all cores, but the behavior of calcium, magnesium, and potassium is more varied. Their ionic concentrations increase with depth in cores Seneca 1 and Seneca A but not in Seneca E, which could be indicative of chemical heterogeneities in the groundwater fluids. A report by Drimie et al. (unpubl.) of highly saline and chemically heterogeneous fluids in Lake Ontario sediments suggests that such phenomena are not limited to the largest of New York's Finger Lakes.
Pooling of saline water in a topographic depression in Seneca Lake—The bottom of Seneca Lake is topographically irregular. A depression in the lake floor at 42°49.95′N, 76°57.95′W (known locally as the Belhurst Castle Hole) has been observed on occasion to contain water with up to twice the conductivity of the rest of the lake below its sill depth of 46 m (Figs. 13 and 14). Sediments in the hole are saline (Seneca cores 8, A, E) but not significantly more so than those of other cores at this end of the lake. It would appear that the morphology of the hole prevents mixing of water below its sill with the rest of the lake. This phenomenon is transient. It persists for at least a few weeks at a time in summer or autumn but can suddenly disappear. Seneca Lake is known to undergo internal waves and seiches with amplitudes of tens of meters (Ahrensbrak 1974). Such events are pre-
sumably sufficient to flush the hole of its salt-enriched water.

Conclusions

Whether the model of Efler et al. (1989) is accurate for Cayuga Lake, it entirely fails to balance the salt budget of Seneca Lake without a significant input of salt from within the lake's basin. Seneca Lake and Cayuga Lake each exhibit large regions of highly saline groundwater within 3 m of the sediment–water interface and a bottom-up conductivity-chloride gradient in the water column consistent with large-scale intrusion of saline groundwater into the water column. For Seneca Lake, no source other than saline groundwater intrusion can account for the high chloride levels. The field data strongly suggest that the same process occurs on Cayuga Lake, albeit to a lesser extent.

In his discussion of salt in the Finger Lakes, Berg (1963, p. 203) wrote of the saline groundwater hypothesis: “This suggests a dimension in regional limnology that has not received much attention in the literature—the possibility that the chemistry of a lake can be affected significantly by the deep-lying strata intercepted by its basin as well as by the surficial lithology of its watershed.” Three decades later, this “dimension” is still underappreciated.

References


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Gas Storage And Single-Point Failure Risk

By John M. Hopper

Accidents at natural gas storage facilities, especially catastrophic ones, are rare. However, loss can be minimized if the facility has been designed to include redundant systems.

On the morning of Aug. 18 I was on a conference call with a prospective customer interested in contracting for firm gas storage service at our Hill-Lake Gas Storage Facility in north Texas. The next morning, following the explosion and fire at Duke Energy Gas Transmission's Moss Bluff storage facility in Liberty County, Texas, I was on the phone fielding questions like: "Could this happen at Falcon's storage facilities?" and "How much insurance coverage does Falcon have?" Fortunately, we've never had anything like this occur at any of our facilities, which are depleted reservoirs, not salt caverns. And we do carry lots of property and casualty insurance, just in case.

The Moss Bluff incident was a real eye-opener. The reported failure of a single emergency shut-off valve severely damaged one of the three salt caverns that had been leached in the Moss Bluff salt dome for the purpose of storing natural gas. The estimated replacement value of the cavern is in the range of $15 to $20 million. Also lost was approximately 6,000,000 MMBtu of gas worth a reported $36 million or more. Fortunately, no serious injuries or loss of life occurred, although many families living in the Moss Bluff area were inconvenienced by an evacuation that lasted several days.

The short-term effects of the Moss Bluff incident—the loss of property and equipment as well evacuation and clean-up costs—presumably will be covered by insurance. More difficult to ascertain are the long-term effects that the incident may have on the gas storage industry as a whole. Customer and investor confidence could be affected adversely. Government oversight may increase at both the state and federal levels. Calls for design changes and additional safety measures may ensue. Casualty insurance premiums may rise. And, of course, the cost of doing business could increase significantly as a result—all at a time when more, not less, gas storage capacity is desperately needed in this country.

Numerous Facilities

According to the Energy Information Administration, there were 307 underground natural gas storage facilities in operation in the United States in 2002, of which 340, or 84%, were depleted reservoir facilities; 38, or 9%, were aquifer facilities and 29, or 7%, were salt cavern facilities. Market and investor confidence in the U.S. gas storage infrastructure—as well as the blessings of government regulators—are essential to the stability and success of the natural gas storage business.

Statistically, the odds are remote that single-point failures involving natural gas storage facilities can produce the
kind of catastrophic losses such as what occurred at Moss Bluff. Be that as it may, they have happened before. In every case, however, a salt cavern storage facility was the culprit, not a depleted reservoir or aquifer gas storage facility. This is an important distinction and underscores the fact that most underground gas storage facilities in the United States—95% of which are either depleted reservoir or aquifer storage facilities—are not susceptible to the kind of catastrophic failure that occurred at Moss Bluff. Nevertheless, prospective storage customers and investors interested in the gas storage business should consider the nature, risks and consequences of single-point failures when making gas storage service choices or storage investment decisions.

Those of us who live in the Houston area undoubtedly will recall the devastating explosion and fire that occurred at the Brenham salt cavern storage facility in April 1992 when a storage cavern was over-filled and leaked liquid petroleum gas (LPG). Several people were killed in that catastrophe. In 1980, a similar LPG leak caused by corrosion casing resulted in an explosion and fire at a salt cavern storage facility located on the Barber’s Hill salt dome, which is home to a multitude of salt caverns comprising the Mont Belvieu salt cavern storage complex, not far from Moss Bluff. Another explosion and fire occurred at the Mont Belvieu storage complex in November 1985, killing two people and prompting the evacuation of the entire town’s population of more than 2,000 residents. Yet another fire and explosion occurred at the Mont Belvieu storage complex in October 1984 that caused several million dollars in property damage. In 1978, a packer failure at a crude oil storage cavern at the West Hackberry salt cavern storage facility in south Louisiana caused the release of an estimated 72,000 barrels of crude oil, which caught fire and killed one worker. More recently, an explosion and fire occurred in January 2001 at the Yaggy salt cavern facility near Hutchison, Kan., resulting in several deaths and substantial property damage.

Losses from other incidents involving salt cavern storage facilities fortunately have been limited to the destruction of plant, property and equipment. In the early 1970s, the Eminence salt cavern gas storage facility in Mississippi experienced such severe salt creep (i.e., the shrinking or collapse of cavern walls) in one of its caverns that almost half of the cavern’s storage capacity was lost. Late last year, a casing leak at Entergy-Koch’s Magnolia salt cavern facility near Napoleonville, La., resulted in a large quantity of gas reportedly being vented to the atmosphere, which forced the shutdown of the facility as well as the evacuation of residents in the area until the leak was contained. In the early 1990s, the now-defunct U.S. energy subsidiary of Germany’s Metallgesellschaft contracted for a third party to develop a salt cavern for natural gas storage at the Stratton Ridge salt dome in Brazoria County near Freeport, Texas. The cavern failed a mechanical integrity test because it leaked gas when pressurized up for storage and had to be abandoned.

MOSS BLUFF, WHAT HAPPENED?
I do not know exactly what happened at Moss Bluff in August. It has been reported that a single emergency shut-off valve failed during cavern de-watering operations. The cavern had just been expanded using the SMUG (Solution mining under gas) process, which permits salt cavern expansion without interrupting gas storage operations. When the valve failed, gas blew out of the cavern, ignited, and ultimately destroyed the single storage wellhead. Regardless of what led to the catastrophe, the inevitable question is: “Can it happen again and, if it does, how will it affect my gas storage inventory?” Or, “How will it affect my investment in a gas storage facility?”

These questions deserve good answers. The first is that not all natural gas storage facilities are the same, just as not all gas pipeline assets are the same. The design characteristics and operational risks that are inherent in one gas storage facility are not necessarily present in another, even though the facilities are similar in purpose. The fact is that salt cavern gas storage poses substantially different developmental and operational risks than depleted reservoir storage.

SINGLE-POINT FAILURE
While single-point failures are not all that unusual in the gas storage business, what is unusual about the events that transpired at the Moss Bluff, Brenham, Barber’s Hill, West Hackberry, Yaggy, Napoleonville and Eminence salt cavern storage facilities is the magnitude of loss caused by failure of a single piece of equipment. In each of these cases, the failure of a single valve, wellhead, packer, joint of casing or the structural integrity of the salt cavern itself caused a catastrophic loss. While we’ve had single-point failures occur at our own depleted reservoir facilities, the worst of them—a damaged compressor shaft—caused a service interruption that lasted only a few days and cost about $150,000 to repair.

A single-point valve failure causes a gas leak, leading to fire and an explosion that engulfs the primary storage well. However, backup withdrawal wells can be employed to withdraw the remaining gas inventory that otherwise would be destroyed.
Prudent due diligence requires that prospective storage customers and investors should consider whether the storage facility in question has design characteristics that are susceptible to single-point failure. If so, then risks should be weighed against the cost of installing redundant systems to serve as backup in case of failure.

The storage cavern damaged at Moss Bluff had only one wellbore installed for injection and withdrawal, which is the standard design for most salt caverns. Under normal conditions this works just fine. However, when a wellhead or valve failure occurs and a gas leak ensues it may not be possible to contain the leak if the well catches fire — especially if the cavern is full and hence fully pressurized. Since a single salt cavern can hold anywhere from 3 to 8 Bcf or more, the loss of an entire wellbore or storage cavern also can result in the loss of a lot of gas, which in fact happened at Moss Bluff.

**BACKUP BENEFITS**

Had there been a backup wellbore and wellhead installed at Moss Bluff at a location sufficiently distant from the wellbore that exploded and caught fire, it would have been possible to withdraw the stored gas and prevent most of it from being consumed by fire. The installation of yet a third backup wellbore could serve as either an additional emergency gas withdrawal well or could be connected to an on-site source of water, brine or an inert gas such as nitrogen — any one of which would have made it possible to flood the cavern, preserving its integrity and preventing further damage. However, salt cavern developers rarely incorporate such redundancy due to cost. But with an incremental investment of about $50 million —approximately the cumulative cost of the losses at Moss Bluff—all three caverns at Moss Bluff could have been equipped with this redundant backup.

In contrast to salt cavern storage, depleted reservoir storage typically has many wellbores that are used for injection/withdrawal. Redundancy is in effect built in. The complete loss of a single wellbore or wellhead at a typical depleted reservoir would in the worst case result in the loss of only that gas that could be drained by that single wellbore, and then for only as long as it would take to cap the well in question.

Moss Bluff vented an estimated 1,000,000 MMbtu per day for several days at extremely high pressures, which prevented the well from being capped until virtually all of the stored gas had been lost. Because storage wells in depleted reservoirs are easier to cap if they were to blow out and drain only a limited area of the reservoir, gas loss would be limited. And if a well is lost or damaged at a depleted reservoir, the remaining wells can be deployed quickly to withdraw remaining gas inventory.

More typical single-point failures involve valves and compressor parts whose failure can cause a shutdown or service interruption at any storage facility. Service interruptions at salt caverns, though, can be significantly longer than those at depleted reservoirs, especially if the structural integrity of the surrounding caverns is at risk. Moreover, unlike a valve or a compressor unit, a salt cavern cannot be repaired or replaced quickly. Leaching a new cavern can take up to two years. And repairing a salt cavern to its original structural integrity may not be possible.

Clearly, not all gas storage facilities are alike. Where a customer decides to store gas or an investor interested in the gas storage business chooses to invest capital are decisions driven by any number of factors. Risks and consequences of single-point failures are just two of them—albeit important ones, as the incident at Moss Bluff reminds us.

**John M. Hopper** is president and CEO of Falcon Gas Storage Co., one of the largest independent owners and operators of high-deliverability, multi-cycle depleted reservoir gas storage in the United States. From 1989 to 1994, Hopper was a vice president of TPC Corp., which developed the Moss Bluff Gas Storage Facility and the Eggn salt cavern storage facility in south Louisiana. He can be reached at jhopper@falcongasstorage.com.

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### Catastrophic Events Involving Salt Cavern Storage Facilities Since 1972

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**Where Only Catastrophic Loss of Property Occurred**

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<td>Gas Leak and Evacuation</td>
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<tr>
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<td>Freeport, Texas</td>
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<td>1990</td>
<td>Cavern Failure/Abandonment</td>
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<td>Fire and Explosion</td>
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<td>Natural Gas</td>
<td>Apr. '72</td>
<td>Loss of Storage Capacity</td>
<td>Salt Creep</td>
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*Source: Falcon Gas Storage Co.*
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RISK ASSESSMENT OF NONHAZARDOUS OIL-FIELD WASTE DISPOSAL IN SALT CAVERNS

Deborah Elcock, David Tomasko, and John Veil
Argonne National Laboratory
Washington, DC, and Argonne, Illinois, USA

ABSTRACT

Salt caverns can be formed in underground salt formations incidentally as a result of mining or intentionally to create underground chambers for product storage or waste disposal. For more than 50 years, salt caverns have been used to store hydrocarbon products. Recently, concerns over the costs and environmental effects of land disposal and incineration have sparked interest in using salt caverns for waste disposal. Countries using or considering using salt caverns for waste disposal include Canada (oil-production wastes), Mexico (purged sulfates from salt evaporators), Germany (contaminated soils and ashes), the United Kingdom (organic residues), and the Netherlands (brine purification wastes).

In the United States, industry and the regulatory community are pursuing the use of salt caverns for disposal of oil-field wastes. In 1988, the U.S. Environmental Protection Agency (EPA) issued a regulatory determination exempting wastes generated during oil and gas exploration and production (oil-field wastes) from federal hazardous waste regulations - even though such wastes may contain hazardous constituents. At the same time, EPA urged states to tighten their oil-field waste management regulations. The resulting restrictions have generated industry interest in the use of salt caverns for potentially economical and environmentally safe oil-field waste disposal. Before the practice can be implemented commercially, however, regulators need assurance that disposing of oil-field wastes in salt caverns is technically and legally feasible and that potential health effects associated with the practice are acceptable.

In 1996, Argonne National Laboratory (ANL) conducted a preliminary technical and legal evaluation of disposing of nonhazardous oil-field wastes (NOW) into salt caverns. It investigated regulatory issues; the types of oil-field wastes suitable for cavern disposal; cavern design and location considerations; and disposal operations, closure and remediation issues. It determined that if caverns are sited and designed well, operated carefully, closed properly, and monitored routinely, they could,
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from technical and legal perspectives, be suitable for disposing of oil-field wastes. On the basis of these findings, ANL subsequently conducted a preliminary risk assessment on the possibility that adverse human health effects (carcinogenic and noncarcinogenic) could result from exposure to contaminants released from the NOW disposed of in salt caverns.

The methodology for the risk assessment included the following steps: identifying potential contaminants of concern; determining how humans could be exposed to these contaminants; assessing contaminant toxicities; estimating contaminant intakes; and estimating human cancer and noncancer risks.

To estimate exposure routes and pathways, four postclosure cavern release scenarios were assessed. These were inadvertent cavern intrusion, failure of the cavern seal, failure of the cavern through cracks, failure of the cavern through leaky interbeds, and partial collapse of the cavern roof. Assuming a single, generic, salt cavern and generic oil-field wastes, potential human health effects associated with constituent hazardous substances (arsenic, benzene, cadmium, and chromium) were assessed under each of these scenarios.

Preliminary results provided excess cancer risk and hazard index (for noncancer health effects) estimates that were well within the EPA target range for acceptable exposure risk levels. These results lead to the preliminary conclusion that from a human health perspective, salt caverns can provide an acceptable disposal method for nonhazardous oil-field wastes.
INTRODUCTION

In a 1996 study, Argonne National Laboratory (ANL) determined that if salt caverns are sited and designed well, operated carefully, closed properly, and monitored routinely, they could be suitable for disposing of nonhazardous oil-field wastes (NOW) (1). This paper presents the findings of an assessment of the potential for adverse human health effects (carcinogenic and noncarcinogenic) resulting from exposure to contaminants released from caverns used for NOW (2). The assessment addressed risks after cavern closure and did not consider potential risks resulting from surface equipment emissions, surface oil leaks, or other equipment-related spills or accidents.

As discussed in the 1996 study, surface salt deposits occur in two forms in the United States: bedded salt and salt domes. Bedded salt formations occur in layers. These layers are separated by such nonsalt sedimentary materials as anhydrite, shale, and dolomite, which are generally of low permeability (3). Salt domes, on the other hand, are large, nearly homogeneous formations of sodium chloride (4). The depth of the salt can be greater than 10,000 ft, and the top width of the domes can be up to 2.5 miles (5). Starting in the early 1900s, salt domes were mined commercially using various leaching methods. Bedded salt was first used in the 1940s (6), and salt domes were first used in about 1951 to store liquefied petroleum gas (LPG). Stored products include propane, butane, ethane, ethylene, fuel oil, gas, natural gas, and crude oil. In 1975, the U.S. Department of Energy (DOE) acquired the rights to use several existing caverns to store crude oil as part of the Strategic Petroleum Reserve (SPR) (7). Private industry operates more than 1,800 caverns for storing liquid petroleum products, petrochemicals, and natural gas in the United States. Typically, these caverns are smaller than those used in the SPR and have an average diameter of about 115 ft (8). European countries have used salt caverns as containment sites for various wastes, but the use of salt caverns for waste disposal in the United States has been limited (1).

This paper addresses potential health impacts of disposing of NOW in domal salt caverns. The NOW would be solid or sludge-like tank bottom wastes (waste material from washing tanks, heater tanks, and stock tanks) consisting of accumulated heavy hydrocarbons, paraffins, inorganic solids, and heavy emulsions (9). Physically, these wastes consist of approximately 50% water, 15% clay, 10% scale, 10% corrosion products, and 5% sand (2). Prior to disposal, a salt cavern used for NOW disposal would be filled with brine. Wastes would then be introduced as a slurry of waste and a fluid carrier (water or brine). This slurry would be pumped down one annulus, and brine would be removed from another. Once filled with waste, the cavern would be sealed, and the borehole would be plugged with cement.

Following closure, the pressure and temperature of the cavern would rise because of salt creep (10) and the addition of sensible heat (11). After closure, inadvertent intrusion or cavern failure could release NOW to the environment, thus potentially affecting human health. The remainder of this paper discusses the sources and probabilities of such events and their impacts on human health.

CONTAMINANTS OF CONCERN

The term “nonhazardous oil-field waste” does not mean that wastes generated during oil and gas exploration and production contain no hazardous contaminants. In 1988, the U.S. Environmental
Protection Agency (EPA) exempted oil and gas exploration and production wastes from regulation under the Resource Conservation and Recovery Act (RCRA) Subtitle C hazardous waste management program (53 FR 25446, July 6, 1988). The EPA provided this exemption because it found that other state and federal programs could protect human health and the environment more effectively, not because oil-field wastes are benign.

The EPA used its 1987 Report to Congress, “Management of Wastes from the Exploration, Development and Production of Crude Oil, Natural Gas, and Geothermal Energy” (the Report to Congress) as the basis for the above regulatory determination (12). In that report, the EPA identified contaminants of concern for produced water and drilling muds. Factors used to select these contaminants included median and maximum concentrations in waste samples; frequency of detection; mobility in groundwater; and concentrations at which human health effects, aquatic toxicity, or resource damage start to occur. Chemicals that the EPA screened as likely to dominate risk estimates included arsenic, benzene, boron, cadmium, and chromium (VI). In 1988, the EPA began evaluating the relative hazards posed by waste streams associated with exploration and production, including tank bottoms, oily debris, workover fluids, produced sand, emulsions, and others (9). It found that tank bottom wastes exceeded RCRA toxicity characteristics for benzene and lead.

Of the potential contaminants of concern identified in these two EPA studies (i.e., arsenic, benzene, boron, cadmium, chromium (VI) and lead), two were eliminated from further consideration in this study: boron because of its high probability of forming insoluble hydroxyborate compounds, and lead because of its low solubility, large distribution coefficient, and large retardation factor (3).

POSTCLOSURE RELEASE CONDITIONS AND CONCENTRATIONS

On the basis of several postclosure accident scenarios identified in a 1995 study of cavern failure modes for LPG (13), the current study examined the following five postclosure scenarios:

(1) Inadvertent intrusion by unintentionally drilling a new well into a closed cavern, which could produce a release of cavern fluid to the ground surface;

(2) Failure of the cavern seal due to increased pressure from salt creep and geothermal heating, which could release contaminated fluid to the groundwater at the depth of the cavern or at more shallow depths;

(3) Release of contaminated fluid through deep cracks to groundwater;

(4) Release of contaminated fluid through leaky interbeds or nonhomogeneous zones composed of higher-permeability material, which could contaminate deep groundwater; and

(5) A partial collapse of the cavern roof, which could release contaminated fluid to deep or shallow groundwater depending on the condition of the cavern seal (2).

Concentrations of contaminants of concern expected at the point of human exposure for each of these scenarios were calculated on the basis of (1) estimated initial concentrations at the release point, (2) hydrogeology of the area, (3) fate and transport mechanisms of the contaminants of concern, (4) release scenarios, and (5) probabilities that the releases would occur.
Initial Concentrations

Conservative estimates of the initial concentrations for each contaminant (i.e., the concentrations of the contaminants leaving the cavern) for use in fate and transport modeling were made by using the maximum concentrations found in produced water (12, 14, and 15), drilling waste data using EPA’s toxicity characteristic leaching procedure (TCLP) (12), and tank bottoms TCLP data (9). These estimates are 20.4 mg/L, 1.7 mg/L, 0.29 mg/L, and 0.85 mg/L for benzene, arsenic, cadmium, and chromium, respectively.

Hydrogeology

The analysis assumed a generic salt cavern located in the Gulf Coast of the United States. Depth to the water table was assumed to be on the order of about 20 ft (2). This shallow groundwater system is composed primarily of sands and is overlain and underlain by deposits of silt and clay. Where the silts and clays have been eroded, the shallow aquifer is unconfined; confined to semiconfined conditions exist where the clays and silt are present (16). Beneath the shallow groundwater system are other sequences of clays and silts, interspersed with beds of sand. The sandy areas constitute other potential groundwater aquifers that are predominantly confined (17). Recharge to the shallow groundwater system is derived from precipitation. The majority of recharge occurs in areas where the clay and silt are absent. Discharge of the aquifer is to surface waters and to underlying deeper aquifers.

In general, water quality decreases with depth. At the depth of salt deposits suitable for disposal, water quality is expected to be poor because of high salinity. In the vicinity of the cavern, hydrological properties are unlikely to favor rapid transport of contaminants (e.g., the groundwater velocity at the depth of the cavern is estimated to be less than 10 ft/yr). At shallow depths, the groundwater velocity is expected to be greater (about 100 ft/yr).

Fate and Transport

Fate and transport of the contaminants of concern were estimated on the basis of the chemical and physical characteristics of the constituents. These characteristics included density, solubility, volatility, distribution, retardation, and biodegradation. Qualitative results are summarized below.

Benzene

Benzene is very soluble in water, and, once in a groundwater system, it is very mobile. Because of biodegradation and volatilization, however, it would have a limited range of travel in an aquifer.

Arsenic

Because of the low solubility and large distribution coefficient of arsenic, its concentration and mobility in groundwater would be very low.

Cadmium

Because of the presence of iron in the tank bottom wastes, cadmium is likely to precipitate out as a hydroxide. Given the low solubility of cadmium hydroxide and its moderate rate of sorption, the mobility of cadmium in groundwater would be low.
**Chromium**

Because of low solubility and high distribution coefficients, both trivalent and hexavalent forms of chromium are expected to have low concentrations and mobilities in groundwater. The mobility of the hexavalent form, however, is expected to be greater than that of the trivalent form.

**Release Scenarios**

Scenarios that could lead to the release of contaminants are summarized below. Estimated contaminant concentrations in the groundwater at the location of a potential receptor at a time 1,000 years in the future, a typical time horizon for risk analyses, are shown in Table 1.

**Inadvertent Intrusion**

For the inadvertent intrusion scenario, contaminated fluids would move quickly to the surface where, if not contained by the drilling blowout-prevention system, the fluids would most likely form a pool on the ground surface. The fluids would not penetrate very far into the ground and could be readily cleaned up. Because the volume of released fluid for this scenario would be small, the effects would be of very short duration, the liquid would not be potable, and such a spill would be quickly remediated, this scenario was eliminated from further analysis.

**Release through the Cavern Seal**

After disposal is completed, the cavern would be sealed and abandoned. At the time of sealing, the cavern would be filled mostly with solids and semisolids that are not fully compacted. Brine would remain between the top of the cavern and the top of the waste mass. The well bore would have cement plugs installed during cavern closure and abandonment. With time, the well casing may deteriorate because of the presence of brine in the vicinity of the caprock, or at the top of the cavern if a caprock is not present. The well casing would be expected to corrode and fail near the top of the cavern first. With additional time, the well casing would fail at shallower depths.

For a deep casing failure, fluid moving up the well bore would move into the deep aquifer and would be transported laterally. The presence of low-permeability beds at shallower depths would prevent vertical transport of the contaminated fluid to overlying aquifers and the ground surface. The extent and magnitude of contamination would depend on the hydrological properties of the material in the vicinity of the failed casing, the volume of fluid that is released, the duration of the discharge, and the transport properties of the contaminants. In the vicinity of the cavern, hydrological properties would unlikely favor rapid transport of the contaminants.

For the second alternative considered for this release scenario, the cavern seal is again assumed to fail; however, the well bore casing at the depth of the cavern is assumed to be intact. Contaminated fluid would then flow up the well bore and exit the casing at a failure point adjacent to a shallow groundwater aquifer. For a release to shallow groundwater, the concentrations would be larger than those discussed above because of shorter travel time. The concentration of benzene, however, would remain at 0.0 mg/L because of its biological degradation.

**Release of Contaminated Fluid through Cracks**

As the combined effects of thermal heating and salt creep lead to increasing pressure on the cavern, cracks might develop that would release fluid into the surrounding material, thereby
reducing the pressure in the cavern. The volume of fluid released would be a function of the pressure in the cavern, the volume of the cracks, and the crack pressure.

**Release of Contaminated Fluid through Leaky Interbeds or Nonhomogeneous Zones**

In this scenario, the cavern is assumed to have a leaky interbed or heterogeneity that allows communication with the outside environment. As the cavern pressure rises due to thermal effects and salt creep, fluid would be discharged into the interbed where it would be transported laterally under existing gradients. Eventually, the entire fluid volume of the cavern would be discharged into the surrounding material. The leaking brine would mix with in-situ water and would be transported downgradient. Because of this mixing, the contaminant concentrations would be reduced by dilution.

**Concentration Estimates**

Maximum exposure point concentrations for each of these scenarios were calculated using a one-dimensional analytical solution to an advection/dispersion transport equation that included adsorption, first-order degradation, and dilution (18). Contaminants were assumed to exit the cavern for a period of 250 years. The contaminant retardation factors for transport were derived from (a) their respective distribution coefficients ($K_d$) that were obtained from the literature — benzene - 0.62 mL/g (19), arsenic - 10 mL/g (20), cadmium - 3 mL/g (20), and chromium - 30 mL/g (20); (b) a bulk density of 1.7 g/cm$^3$; and (c) a porosity of 0.10 (3). The duration of the source used in the calculations is expected to be conservative because of the self-healing ability of any cracks in the salt matrix and the small volumes of fluid that would be released. Table 1 summarizes the maximum contaminant concentrations associated with the specified release scenarios at a point 1,000 years in the future.

**Release Probabilities**

To assess human health risks the expected exposure-point concentrations and the probability that a given scenario would occur are required. Because there is no operational history for disposing of NOW in salt caverns, the probabilities of occurrence for the release scenarios described above are uncertain. Under the most optimistic conditions, no releases would occur, and the associated probabilities of occurrence would be 0.0. For the most pessimistic conditions, releases would always occur and the probabilities of occurrence would be 1.0.

To reduce the uncertainty in the range of the probabilities of occurrence, a questionnaire was distributed to experts in the field of salt caverns. The experts were asked to provide both a “best-” and a “worst-case” estimate of the probability of occurrence for each release scenario. In the context of this questionnaire and study, best case referred to the most likely probability of occurrence in the best judgment of the expert; worst case referred to the least likely probability of occurrence in the best judgment of the expert.

Responses from the expert panel were aggregated to form consensus values for each of the probabilities of occurrence using an arithmetic average to represent the aggregate value for the probabilities of occurrence.
Table 1 presents best- and worst-case aggregated probabilities of occurrence for each release scenario. The highest probabilities of occurrence were for a partial fall of the roof (0.10 and 0.29, respectively). The smallest probabilities of occurrence were for a partial roof fall with a cavern seal failure and release to a shallow aquifer (0.006 and 0.051, respectively), and a cavern seal failure with subsequent release to a shallow aquifer (0.012 and 0.040, respectively).

Exposure point concentrations for use in the risk assessment were calculated through multiplying the calculated exposure point concentrations (assuming the release scenario occurs) by the associated probabilities of occurrence. The results are shown in Table 1.

**RISK ASSESSMENT**

Human health risks associated with NOW contaminants released from a waste disposal cavern may be carcinogenic or noncarcinogenic. Carcinogens are believed to act via a “nonthreshold” mechanism of action; that is, a risk would be associated with any exposure level, no matter how small. Noncarcinogens are believed to act via a “threshold” mechanism of action; that is, there is some level of exposure (the threshold) below which the contaminant is unlikely to have an effect.

**Human Health Hazards of NOW Constituents**

Human health hazards associated with arsenic, benzene, cadmium, and chromium are summarized below. For all release scenarios, the potentially exposed population would be residents living near the salt caverns who drink the contaminated groundwater.

**Arsenic**

Arsenic exposure comes from ingesting contaminated water or soil or breathing contaminated air. High levels (60 ppm [mg/L]) in food or water can be fatal; lower levels can cause nausea, decreased production of blood cells, and abnormal heart rhythms. Arsenic is a known carcinogen; ingesting inorganic arsenic increases the risk of skin cancer and tumors of the bladder, kidney, liver, and lung. The EPA has set a maximum contaminant limit (MCL) of 0.05 ppm for arsenic in drinking water.

**Benzene**

The most common exposure route for benzene is inhalation, but it can also be ingested. Benzene is a known human carcinogen and is associated with leukemia. EPA has set a maximum permissible level of benzene in drinking water of five parts per billion (ppb) ($5 \times 10^{-9}$) per day for a lifetime of exposure. The EPA has set a maximum contaminant limit goal (MCLG) of 0 ppb for drinking water and rivers and lakes.

**Cadmium**

Cadmium can accumulate in the human body from many years of low-level exposure. Exposure comes from eating foods that contain cadmium and from drinking contaminated water. On the basis of weak evidence of lung cancer in humans from breathing cadmium and strong evidence from animal studies, cadmium and cadmium compounds may be reasonably anticipated to cause cancer in humans. It is not known whether cadmium causes cancer from eating or drinking contaminated food or water. The EPA has set an MCL of 5 ppb for cadmium in drinking water.
Chromium

Human exposure to chromium comes from ingestion or inhalation. At high levels, all forms of chromium can be toxic, but chromium VI is more toxic than chromium III. Long-term exposure to high or moderate levels of chromium VI can damage the nose and lungs. Ingesting large amounts of chromium can cause stomach upsets and ulcers, convulsions, kidney and liver damage, and death. Certain chromium VI compounds are known carcinogens. The Agency for Toxic Substances and Disease Registry (ATSDR) has insufficient data to determine if chromium VI or chromium III are carcinogens. The EPA has set an MCL for total chromium of 0.1 mg/L.

Characterization of Cancer Risks

To estimate the amount of contaminant actually received from drinking contaminated water, assumptions regarding intake rate, exposure time, exposure frequency, and duration of exposure to the water were made. Unless otherwise indicated, standard EPA default exposure factors are used in the assumptions (21). Using these assumptions and the exposure-point concentrations presented in Table 1, an intake rate for each contaminant of concern was calculated using the following equation:

\[
I_i = \frac{C_i \times IR \times ET \times EF \times ED \times CF}{BW \times AT}
\]

where

- \(I_i\) = Intake of contaminant \(i\);
- \(C_i\) = Exposure point concentration of contaminant \(i\), in g/L;
- \(IR\) = Intake rate in L/d (assumed to be 2 L/d);
- \(ET\) = Exposure time, in h/d (assumed to be 24 h/d);
- \(EF\) = Exposure frequency, in d/yr (assumed to be 350 d/yr);
- \(ED\) = Exposure duration, in yr (assumed to be 30 yr);
- \(CF\) = Conversion factor of 1 d/24 h;
- \(BW\) = Body weight of the receptor, in kg, (assumed to be 70 kg); and
- \(AT\) = Averaging time, in d (for carcinogens, \(AT = 25,550\) d (70 years); for noncarcinogens, \(AT = 365\) d/yr \(\times ED\))

Cancer risks were calculated for each contaminant and were then summed over all contaminants. Because the only exposure pathway for potential contaminant releases from a disposal cavern would be groundwater, the only exposure route is ingestion.
Human cancer risks associated with disposal of NOW in salt caverns were estimated for the release scenarios using the following equation:

\[ R_i = I_i \times SF_i \]  \hspace{1cm} (2)

where

\[ R_i = \text{Risk from contaminant } I_i; \]
\[ I_i = \text{Intake of contaminant } I_i; \] and
\[ SF_i = \text{Slope factor for contaminant } I_i. \]

Slope factors are used to estimate the toxicities of carcinogens; a slope factor is defined as a plausible upper-bound estimate of the probability of a response per unit intake of a chemical over a lifetime. Oral slope factors of 1.5 and 0.029 (1/mg/kg-day) were used for arsenic and benzene, respectively. These values were obtained from the EPA’s Integrated Risk Information System (IRIS).

The total cancer risk for each release scenario is the sum of the individual cancer risks for all contaminants of concern. Because there are no slope factors available for cadmium and chromium, and the exposure-point concentration of benzene would be 0.0 for all of the release scenarios, the total cancer risk is equal to the risk estimate for arsenic. Total estimated cancer risks for each release scenario under best- and worst-case probability assumptions are presented in Table 2.

**Noncancer Risks**

The risk associated with a noncarcinogen is expressed as a hazard quotient, which is the intake of a particular contaminant divided by its reference dose (RfD). The RfD is the estimated “safe” dose for humans; when a hazard quotient exceeds 1, there is a potential for adverse noncarcinogenic effects. Hazard quotients are summed over contaminants and exposure routes to obtain an overall hazard index. However, for salt caverns, the only exposure route would be the oral pathway (ingestion of groundwater). For a single contaminant, \( I_i \), the hazard quotient is calculated according to the equation,

\[ HQ_i = \frac{I_i}{RfD_i} \]  \hspace{1cm} (3)

where

\[ HQ_i = \text{Hazard quotient from contaminant } I_i, \]
\[ I_i = \text{Intake of contaminant } I_i; \] and
\[ RfD_i = \text{Reference dose for contaminant } I_i. \]
Noncancer risks were estimated for each of the individual contaminants for the release scenarios assuming both best- and worst-case probabilities of occurrence. The results are shown in Table 2. All of the contaminants of concern have calculated hazard quotients much less than one. Even when the hazard quotients are summed for all contaminants in a given release scenario, the greatest hazard index under worst-case probability assumptions would be $6 \times 10^{-5}$. For best-estimate conditions, the largest total hazard index would be less ($1.4 \times 10^{-5}$).

**CONCLUSIONS**

On the basis of assumptions that were developed for a generic cavern and generic oil-field wastes, the estimated human health risks for worst-case probability estimates are very low (excess cancer risks of between $1.1 \times 10^{-8}$ and $2.0 \times 10^{-11}$), and hazard indices (referring to noncancer health effects) are between $6 \times 10^{-1}$ and $1.0 \times 10^{-7}$. Normally, risk managers consider risks of $1 \times 10^{-6}$ and less and hazard indices of less than 1 to be acceptable. For best-case probability estimates, the estimated excess cancer risks and hazard indices are lower.

These results should be viewed in the context of several considerations. First, this assessment did not address risks to workers at the cavern disposal site. Such risks would be comparable to or less than worker risks associated with hydrocarbon cavern storage operations. (For example, explosions are possible at hydrocarbon storage operations.) Also, the assessment did not determine whether any health effects would occur in the future; it only estimated potential cancer risks and noncancer effects. Third, risks were estimated only for contaminants for which toxicity values were available; the absence of a toxicity value does not indicate zero risk. Finally, the assessment was limited to human health effects produced by nonradioactive contamination; it did not address the possible ecological risks associated with salt cavern disposal, nor did it estimate risks associated with naturally occurring radioactive materials that may be included in oil-field wastes.
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Table 1. Estimated Contaminant Concentrations

<table>
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<tr>
<th>Scenario</th>
<th>Contaminant</th>
<th>Initial Conc.</th>
<th>1,000-Year Conc.</th>
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Table 2. Estimated Cancer and Noncancer Risks

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Faulting and fluid flow through salt

IAN DAVISON
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Abstract: Halite and other evaporite rocks are often considered to be viscous materials that never deform by brittle faulting. However, fractures and faults are observed very locally in some salt domes and glaciers, and are indicated by data or shocks from seismically active areas. Rock mechanics experiments show that halite begins to deform by faulting once strain is large enough. However, it is very rare that such high strain rates occur in salt. Faulting in salt is most likely to occur where effective confining stress is significantly decreased by fluid overpressure, so that the salt fails at much lower differential stress. Several examples are presented of diastrophic veins oriented in several directions, which strongly indicate the presence of overpressured fluids during fracturing. Hydrocarbon maturation in shales deposited within the salt interval or metamorphic reactions of evaporite minerals often produce fluid overpressure. Mining-induced fractures in the Boulby Mine, NE England produced 300 000 m³ of brine and 100 m³ of Carboniferous-derived oils through the Permian salt over a 1 year period. Evaporite beds are the most effective seal in a hydrocarbon system, but they are not a perfect seal and commercial volumes of hydrocarbons can occasionally migrate through salt over short time scales.

Evaporites are generally perceived to be the weakest lithology in a sedimentary basin and assumed to always deform only by deformation mechanisms that approximate to viscous or power-law flow processes (pressure solution, solid-state diffusion and dislocation creep). However, examples of brittle faulting in evaporites do occur in very localized areas in some mines and surface exposures of salt domes and extrusions. This paper reviews these rare examples of natural faulting in salt, and briefly summarizes what is known about brittle deformation and fluid flow through salt from laboratory studies. Many of the faults in salt are disguised by later ductile shearing, so that shear zones are developed that contain vestiges of the original faulting such as breccia zones with rounded fragments and sheared veins associated with fluid flow. Such palaeo-faulted intervals have been documented in natural diapirs in Oman where oil is leaking from large anhydrite inclusions within the salt, and from the salt itself, which had lost its sealing capacity (Schoenherr et al. 2007). These ‘anomalous’ zones exhibit unusually large grain-size salt with high gas and fluid content, and oil and bitumen staining (Kupfer 1962, 1976, 1990; Neal et al. 1993; Eghartner et al. 1998). ‘Anomalous’ zones can cause gas outbursts into salt mines during mining operations, which create large inverted funnel-shaped caverns in the roof of mine galleries that can have volumes up to 45 000 m³ (Fig. 1, Eghartner et al. 1998; Menzengrabern, potash mine no. 3, southern Harz region, Gimm 1968). The gas outbursts can contain methane, carbon dioxide, hydrogen sulphide, and nitrogen (Baar 1977), which have been responsible for miners’ deaths both down the mine and at the surface, where CO₂ outbursts have ponded in topographic depressions. Several mines have been abandoned because of the high number of casualties (Baar 1977).

Brittle deformation mechanics of halite

Laboratory experiments on halite indicate that it deforms in a brittle manner when the strain rate increases to a critical level and salt enters the dilatancy domain (e.g. Spiers et al. 1989; Thorel & Ghoreyehi 1996; Critescu & Hunsche 1998). At a confining pressure of 20 MPa (equivalent to 1 km of burial), failure occurs at differential stresses ranging from 25 to >50 MPa (Fig. 2). Using the viscous steady-state creep law of Critescu & Hunsche (1998, p. 51, Table 2.2, second law) for dry salt deforming at a temperature of 50 °C with a differential stress of 25 MPa, the strain rate at brittle failure would be 5 × 10⁻⁹ s⁻¹. This is a very high strain rate, which could be caused by earthquake shocks (see below) but is unlikely to occur in most normal salt tectonic settings, where strain rates rarely exceed 10⁻¹² s⁻¹. However, where the pore fluid is overpressured and the effective stress is low, salt will fault at much lower differential stress and strain rates (Schleder et al. 2007).

High stresses, strain rates and fluid pressures in naturally deformed salt

As salt is most likely to fault when the effective stresses are relatively low (Critescu & Hunsche 1998) it is worth examining how large fluid pressures build up in salt.

High fluid pressures

Fluid pressures close to lithostatic pressures are common in salt and this contributes to faulting and hydraulic fracturing (Schleder et al. 2007; Schoenherr et al. 2007). Fluid pressures build up in evaporites undergoing burial through important metamorphic reaction thresholds such as the transition from gypsum to anhydrite, which releases bound water from the crystal structure (CaSO₄·2H₂O → CaSO₄ + 2H₂O) and can increase the volume of the system by a factor of 38% (gypsum molar volume 74.7 cm³ mol⁻¹ and anhydrite molar volume 46 cm³ mol⁻¹). This transition occurs at depths from several metres to several kilometres depending on various parameters such as pore fluid salinity, pore fluid pressure, salt composition, grain size and geothermal gradient. The gypsum anhydrite conversion has been observed to occur between 70 and 105 °C (Hardie 1967; Jowett et al. 1993). Hence, when salt layers are buried to depths of 2–3 km any included gypsum will dehydrate and the liberated fluid
is likely to hydraulically fracture a temporary migration pathway out of the salt, which usually then reseals. The other main volume-changing reaction in evaporite sequences is the carnallite to sylvite transition (K\text{MgCl}_3\cdot 6\text{H}_2\text{O} + 4\text{H}_2\text{O} \rightarrow \text{KCl} + \text{MgCl}_2 + 2\text{Cl}^- + 10\text{H}_2\text{O}). This reaction involves volumetric increases of 40% (estimated by Schleder et al. 2007). This can cause large-scale fluid escape from the carnallite layer. High fluid pressures created by metamorphic reactions can cause diffuse dilatancy, leading to the formation of interconnected fracture networks that greatly increase permeability (e.g. Connolly et al. 1997; Holness & Watt 2002).

Generation of oil and gas from shales included within the evaporite sequence also creates large volume increases that lead to fluid overpressure. The fracturing in the Pugwash, Magdelen and Gorluben salt mines described below is thought to be caused by maturation of organic shales.

Even in the absence of dilatancy, the juxtaposition of brines and a brine-free rock can result in spontaneous fluid infiltration driven by the resultant decrease in the total internal energy of the system (M. Holness, pers. comm.). This is because the low dihedral angle (<60°) in the water–halite system stabilizes an interconnected network of fluid-filled channels along grain boundaries where three grains meet (Lewis & Holness 1996; Holness & Lewis 1997). This is a lower energy configuration compared with an initially brine-free halite (M. Holness, pers. comm.).

Lewis & Holness (1996) showed that at temperatures >100 °C and pressures of 70 MPa the brine–halite dihedral angle is less than the critical value (60°) required for the stabilization of the grain-edge channels. The resultant increase in permeability reaches millicdyrity levels. Schleder et al. (2007) calculated that this level of hydrostatic stress would occur at 3–4 km depth.

**High stresses and rapid strain rates in salt**

In general, differential stress is low in stable salt. For example, Schoenherr et al. (2007) have measured the differential stress in a salt mine within a stable buried salt body using sub-grain sizes and concluded that the maximum differential stress (\(\sigma_1 - \sigma_3\)) is less than 2 MPa, indicating that this is a nearly uniform stress field. There are certain situations, however, in which salt is highly stressed and where any weak overburden sediments deposited over the diapir may then slump off (e.g. Davison et al. 2000).

Salt diapirs. At high stress levels, which produce rapid strain rates, salt can be stronger than shallow-buried un lithified sediment, and it is only after several metres to hundreds of metres of burial that the salt will become weaker than the partially consolidated overburden sediment. This is important, as many diapirs grow by downbuilding where the crest of the salt diapir remains near the sediment surface over long periods of time, and where any weak overburden sediments deposited over the diapir may then slump off (e.g. Davison et al. 2000).

Where buoyancy forces or regional tectonic compression produce active salt dome uplift, the top salt surface moves upward in relation to the geoid. For example, the Weeks Island Dome, Gulf Coast of Mexico, has uplifted capping sediments by...
Occurrence in sedimentary basins. (a) Earthquake propagating up at a rate of c. 1.5 - 2 mm/a-1 from Miocene to Pliocene time (Wu et al. 1990; quoted by Talbot 1998). This time-averaged rate is equivalent to a horizontal strain rate of \(1 \times 10^{-3} \text{s}^{-1}\) for a 10 km wide salt sheet. These rates are below the critical strain rate for brittle fracture of salt.

Basal detachments. The rates at which rafts of Albian carbonate slid downslope over Aptian salt off the shore of the West African Atlantic margin have been constrained by Rouby et al. (2003). They estimated a maximum displacement rate of 2200 m Ma-1, which is equivalent to a horizontal strain rate of \(1.5 \times 10^{-14} \text{s}^{-1}\) assuming a 25 km long system averaged over a 10 Ma period.

Active basement faulting propagating up through a salt layer. Wherever active faults are propagating up from the basement into salt structures, major faults can be expected to displace the sedimentary layers by several tens of centimetres to metres in a few seconds. The salt will respond by brittle faulting, where the fault tip is propagating at seismic velocities (3-4 km/s). The ground surface over the crest of a large salt diapir on the Greek island of Strophades was ruptured by a seismically vertical thrust with a displacement of 10 cm and a strike-slip movement of 12 cm during the Mw 6.5 earthquake on 18 November 1997 (Stiros 2005). The hypocentre of the earthquake was estimated at 32 ± 3 km depth; this is well below the evaporite layer and indicates that the fault propagated up through the salt diapir, which is estimated to be several kilometres in height (Stiros 2005).

The Gulf of Suez and northern Red Sea area onshore Egypt are undergoing active extensional tectonics. Historical newspaper articles have documented earthquake displacements on normal faults rupturing the ground surface and causing small (<1 m) fault scarps to develop (W. Bosworth, pers. comm.). The fact that these areas are underlain by continuous salt layers strongly suggests that the salt layer has also been faulted, as the earthquakes are propagating from focal depths of c. 10-15 km (Jackson et al. 1988).

Examples of natural faults, tensile fractures and veins in evaporites

Boulby Mine

The Boulby Mine is located in a Zeolite evaporite sequence in the Cleveland Basin of northern England, which forms the...
western margin of the North Sea Basin (Talbot et al. 1982; Botterell et al. 1996). The mine workings reach a depth of
1.3 km below sea level and extend some 8 km beyond the coast
beneath the North Sea. The Zechstein sequence consists of cycles
of dolomite, anhydrite, halite, carnallite and shale. Normal faults
were produced during a phase of post-Triassic extension that cut
the salt layer (Fig. 5), but the faults are probably reactivated
Carboniferous rift faults. The offset of the top salt is c. 300 m,
but at base salt there is very little offset. There may have been
some dissolution of the salt in the hanging wall of the fault,
where the Zechstein layer is noticeably thinner (Fig. 5).

Thrust faults have also been produced by basin inversion of
post-Triassic age. The actual age of inversion is difficult to
determine exactly but it is thought to have occurred during the
Cenozoic, when regional uplift and denudation occurred in the
area (Menpes & Hillis 1996). A thrust fault with c. 17 m of
displacement has been mapped in Panel 600, which probably
nucleated in the dolomite layers and propagated through into the
evaporite layers. The evaporites show intense mylonitic shearing
fabrics adjacent to the fault plane (Fig. 6), and the grain size of
the salt increases from 4 mm average to 8 mm in the vicinity of
the fault and the grain flattening in the xz-plane of the strain
eclipse reaches 6:1. The mylonitization dies out rapidly in the
evaporites and the Boulby Halite decreases in thickness from
33 m in the footwall of the fault to 12 m in the hanging wall
(Fig. 6a). Further along in Panel 600, there are zones with many
dilational veins of up to 10 cm width (Fig. 7a), which are filled
with euhedral sylvite crystals (Fig. 7b). These veins are in
several orientations (including horizontal) and indicate that fluid
pressures rose to exceed the lithostatic pressure. The 2–5 cm
wide veins must have been propped open by migrating fluids to
allow the euhedral cubic crystals to grow.

The mine gallery in Panel 572 intersected fluids migrating
along fracture surfaces. The first brine influx occurred from an
old 5 cm wide exploratory horizontal borehole drilled through
the salt. The roof to floor closure increased soon after this, and
after 2 weeks fluids started to flow directly up through fractures
induced by the mining operation as they widened by fluid
dissolution. The fractures produced c. 300 000 m³ of brine over a
1 year period (Holmes 2001; R. Holmes, pers. comm.). This
produced a brine pool on the floor of the mine gallery that had to
be pumped out to the surface (Fig. 8). An estimated 100 m³ of
oil and an unquantified amount of methane gas were also
produced in the first year. The flow still persists 10 years later,
but at a much slower rate of several litres per day. The oil has
been analysed and was linked to the Carboniferous land plant
kerogen types of the Coal Measures (C. Cornford, pers comm.).
The mine gallery is situated around 200 m above the base of the
Permian salt sequence, indicating that open fractures are cutting
through at least this amount of rock to reach the mine gallery.
The mine gallery is an artificial opening, and the faulting and
fracturing were induced by the high stress concentration around
this rapidly opened void. However, this example indicates how
faults and fractures can permit large fluid volumes to migrate
through a thick salt sequence (several tens to hundreds of
metres).

Aptian age salt in Brazil

Taquari–Vassouras Potash Mine (Aracaju), Sergipe–
Alagoas Basin, NE Brazil

The Companhia Vale do Rio Doce (CVRD) Taquari–Vassouras
Potash Mine, Sergipe State, Brazil Mine near Aracaju is situated
at c. 300 m below the ground surface in the Sergipe–Alagoas
Basin of NE Brazil (Carvalho et al. 1993; Machado & Szatmari
2008). The late Aptian evaporites (c. 114–116 m) are affected by
numerous small thrusts (<1.5 cm displacement (Fig. 9b)) and
probable strike-slip faults (Fig. 9a) which affect the halite,
carnallite, siltstone and organic shale layers. Carnallite is much
weaker and more ductile than halite, but this is also faulted in
the example shown in Figure 9a. The age of the faulting is not

![Seismic section several kilometres south of the Boulby Mine, showing an oblique extensional fault cutting through the Zechenstein sequence and equivalent approximate level of mine gallery. The top and base salt horizons are offset by the faulting. TWT, two-way travel time.](image-url)
known but it probably occurred in Cretaceous times, when large-scale extensional faults continued to be active after salt deposition. The fault planes are commonly filled with crenulated dark grey halite crystals. Open dilation fractures have developed in the salt, which are at a depth of 540 m (Carvalho et al. 1995). The fractures trend 030° and are parallel to small-scale anticlinal fold hinges.

Occasionally, the fault planes have isolated voids up to 6 cm wide, which contain overpressured methane gas and are rimmed by crenulated cubic halite crystals up to 2 cm in diameter (Fig. 9c). These have been known to cause catastrophic outbursts when mined (A. Carvalho, pers. comm.). The methane gas was probably generated from an interbedded organic-rich source that is currently mature for oil and gas generation in the offshore area but is immature onshore in the region of the mine.

**Salt in Santos Basin, Brazil**

High-resolution seismic data from the central Santos Basin indicate that the late Aptian age salt layers are faulted by normal faults (Fig. 10, Freitas 2006). The faults offset the internal reflections within the salt body by c. 10 m and they cut through all the tachydrite, halite, carnallite and anhydrite layers. The age of the faulting is not known, but the faults offset the top salt horizon and the Albian carbonates, indicating that it is post-Albian.

**Carboniferous age salt in Nova Scotia**

**Pugwash salt diapir**

The Pugwash salt diapir in Nova Scotia is a >2 km high structure of Carboniferous (Viséan) age halite and interbedded anhydrite units that have been highly deformed by halokinesis during the late Carboniferous period (Evans 1965; Carter 1990). Two small faults have been observed in the mine galleries at depths of c. 250 m (830 foot level) (Fig. 11; B. Wile, pers. comm.). One fault has a normal displacement sense, with clear offset of bedding by several tens of centimetres (Fig. 11). Polished slickenside surfaces are present in the salt along the fault plane with scratched striae markings. The fault has a slow oil seep (several litres per month) associated with it, which was active for several years before drying up (B. Wile, pers. comm.). The fault zone has associated veins of blue crenulated halite. This unusual coloured halite is thought to be due to the presence of numerous fluid inclusions (geochemical analysis did not reveal any detectable salt impurities). Oil seepage sourced from the Macumber Limestone Formation located near the base of the Windsor salt interval (tens of litres per year) indicates that fluid movement has taken place over several years.

**Magdalen Island salt mine**

The Magdalen Island Mines Seleine salt dome on Gros Isle, Quebec, is composed of Viséan age salt (Fig. 12). The salt contains
fluid inclusions that contain oil and gas, indicating fluid flow through the salt (Zentilli et al. 2008). Brecciated zones of halite with vein infill of pink halite and sylvinites occur on level 3 of the mine at a depth of ~223 m (M. Zentilli, pers. comm.). This type of 'explosive' brecciation is strongly suggestive of high overpressure built up within the salt, which has provoked the fracturing.

**Iranian salt**

**Fracturing in the Qum Kuh salt extrusion**

The Qum Kuh salt diapir is currently producing a surface glacier that is extruding at a rate estimated at 82 mm a⁻¹ (Taibot & Aftabi 2004; Aftabi et al. 2005). This equates to a strain rate of \(8 \times 10^{-13} \text{s}^{-1}\). This relatively rapid rate of extrusion is due to the continental collision occurring in central Iran. The outward radial flow of salt away and downslope from the extrusive orifice has caused both radial and concentric brittle fracturing of the salt (Taibot & Aftabi 2004). The fractures are widest (less than a few centimetres) within 10 cm of the salt surface, and some of the largest taper downwards for at least 30 m below the salt surface (Fig. 13c). Some joints extend over several hundred metres laterally and these probably extend much deeper (>100 m) into the Qum Kuh glacier. Both radial and concentric fractures have been mapped in a systematic pattern indicating the 3D expansion of the top salt surface flowing away from crest of the dome (Fig. 13a and b).

**Faulting in the Eivanekey plateau in Central Iran**

Faults are common along the eastern margin of the Eivanekey plateau in front of the advancing Alborz Mountains. Two exposed fault surfaces in halite in a Cenozoic age salt quarry several metres below ground surface show transcurrent slickenlines, indicating frictional wear and tooling of harder grains in the salt (Fig. 13d).

**Gorleben salt diapir, northern Germany**

The Gorleben salt diapir in northern Germany is one of the most studied salt domes in the world as it has been used as a research

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Fig. 7. (a) Tensional vein network in sylvinites in Panel 600. Veins are filled with sylvite. (b) Close-up of euhedral cubic crystals of sylvite in tensional veins indicating that the veins were open voids during sylvite crystallization, which were held open by fluids at supra-lithostatic pressures.

Fig. 8. Brine pool on the floor of the Douby mine gallery caused by fluid infiltration along a mining-induced fracture. This fault produced 300 600 m³ of brine fluid over a 1 year period together with a small amount of oil derived from underlying Carboniferous source rocks.
Fig. 9. (a) Strike-slip fault in CVRD Taquari–Vassouras Potash Mine, Sergipe near Aracaju in the Sergipe–Alagoas Basin, NE Brazil. The faults are truncating both halite and carnallite layers, with recrystallized coarse-grained dark grey euhedral halite crystals present along the fault plane (arrowed). (b) Thrust faults in same mine; dark-coloured recrystallized cubic halite crystals along the fault planes. Fault planes are indicated by light-coloured arrowheads. (c) Open fracture in halite rimmed with euhedral cubic halite crystals. Methane outbursts from these open fractures have killed miners in the past (A. Carvalho, pers. comm.).
mine for studying the possibility of storing nuclear waste (Bornemann 1991; Zirngast 1996). The detailed mine mapping (Bornemann 1991) indicates zones of intense shearing where large competent sections of the Zechstein stratigraphy are locally missing. In one of these zones a 2–5 m wide zone of breccia is observed in mine galleries 800 m deep. This is interpreted by the author as a sheared breccia zone where angular fragments have been broken and subsequently sheared and rounded to give a mixed mylonite-breccia zone (Fig. 14a). One of the outer edges of the sheared zone has a knife-sharp planar contact with the less deformed halite that exhibits all the attributes of a brittle fault plane (Fig. 14a). There are also zones c. 2–3 m wide that are more permeable and porous than normal salt, and oil is slowly oozing from the mine gallery walls at a rate of several tens of litres per year (Fig. 14b). Both the fault zone in Figure 14a and the oil-stained zone (outlined with block paint lines in Fig. 14b) are oriented parallel to bedding.

Gulf Coast of Mexico salt domes

Anomalous sheared and faulted zones have been described from several onshore salt domes in the Gulf Coast of Mexico (Kupfer 1962, 1976, 1990; Neal et al. 1993). One shear zone in the Big Hill Dome crosses the entire salt stock and links to a graben-
forming fault in the overlying cap rock (Neal et al. 1993). These "anomalous" zones are characterized by the following: (1) increased shearing, faulting and slickensides; (2) increased salt porosity and permeability; (3) reduced density and sonic velocity of salt; (4) halite recrystallization; (5) seeps of brine or hydrocarbons; (6) association with gas outbursts; (7) variable colours of salt (Balk 1949; Muellberger 1960; Kupfer 1990; Neal et al. 1993).

The zones can be up to 100 m wide and their long dimension can be the whole width of the salt dome (although the 3D shape has not yet been determined because of the lack of 3D control in the salt domes). Some 150 barrels of liquid hydrocarbons were produced from a shear zone in the Big Hill salt stock in leached cavern 114 (Neal et al. 1993). In the Weeks Island Dome, a methane gas outburst from an anomalous zone produced 50 million cubic feet of gas into the Morton Mine (see Fig. 1; Ehgartner et al. 1998). This is probably thermally derived gas that has been generated from shales within the salt and trapped at lithostatic pressure in porous salt (Iannaccione & Schatzel 1985). The ejected grains of salt from the outbursts are known as popcorn salt, as they make a popping sound as one walks over them (Ehgartner et al. 1998).

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<table>
<thead>
<tr>
<th>Basin and locality</th>
<th>Evidence</th>
<th>Displacement</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Red Sea</td>
<td>Earthquake faulting propagated from pre-salt basement causing 1 m offset of beach terraces at surface</td>
<td>Normal 1 m</td>
<td>W. Bosworth (pers. comm.)</td>
</tr>
<tr>
<td>Nova Scotia Maritime Carboniferos Basin; Pugwash Mine</td>
<td>Faults in salt mine at 600 m depth with euhedral blue halite crystals and oil staining and striae along fault plane</td>
<td>Normal fault &lt;0.5 m apparent displacement</td>
<td>This paper</td>
</tr>
<tr>
<td>Sergipe-Alagoas Basin, NE Brazil</td>
<td>Numerous thrust and strike-slip faults with methane migration along open fault planes or recrystallized halite crystals</td>
<td>Thrust and strike-slip &lt;1 m displacement</td>
<td>This paper and Carvalho et al. (1995)</td>
</tr>
<tr>
<td>Boulby Mine, Cleveland Basin, Zechstein, NE England</td>
<td>Thrust fault in mine gallery</td>
<td>10 m</td>
<td>This paper and R. Holmes (unpubl. data)</td>
</tr>
<tr>
<td>Strophades, West Hellenic arc</td>
<td>Offset of ground surface</td>
<td>Co-seismic thrust 10 cm, strike-slip 12 cm</td>
<td>Stiros (2005)</td>
</tr>
<tr>
<td>Kuh e Namaq, Zagros Mountains, Iran; Eivaneky plateau, Alborz Mts</td>
<td>Radial and concentric tensional fracturing in salt surface exposures; faults with slickenlines in salt quarry</td>
<td>Maximum c. 10 cm tensional opening</td>
<td>Talbot &amp; Aftahi (2004)</td>
</tr>
<tr>
<td>Werra Salt, German Zechstein basin</td>
<td>Faults in overburden linked to shear zones and sink holes</td>
<td>Normal metre scale</td>
<td>Schilder &amp; Schwandt (1983)</td>
</tr>
</tbody>
</table>

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5: Critescu & Hunsche date not as in ref. list. Please make consistent
6: Critescu & Hunsche 1998 is 1988 in reference list
7: Critescu & Hunsche date not as in ref. list. Please make consistent
8: "factor of 285" - 1 remember 38 vol% thus give a reference.
9: Hardie 1967 is 1966 in reference list
10: Hardie date not as in ref. list. Please make consistent

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Fig. 12. Breciated salt (dark) and vein infill of reddened halite with iron staining and sylvinite, from Magdalen Island Mines Seleine, Quebec. Courtesy of M. Zentilli.
Fig. 13. Map of (a) concentric joints and (b) radial joints in the surface of the Qum Kuh salt glacier. Topographic contours are in metres. Reproduced from Talbot & Afabi (2004). (c) An unusually long joint (>30 m) in the upper reaches of the southern extrusion of Kuh-e Namak (Dashiti). The lighter rocks in the foreground are country rocks, and the main cliff face is halite. Photo courtesy of C. Talbot. (d) Two exposed fault surfaces in halite in a Cenozoic age salt quarry several metres below ground surface at the SE edge of the Eivanekey plateau in Central Iran. Slickenlines on fault surface are covered in brown clay. Faults like these are common along the eastern margin of the plateau in front of the advancing Alborz Mountains. Photo courtesy of C. Talbot.

11: active salt dome uplift - Are we still considering downsilted diapirs?
12: strain rate formula - please confirm position of outer ( ) is ok
13: 'causing small ... fault scars' - Where? In Aden?
14: Fig. 5 - please confirm change in fig. no. is correct
15: 'there is very little offset' - as this salt was confined during the 'folding' I would expect it to be mylonitized, as in the visible fault in fig. 6
16: Fig. 5 - please confirm change in fig. no. is correct
17: 'propagated through' - dissipated in?
18: 'adjacent to the fault plane' - is there a fault plane IN THE SALT?
19: Fig. 6 - please confirm change in fig. no. is correct
20: 'adjacent to the fault plane' - Is this in panel 600 or in the shaft bottom? Woods published a similar diagram of the fault exposed in the shaft bottom.
29: ‘One fruit’ - Is it a fruit or an offset along a non-halite inflating vein? Are the striations in halite or the infill?
36: ‘oil-stained zone’ - The oil stain appears to be perpendicular to the horizontal bedding (are they tool marks)? Clarify.
31: Acres - should author be American Acres Inc.? 32: Ahfal et al. - please give editors.
13: Bitman - is this a series title related to the volume number?
34: Bottrell et al. - is something missing in the journal title after 'Transactions'? 35: Carter - please confirm town for publisher is correct
37: Carter & Hansen - where in text should this ref. be cited?
37: Carter & Heard - where in text should this ref. be cited?
39: Carvalho et al. - please complete the second author's surname
39: Chester - where in text should this ref. be cited?
40: Freitas - please give town for university
41: Iannachione & Shatzel - please give editor's, publisher's name + town, and page nos of paper
52: Iavutich - please give editors, publisher's name + town, and check the page range
26: Schoenherr & Urai - where in text should this ref. be cited?
44: Shulev - where in text should this ref. be cited?
45: Ulreich & Golicher - please give publisher's name + town
50: permission has been obtained and add note as appropriate
Fauniting and Fluid Flow Through Salt

Conclusions

1. Brittle faulting and fracturing, and fluid and gas flow have been observed in salt. Laboratory experiments indicate that salt will fracture at strain rates greater than $10^{-9}$ s$^{-1}$. However, such rapid strain rates rarely occur in salt bodies, except where earthquake faulting propagates up through the salt layer. Fracturing and faulting are most likely to occur in the presence of overpressured fluids. Several examples of dilational veins are presented that are strongly indicative of fluids reaching lithostatic pressure. Faults are observed even in caverns, which is much more ductile than halite. The faults can be found for 10 years or more when high pressure fluid is maintained. This can be enough time to allow transport of commercial volumes of hydrocarbons through salt layers as long as high fluid pressures are maintained. Salt is the best hydraulic seal in a sedimentary basin but it is not a perfect seal. Fluids can migrate either along grain boundaries at depths of 3–4 km or through faults and fractures, which are usually induced by high fluid overpressure created by metamorphic reactions in the evaporite sequence.

I thank R. Holmes for providing information on the Boughly Mine, and Cleveland Potash Ltd for permission to publish these data. C. Talbot provided a very helpful and thorough review of this paper and Figure 13. O. Schulze, J. Urai and M. Holness kindly led me through the labyrinth of salt creep laws and failure criteria. M. Zentilli provided the photograph from the Magdalen Island salt mine.

References


Fig. 14. (a) Photograph of brecciated fault zone in Golrurh mine, northern Germany. Breccia fragments are interpreted to be a result of ductile deformation after fracturing, (b) Oil-stained shear zone in Golrurh. The bedding and shear zone fabric is vertical. Zone of oil staining has been outlined with black paint lines. Horizontal tool marks caused by mining operations are also visible.

24: Fig. 7a - please confirm change in fig. no. is correct
25: Fig. 7b - please confirm change in fig. no. is correct
26: Fig. 8 - please confirm change in fig. no. is correct
27: <1.5 cm - please confirm the added unit is correct
STANDARD AND SPECIFICATIONS
FOR VEGETATING WATERWAYS

Definition
Waterways are a natural or constructed outlet, shaped or graded. They are vegetated as needed for safe transport of runoff water.

Purpose
To provide for the safe transport of excess surface water from construction sites and urban areas without damage from erosion.

Conditions Where Practice Applies
This standard applies to vegetating waterways and similar water carrying structures.

Supplemental measures may be required with this practice. These may include: subsurface drainage to permit the growth of suitable vegetation and to eliminate wet spots; a section stabilized with asphalt, stone, or other suitable means; or additional storm drains to handle snowmelt or storm runoff.

Retardance factors for determining waterway dimensions are shown in Table 5B.1 and “Maximum Permissible Velocities for Selected Grass and Legume Mixtures,” are shown in Table 3.6.

Design Criteria
Waterways or outlets shall be protected against erosion by vegetative means as soon after construction as practical. Vegetation must be well established before diversions or other channels are outletted into them. Consideration should be given to the use of synthetic products, jute or excelsior matting, other rolled erosion control products, or sodding of channels to provide erosion protection as soon after construction as possible. It is strongly recommended that the center line of the waterway be protected with one of the above materials to avoid center gullies.

1. Liming, fertilizing, and seedbed preparation.
   A. Lime to pH 6.5.
   B. The soil should be tested to determine the amounts of amendments needed. If the soil must be fertilized before results of a soil test can be obtained to determine fertilizer needs, apply commercial fertilizer at 1.0 lbs/1,000 sq. ft. of N, P₂O₅, and K₂O.
   C. Lime and fertilizer shall be mixed thoroughly into the seedbed during preparation.
   D. Channels, except for paved section, shall have at least 4 inches of topsoil.
   E. Remove stones and other obstructions that will hinder maintenance.

2. Timing of Seeding.
   A. Early spring and late August are best.
   B. Temporary cover to protect from erosion is recommended during periods when seedings may fail.

3. Seed Mixtures:

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>Rate per Acre (lbs)</th>
<th>Rate per 1,000 sq. ft. (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Birdsfoot trefoil or ladino clover¹</td>
<td>8</td>
<td>0.20</td>
</tr>
<tr>
<td>Tall fescue or smooth bromegrass</td>
<td>20</td>
<td>0.45</td>
</tr>
<tr>
<td>Redtop²</td>
<td>2</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.70</td>
</tr>
<tr>
<td>OR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Kentucky bluegrass³</td>
<td>25</td>
<td>0.60</td>
</tr>
<tr>
<td>Creeping red fescue</td>
<td>20</td>
<td>0.50</td>
</tr>
<tr>
<td>Perennial ryegrass</td>
<td>10</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>1.30</td>
</tr>
</tbody>
</table>

¹ Inoculate with appropriate inoculum immediately prior to seeding. Ladino or common white clover may be substituted for birdsfoot trefoil and seeded at the same rate.

² Perennial ryegrass may be substituted for the redtop but increase seeding rate to 5 lbs/acre (0.1 lb/1,000 sq. ft).

³ Use this mixture in areas which are mowed frequently. Common white clover may be added if desired and seeded at 8 lbs/acre (0.2 lb/1,000 sq. ft.)
4. Seeding

Select the appropriate seed mixture and apply uniformly over the area. Rolling or cultipacking across the waterway is desirable.

Waterway centers or crucial areas may be sodded. Refer to the standard and specification for Stabilization with Sod. Be sure sod is securely anchored using staples or stakes.

5. Mulching.

All seeded areas will be mulched. Channels more than 300 feet long, and/or where the slope is 5 percent or more, must have the mulch securely anchored. Refer to the standard and specifications for Mulching for details.

6. Maintenance

Fertilize, lime, and mow as needed to maintain dense protective vegetative cover.

Waterways shall not be used for roadways.

If rills develop in the centerline of a waterway, prompt attention is required to avoid the formation of gullies. Either stone and/or compacted soil fill with excelsior or filter fabric as necessary may be used during the establishment phase. See Figure 3.2, Rill Maintenance Measures. Spacing between rill maintenance barriers shall not exceed 100 feet.
FIRE PROTECTION AND RESPONSE FOR LPG BULK STORAGE INSTALLATIONS

BY CRAIG SHELLLEY AND ANTHONY COLE

IN DEVELOPING FIRE PROTECTION METHODS AND response guidelines for liquefied petroleum gas (LPG) bulk storage facilities, the chief concern is a massive failure of a vessel containing a full inventory of LPG. The probability of this type of failure occurring can be mitigated or at least controlled to a reasonable and tolerable figure with appropriately designed and operated facilities, coupled with a local fire department/brigade response. Since most LPG fires originate as smaller fires that become increasingly more dangerous, this article will focus on fire protection methods and guidelines in relation to small leaks and fires in LPG spheres. Of greater importance to the fire protection engineer is the more likely event of a leak from a pipe, a valve, or another attached component leading to ignition, a flash fire, a pool fire, and eventually a pressure fire at the source.

LPG PROPERTIES

LPG was first discovered in the 1900s. Its applications and uses range from cooking and refrigeration to transportation, heating, and power generation, making it an all-purpose, portable, and efficient energy source.

LPG consists of light hydrocarbons (propane, butane, propylene, or a mixture) with a vapor pressure of more than 40 psi at 100°F. At standard temperature and pressure, LPG is a gas. It is liquefied by moderate changes in pressure (i.e., in a process vessel) or by a drop in temperature below its atmospheric boiling point. The unique properties of LPG allow it to be stored or transported in a liquid form and used in a vapor form. LPG vapors are heavier than air and tend to collect on the ground and in low spots. After LPG is released, it readily mixes with air and could form a flammable mixture. This mixture could ignite and cause a vapor cloud explosion (VCE).

<table>
<thead>
<tr>
<th>Table 1. Properties of Two Common LPGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
</tr>
<tr>
<td>Specific Gravity</td>
</tr>
<tr>
<td>Vapor Pressure at 60°F</td>
</tr>
<tr>
<td>Boiling Point</td>
</tr>
<tr>
<td>Cubic feet of gas at 60°F</td>
</tr>
<tr>
<td>Lower flammable limit (LFL) % in air</td>
</tr>
<tr>
<td>Upper flammable limit (UFL) % in air</td>
</tr>
<tr>
<td>Gross Btu/ft³ of gas at 60°F</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Table 2. Tank Pressures for Two Common LPGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Temperature</td>
</tr>
<tr>
<td>31°F</td>
</tr>
<tr>
<td>60°F</td>
</tr>
<tr>
<td>100°F</td>
</tr>
<tr>
<td>130°F</td>
</tr>
<tr>
<td>140°F</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Table 3. Vapor Volumes Obtained for Two Common LPGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
</tr>
<tr>
<td>Propane</td>
</tr>
<tr>
<td>n-Butane</td>
</tr>
</tbody>
</table>

A VCE can occur when a large amount of flammable vaporizing liquid or gas is rapidly released into the surrounding air and is ignited before being diluted in air below the lower flammable limit (LFL). As a release occurs, there will be an area closest to the release that is above the flammable range, an intermediate area that may be in the flammable range, and areas that will be below the flammable range. Mixing of natural currents and diffusion of LPG vapors affect the size and extent of these areas. If these processes continue, eventually the mixture is diluted to below the LFL (Tables 1, 2, 3).

Other characteristics of LPG include:

- LPG exerts a cooling effect as a result of vaporization resulting from releases at low pressure (also called autorefrigeration).
- The density of LPG is almost half that of water; therefore, water will settle to the bottom in LPG.
- Very small quantities of liquid will yield large quantities of vapor.
- When vaporized, LPG leaves no residue.
- When LPG evaporates, the autorefrigeration effect condenses the surrounding air, causing ice to form. This is usually a good indication of a leak.
- LPG is odorless; agents such as ethyl mercaptan are added to commercial grades in most countries for better detection.

**PRODUCTION AND OPERATIONS**

LPG is derived from two main energy sources: natural gas processing and crude oil refining. When natural gas wells are drilled into the earth, the gas released is a mixture of several components. For example, a typical natural gas mixture may be methane or "natural gas" (90%); the remaining percentage of components (10%) is a mixture of propane (5%) and other gases such as butane and ethane (5%). The gas is shipped in tankers or through a pipeline to secondary production facilities for further treatment and stabilization. From these facilities it is sent by bulk carrier or pipeline to various industrial plants, gas-filling operations, and power-generation facilities.

LPG is also collected in the crude oil drilling and refining process. LPG trapped inside the crude oil is called associated gas, which is further divided at primary separation sites or gas-oil separation plants (GOSPs); central processing facilities (CPFs) for offshore installations; or drilling, production, and quarters platforms (DPQs). At these facilities, the fluids and gases produced from the wells are separated into individual streams based on their characteristics and properties and sent on for further treatment.

In refineries, LPG is collected in the first phase of refining or crude distillation. The crude oil is then run through a distillation column in which a furnace heats it to high temperatures. During this process, vapors will rise to the top and heavier crude oil components will fall to the bottom. As the vapors rise through the tower, cooling and liquefying occur on "bubble trays," aided by the introduction of naphtha. Naphtha is straight-run gasoline, and the heavier naphtha is generally unsuitable for blending with premium gasolines. Therefore, it is used as a feedstock in various refining processes such as in a reformer. These liberated gases are recovered to manufacture LPG.

In commercial applications, LPG is usually stored in large horizontal vessels called bullets, ranging in volume size from 150 to 50,000 gallons. In industrial applications, LPG is typically stored in large vessels that are spherical or spheroid shaped, the large "golf ball" shaped and oval vessels commonly seen at refineries and similar occupancies. In this article, we will deal primarily with the protection of LPG spheres.

**STANDARDS**

Various sources of standards and codes exist for dealing with LPG facilities and proper fire protection. Some of these sources include:

- IP Code of Practice for LPG.

Additional sources of information are available from various organizations such as the British Standards Institute, the World LP Gas Association, the LP Gas Association, and industry producers and suppliers. For the purpose of this article, we will focus on some of the above-mentioned sources that are typically accepted as the industry standard.

**FIRE PROTECTION DESIGN CONSIDERATIONS**

To reduce the fire risk at LPG facilities, adherence to various design considerations and requirements such as layout, spacing, and distance requirements for vessels, drainage, and containment control will help to limit the extent of fire damage. Additional considerations such as fireproofing, water-draw systems, and relief systems are also important with respect to the integrity of the installation and the risk reduction. These considerations address the various ways to prevent leaks or releases that may lead to a fire.

Equally as important to the prevention of a leak or release is a properly designed, installed, and maintained fire protection system. These systems attempt to minimize or limit the fire damage once a fire occurs. In the situation in which a fire does occur, the levels of required fire protection are affected by several factors such as location and remoteness of the fire and the availability of water.
To determine if cooling water is required, the anticipated radiant heat flux from an adjacent tank, the maximum tank shell temperatures if the vessel shell is not cooled, and other specific risk management guidelines must be analyzed. API 2510A contains a procedure to identify the point at which cooling water should be applied based on the size of the pool fire and the distance between the vessel and the center of the fire (Figure 1). Additionally, an analysis of the relief valve parameters is necessary to maintain certain internal vessel pressures. Although computer models are available to more accurately anticipate the heat fluxes, this procedure helps to determine if a more detailed study is needed.

Figure 1 considers the radiant heat flux from a pool fire, assuming a 20-mile-per-hour wind. To illustrate this procedure, first locate the diameter of the pool fire along the x-axis. Using an imaginary line from the designated point along the x-axis, locate the corresponding point of intersection on the 7,000 Btu/hr-ft² line. Next, extend an imaginary horizontal line to the y-axis. The corresponding point of intersection on the y-axis is the distance between the vessel and the pool fire at which cooling water must be applied. For example, if a pool fire is 30 feet in diameter, it is necessary to apply cooling water when the distance between the vessel and the center of the pool fire is approximately 120 feet.

In general, there are three primary methods to apply water for cooling or extinguishing fire on LPG vessels: water deluge, fixed monitors, and water spray. Additionally, portable equipment such as ground and trailer-mounted monitors can be used but should not be considered a primary means of water delivery. This is mainly because of the potentially extended setup times, logistics, and requirement of human intervention that is not necessarily reliable.

<table>
<thead>
<tr>
<th>Table 4. Various Water Application Methods for LPG Sphere Fires</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
</tr>
<tr>
<td>Water Deluge</td>
</tr>
<tr>
<td>2. Can be automatic</td>
</tr>
<tr>
<td>3. Lack of piping</td>
</tr>
<tr>
<td>4. Effectiveness with jet fires</td>
</tr>
<tr>
<td>Fixed Monitors</td>
</tr>
<tr>
<td>2. Can be automatic</td>
</tr>
<tr>
<td>3. Effective for jet fires</td>
</tr>
<tr>
<td>4. Monitors may be changed unknowingly</td>
</tr>
<tr>
<td>Water Spray</td>
</tr>
<tr>
<td>2. Wetting</td>
</tr>
<tr>
<td>and run down</td>
</tr>
<tr>
<td>3. Can be automatic</td>
</tr>
<tr>
<td>Portable Equipment</td>
</tr>
<tr>
<td>3. Portability for multiple hazards</td>
</tr>
<tr>
<td>Equipment</td>
</tr>
</tbody>
</table>

Table 4 describes some of the advantages and disadvantages of the three primary water application methods and the use of portable equipment.

The first method involves the use of a water deluge system and some form of water distributor. This could include high-volume spray heads, perforated pipe, or a distribution weir. An underflow or overflow weir allows water to be evenly distributed over the surface area of a sphere; water flows up the piping network, over the top of the sphere, and out of the weir. This type of water distributor is commonly used but is prone to corrosion from standing water and clogging and requires increased preventative maintenance. Additionally, wind may not be as effective on bullets and are often greatly affected by wind. The remaining components of this method are similar to other deluge installations. The typical deluge system contains a supply piping network, deluge valve and trim, and branchline-piping network near the top of the sphere. Newer installations are usually activated automatically, whereas older installations are commonly activated manually. The decision of which activation method to use requires evaluation of spacing, available protection, exposures, and other factors.

The principle behind the deluge or weir system for LPG sphere protection is that the geometric shape of the sphere and gravity work together as an advantage. As water is applied to the top of the vessel, the shape of the sphere and the force of gravity facilitate the flow of the water as it covers the surface area of the vessel. This type of protection is very effective to facilitate an even distribution of water over the surface area. Caution should be exercised, however, because paint, corrosion, dust, and other environmental influences can cause changes in the surface of the sphere, resulting in uneven water distribution. Additionally, settling and other conditions inside the weir can also cause uneven water flow over the sphere's surface.

Fixed monitors, the second method of water application, permit the use of fixed hydrant-mounted monitors or individual
monitors connected to the fire main to apply water to the fire area. In this case, water is applied by operators manually opening valves to allow the flow of water to the LPG sphere. This procedure exposes operators to high heat fluxes and places them dangerously close to vessels under fire conditions. It is important to carefully study the plant and vessel layout if this method is elected. Proper placement, location, and quantity of fixed monitors must be reviewed and field tested to ensure that proper application and even distribution of water to all parts of the vessel are accomplished. In some cases, remote activation and operation are suggested when proper spacing of monitors is not a possibility. Additionally, annual testing and preventative maintenance are necessary to ensure parameters have not changed and coverage is still adequate.

The third method of application is the use of water spray systems, comprised of a piping network of spray nozzles that distribute water over the surface area of an LPG sphere. The spray nozzles are positioned to form a grid pattern that facilitates the complete coverage of the sphere’s surface area. Larger orifices and piping should be considered to help reduce blockage because of scale and mussel buildup and other potential problems. It is also important to properly size the strainer to prevent blockage. Inspection of strainers should be part of the preventative maintenance program.

The last method available is the deployment of portable monitors and hoses. This method uses hand-carried portable or trailer-based monitors deployed by the fire department. Although it is not one of the three primary methods of water application, preparation and planning for this type of application should not be forgotten. Quantity of monitors, monitor flow calculations, and predetermined hoselines should be reviewed prior to an incident to ensure adequate capabilities are available. This method is considerably more dangerous than the previously mentioned methods because of the exposure of personnel to the hazards and risks associated with LPG firefighting.

When using the four water application techniques discussed previously, a combination of techniques such as the use of a deluge or water spray system and portable monitors provides ample fire protection. A combination of a water deluge/distributor with a fixed water spray system with portable monitor backup from the fire department provides excellent coverage.

A water application rate for these fixed fire protection systems depends on the type of fire situation. When a vessel is exposed to only radiant heat without direct flame contact, a density of 0.1 gpm per square foot of vessel surface area is the minimum. If direct flame contact or impingement occurs, a density larger than 0.1 gpm, up to 0.25 gpm per square foot of vessel surface area is the minimum.

When using fixed or portable monitors, 250 to 500 gpm is the minimum flow that should be considered initially. However, field verification and flow testing are necessary to ensure adequate and proper coverage. Monitor placement must also be field verified against approved plans to ensure acceptable spacing and access.

Vapor, heat, or flame detectors mounted in the vicinity of a vessel can complete automatic activation of these systems. Vapor detection provides early detection and warning, but activation of water application systems must be confirmed through flame detection. Flame detection provides quick activation, but use caution when positioning these detectors to prevent false activation from sunlight. Also consider installing UV/IR combination detectors to reduce the false indication rate. These devices require testing and preventative maintenance programs. An evaluation of the facility is necessary to determine the correct type and location of devices.

**RESPONSE**

Even with the properly installed fixed fire protection systems, the importance of emergency response to LPG fires cannot be disregarded. LPG fires can escalate quickly, and a lack of manual activities by the fire department can lead to vessel failure. As part of this response, an up-to-date and complete emergency response/preincident plan should include the following:

- Facility name and location.
- Map of facility.
- Emergency phone numbers for key plant personnel.
- Hydrant layouts and capacities.
- Additional water supplies—e.g., ponds, canals (Are they available in freezing weather conditions?)
- Hoselines and lengths required.
- Multiple response approaches (wind-dependent).
- Vessel inventories.
- Fixed fire protection information.
- Scenarios for both unignited and ignited leaks.

Emergency response/preincident plans should also identify the emergency response structure of the industrial plant as well as the incident/unit/department structure that will be used. In some instances, a plant operations person may be acting as the incident commander, with the municipal/town/volunteer department operating in a support role. It is better to have this organized during preincident planning than on the fireground.

The emergency response/preincident plans must be exercised frequently and updated as necessary. Since recent events throughout the world have increased security in industrial plants, obtaining information for preincident planning may be difficult. It is imperative that discussions with plant personnel remain open and take place frequently to maintain a team spirit and facilitate information sharing. Once information is obtained, it is important that fire departments maintain operational security for this information. Emergency response/preincident plans should be secured on the apparatus, and numbered copies should be tracked. These copies should be inventoried on a scheduled basis to maintain operational security.

When responding to an LPG facility, preplans may indicate that responding personnel remain at a staging area, usually near the main gate or other location (depending on wind direction) until directions are received from plant personnel,
especially in the case of a leak. We know of instances where vehicles were the source of ignition for a leak. In one case, although not an LPG incident, the fire department apparatus was the source of ignition for a natural gas explosion that destroyed a number of city neighborhood blocks. In another instance, a plant security vehicle investigating a reported leak was the source of ignition, causing a catastrophic loss to the facility.

On arrival, initial assessment of the situation is essential for the safety of personnel. During fire situations, if there has been flame impingement on a vessel, especially on the vapor space, and there is no water cooling of the area or fireproofing on the area of flame impingement, vessel failure could be imminent. If these conditions have been present for 10 minutes or more from the initial impingement (not the fire department arrival), an immediate evacuation is recommended. It is important to remember that the initial time of the notification to the fire department may not be the time the incident started.

If it has been determined that a fire is safe to approach, develop an incident action plan (IAP). This plan does not have to be written initially, but it should contain the following objectives:

- Cooling of exposed storage vessels.
- Water application rates and water supplies available.
- Shutting down fuel supply.
- Monitoring of the surrounding area using combustible gas indicators (CGI).
- Evacuation of nonessential personnel.
- Evacuation routes for responders and plant personnel in case of emergency.

Use unmanned monitors when cooling exposed vessels. As in smaller LPG fire operations, do not extinguish the fire. Instead, shut down the gas supply. Where there is direct flame impingement on an exposed vessel, apply a minimum of 500 gpm of water at every point of flame impingement.

If a liquid pool has not ignited, use water spray to control/dilute the vapors. Water should not contact the spilled material where possible because it will increase the vaporization. Use combustible gas indicators to determine the extent of the vapors. Always remember to position fire apparatus upwind and uphill.

The fire department alone cannot control the incident. Expert advice, cooperation, and remedial actions by plant personnel are needed. Begin to foster this cooperation and identify those plant personnel who can assist the fire department during preincident planning and familiarization visits.

... Since most LPG fires originate as smaller fires that become increasingly more dangerous, quickly using the three primary water application methods can help reduce the risk of vessel failure. Deploying portable monitors and hoses, although not one of the three primary methods of water application, is an important backup to the primary methods. LPG fires can escalate quickly, and a lack of manual suppression by the fire department can lead to vessel failure. You must, however, take control of the fuel source before attempting to suppress the fire. In any case, an emergency response plan, along with proper training and drills, is important to reduce the risk of injuries and promote a quicker and safer response.

References and additional reading


CRAG SHELLEY, CFO, EFO, MiFireE, is a fire protection advisor for a major oil company working in the Middle East. He has previously served as the chief of marine operations for the Fire Department of New York and as the chief of the Rutland (VT) Fire Department. He has served as a task force leader for FEMA's USAR NY TF-1. Shelley has a bachelor's degree in fire service administration and a master's degree in executive fire service leadership and has served on two National Fire Protection Association technical committees.

ANTHONY COLE, CFPS, CFEI, MiFireE, is a fire protection engineer with a major oil company operating in the Middle
East. He previously served with an iron and steel facility in the Middle East as a fire protection engineer and fire chief. Cole has also been a paid firefighter in Ohio and Mississippi and has served on various volunteer fire departments in Ohio, Kentucky, Missouri, and Mississippi. Cole has a bachelor's degree in fire protection engineering technology from Eastern Kentucky University and is working toward his master's degree in fire protection engineering from Worcester Polytechnic Institute. He serves on two Society of Fire Protection Engineers committees and three National Fire Protection Association Technical Committees and is a member of the International Association of Fire Chiefs.
November 10, 2011

David L. Bimber
Deputy Regional Permit Administrator
New York State Department of Environmental Conservation
6274 East Avon-Lima Road
Avon, New York 14414-9516

Re: Proposed Finger Lakes Liquefied Petroleum Gas Underground Storage Facility in Reading, NY (DEC Facility ID 8-4432-00085)

Dear Mr. Bimber,

On behalf of members of the Finger Lakes Group of the Atlantic Chapter of the Sierra Club, I appreciate the opportunity to offer comments concerning the proposal by Finger Lakes LPG Storage Facility LLC to construct an underground storage facility for liquid propane and butane, as well as a rail and truck loading and off-loading site, in abandoned salt caverns owned by U.S. Salt outside of Watkins Glen, New York.

After reviewing the Draft Supplemental Environmental Impact Statement prepared by the applicant for storage of LPG in salt mines members of the Finger Lakes Group’s Executive Committee feel that many questions remain concerning the environmental, economic, and cultural impact of this project on Seneca Lake and Schuyler County. I wish to briefly highlight some of our groups most pressing concerns.

The applicant claims that much of the truck traffic will occur in the winter months when “there is not tourism in the area.” Has the DEC studied the recent growth of tourism in the area over the wintertime? Doesn’t the applicant realize that propane delivery begins in August and continues through autumn months in this region, when tourism is at its peak?

Apparently, though purely anecdotal the group has heard that some businesses and industry have postponed plans to develop or are selling before their businesses are impacted by the LPG facility. There is a need to preserve existing business and promote industry that can coexist and enhance what we already have in this region, not frighten prospective growth away. Whether this proposed facility is sufficient to drive businesses away, becomes the operative question.

Economic and safety issues:

Since catastrophic failures of salt cavern hydrocarbon storage happen more often than failures with other types of hydrocarbon storage structures, are our small local fire departments expected to deal with catastrophic failure at this facility? Who will pay for training and equipment needed? Is our small local hospital equipped to handle an industrial catastrophe? In fact the applicant provided only a cursory inventory of emergency responder capabilities in the immediate 10 square mile vicinity of the facility, so it is not clear whether the applicant is even fully aware of what is or is not available locally.

What are the risks of building this facility on a sloped hillside versus a flat location? The lake shores and water create a “bowl” shape. In the event of an accidental release, and since LPG is heavier than air, what are the risks if a vapor fog forms and sinks over the lake? Clearly, the stronger the wind the greater the risk. What will the impact be in this scenario, and is there an evacuation plan in place?

What are the risks associated with hydrocarbon storage next to NYSEG proposed compressed air storage facility (CAES)? Will any fires or explosions that ignite at the gas storage facility be magnified if they come into contact with the compressed air stored nearby? And will the frequent alternating pressure differentials in the CAES facility increase the potential for destabilization of the salt caverns.

What impact will the volatile organic compounds produced by the diesel trucks have on our crops and agriculture? Will these trucks or any portion of the applicant’s proposal, includ-
ing pipeline, impact Grade A farmland? Although the applicant insists most of the truck traffic will be occurring during the winter months, publications from the Union of Concerned Scientists indicate that, with Climate Change and increasing emissions, ozone levels are rising to dangerous levels even in winter months.

What kind of security measures have been established for the 24-32 railcars per day carrying thousands of gallons of highly explosive LPG traveling over miles of track near residences and also over a bridge across our beautiful Watkins Glen Gorge? The Route 329 Bridge that the trains plan to use is in poor condition and is unsafe for transport of explosive material. Have security measures been established for the pipelines or off-site aspects of the project? According to the DSEIS, the applicant assumes no responsibility for emergency preparedness of truck and rail haulers.

There are fault lines on the Western shore of Seneca Lake. In light of the recent seismic activity felt in Watkins Glen, what would be the impact of an earthquake involving those fault lines and the gas stored within the caverns so close by? How adequately have these fault lines been studied? The application to store spent nuclear rods in these caverns was denied due to these fault lines. Why then is storing LPG in these same caverns being considered?

There is no mention in the DSEIS of consideration for mitigating the impacts of accumulating levels of NORM onsite in the pipelines and equipment. According to *The Guide to Naturally Occurring Radioactive Materials (NORM)*, published by Canadian Association of Petroleum Producers CAPP in 2000 and reviewed in 2003 (see enclosed), "1.3 Transport and Delivery of Propane and LPG: Propane transport equipment may be contaminated with NORM. This includes pipelines, rail cars and truck tanks. Even if the production site does not concentrate significant amounts of radon, loading contaminated transport tanks that vent into the facility may contaminate the loading facilities." Apparently radon is more soluble in liquid propane and thus concentrates there. It would therefore behoove the applicant to recognize this and take precautions for its employees, as well as its sub-contractors.

How will this facility affect local property values and the tax base—on the lake, near the facility, and along the roads leading to the facility? How will added traffic and industrial activity affect tourist businesses in the area? Franklin Street, the main street in Watkins Glen, has applied to be a Historic District. How can added LPG truck traffic coexist with a historic site designation? How much more traffic can the retail shops and homes on Franklin Street withstand? The Town of Reading has no zoning and, when asked, the Town Assessor admits that the property owners immediately adjacent to the facility will see property values decline.

Ecological and other issues:

Are you seriously considering the impact of noise (truck, rail, compressors, flares and other industrial activity) in a lake region where even random small sounds reverberates across and around the entire lake valley?

The brine pond is a huge concern. Though, according to the DSEIS, the brine pond is contained within a double layer, leak detecting liner, there is no manufacturer listed for the materials used in the liner's construction, nor is there a projected life-expectancy for the liner. What provisions are in place for liner replacement procedures. On top of the aesthetic damage to the hillside overlooking Seneca Lake, a brine pond on the side of a hill can spill or leak into the lake and local water sources, leaving the village and local residents with compromised water. The water table is very high where the proposed brine pond is to be located. How porous or permeable is the soil beneath the brine pond? In the event of a brine leakage, how long would it take for the brine to contaminate the water table?

According to a paper submitted to US Fish and Wildlife, there is high morbidity and toxicology associated with salt water and migratory birds and waterfowl. The impact of the brine pond to our migratory birds and waterfowl, including the threatened loon, is not adequately addressed in the DSEIS. How would this facility impact the recently established Bald Eagle? What about the ecological health of nearby wetlands? The DSEIS suggests that since our wetlands are small, no impact or mitigation measures are required, but there is no reason to claim this. The DSEIS does not adequately assess the flora and fauna at the site. An independent study should be undertaken and completed over several seasons.

Have you adequately dealt with the impact on unexplored Seneca Indian sites? No independent archeological survey was completed. This must be done to determine whether there are any archeologically sensitive sites. The database of historical archeological sites kept by NYS
is woefully anemic, so that it is hardly adequate to rely on available archeological records.

Doubts about the company Inergy and their plan:

As a matter of public record, Inergy, the parent company of Finger Lakes LPG Storage LLC and owner of U.S. Salt, does not have experience building a facility of this type and size from the ground up. Do we want them experimenting on us?

Inergy largely relies on the 1992 GEIS for information in their proposal. This GEIS deals with hydraulic drilling of vertical wells, NOT storage of LPG in salt mines.

What are the long term, cumulative effects of Inergy’s planned expansion? There is a disparity between what they tell us in the DSEIS compared to what they are telling investors. In the DSEIS, they do not mention expansion, although their investors are told that Inergy wants to make this the major distribution facility for the Northeastern United States. They have big hidden plans, involving many salt mines and a growing industrial facility. Once this initial permit application is approved, they will expand and increase their negative effects on our community. The DEC should investigate the full expansion plans listed in Inergy’s Initial Public Offering to investors and demand full-disclosure from Inergy.

The character of this company is questionable and needs to be fully considered. They do not have our local interests in mind. Instead they are working purely on a profit motive. Inergy was sued by the State of Michigan’s Attorney General for price gouging. They have had accidents and been fined in other areas. They have taken individual’s property through eminent domain for their own profit and expansion.

The next logical steps:

Considering the obvious threat this project brings, it is only reasonable to have an independent Qualitative and Quantitative Risk Analysis (QRA) to thoroughly and impartially evaluate the risk and impact that this facility would have on the region. Local governments and residents should choose the people who make this risk analysis. It should be paid for by the applicant. If the project is worth the risk, the company should have nothing to fear from a QRA.

Secondly, a thorough and independent geologic and seismic study of the region should be conducted to determine the soundness and suitability of the strata in question for this and future ventures. AND this study should be fully disclosed, not withheld as proprietary information.

Thank you for considering our concerns and suggestions.

On Behalf of the Executive Committee of
The Finger Lakes Group of the Atlantic Chapter of the Sierra Club,

Annie Koreman
Vice-Chairman
Guide

Naturally Occurring Radioactive Material (NORM)

June 2000
The Canadian Association of Petroleum Producers (CAPP) represents 150 companies that explore for, develop and produce natural gas, natural gas liquids, crude oil, synthetic crude oil, bitumen and elemental sulphur throughout Canada. CAPP member companies produce approximately 97 per cent of Canada's natural gas and crude oil. CAPP also has 120 associate members who provide a wide range of services that support the upstream crude oil and natural gas industry. Together, these members and associate members are an important part of a $52-billion-a-year national industry that affects the livelihoods of more than half a million Canadians.