Storage cavern	Time and place of accident	Reserve resource	Accident description	Accident cause	Economic loss	Number of casualties	Influence scope
Petal City	1974, Mississippi, USA	Liquid butane	Fire & explosion	Human error leading to overfilling	Homes destroyed within 7 km	24 injured	Influence range was 7 km, 3000 evacuated
West Hackberry	1978, Louisiana, USA	Petroleum	Fire & blowout	Packer failure during repair of casing	72,000 bbls (about 11,446 m^3) crude oil leaked, US $ 14-20 million loss in total	1 fatality, 1 injured	Influenced area was 90,000 m^2, environment polluted
Mont Belvieu	1980, Texas, USA	Liquid propane	Fire & explosion	Casing failure-corrosion	23 million m^3 of propane loss	At least 1 fatality	75 families (300 people) evacuated for 180 days
Conway	1980-2002, Kansas, USA	Liquid propane	Gas leaking into the groundwater	Hydrated cap rock	Gas found in wells and local groundwater possibly caused by wet rockhead	None	Area near the storage cavern, 30 homes bought, 110 people relocated
Mont Belvieu	October, 1984, Texas, USA	Liquid propane	Fire & explosion	Casing failure	Several million US $ loss	None	
Mont Belvieu	November, 1985, Texas, USA	Liquid propane	Fire & explosion	Transmission pipeline cut off	110 m^3 of propane consumed and a large amount of propane leaked	2 fatalities	More than 17,000 evacuated
Viriat	1986, France	Ethylene	Gas cloud	Ground facilities broken	All gas leaked	None	
Teutschenthal	1988, Halle, Germany	Ethylene	Surface dome and crack	Casing broken	60-80% of ethylene leaked	None	An area of approximately 8 km2 evacuated
Clute	1988-1989, Texas, USA	Ethylene	Gas escaping	Drilling operation resulting in tightness failure	About 20,000 m^3 of ethylene loss	None	10 families evacuated
Brenham	1992, Texas, USA	Liquefied petroleum gas(LPG)	Fire & explosion	Overfilling and valve failure	332,000 barrels (about 52,500 m^3) US$5.4 million & US$1.38 million punitive damages awarded	3 fatalities, 23 injured	About 3 km radius of plant, 26 homes destroyed
Mineola	1995, Texas, USA	Propane	Fire underground and on the surface	Pillar cracks	Cavern cycling connected adjacent cavities, pressure buildup and casing leak	None	The two caverns and region within 15 m on the surface
Yaggy	2001, Kansas, USA	Natural gas	Fire & explosion	Casing bend and damage	About 5,600,000 m^3 natural gas loss. Gas surfaced in old brine pipeheads. US$800 million law suit	2 fatalities	Part of the town influenced,some 250 people evacuated
Fort-Saskatchewan	2001, Saskatchewan, Canada	Ethylene	Fire lasting 8 days	Failure of pipeline connecting two caverns	14,500 m3 ethylene loss in	None	Area near the plant
Magnolia	2003, Louisiana, USA, near Napoleonville	Natural gas	Gas escaping	Casing crack	More than 1,000,000 m^3 natural gas leaked	None	About 30 people evacuated from Grand Bayou
Odessa	2004, Kansas, USA	Liquid propane	Gas escaping	Ground facilities broken	More than 100 t (about 90,000 kg) liquid propane leaked	None	
Clute	2004, Texas, USA	Ethylene	Fire & explosion	Drilling operation resulting in tightness failure		None	10 families evacuated
Moss Bluff	2004, Texas, USA	Natural gas	Fire & explosion (300m high flame)	Brine pipe corrosion, well casing separation	At least 36 million US $ loss in gas inventory	None	Influence range was 120 m, 1000 people within 5 km evacuated

Table 13.7. Accidents associated with oil and gas storage facilities (after Yang et al., 2013; Evans,2009).

Compared to the other salt domes of the Five Islands, Cote Blanche Island has benefited from a safe, stable salt mine operation throughout the mine life (Autin, 2002). Reasons for this success to date are possibly; (i) mining operations have not been conducted as long at Cote Blanche Island as other nearby domes, (ii) the Cote Blanche salt dome may have better natural structural integrity than other islands, thus allowing for greater mine stability (although it too has anomalous zones, a salt overhang, and other structural complexities), and (iii) the salt is surrounded by more clayey (impervious) sediments than the other Five Islands, perhaps allowing for lower rates of crossflow and greater hydrologic stability.

Groundwater breakout tied to Anpeng Trona, China

At a depth of more than 2,000 m, the Anpeng trona salt mine, China, exploits the deepest and second largest trona deposit yet discovered in the world. The mine is located in hilly country and is solution mining Eocene sediments in the fault-bound Biyang depression, via a linked series of injector and extractor wells (Chapter 12). Since October 2008, groundwater bursting or breakout has occurred, even under rainless weather conditions in and around Cao Village, Anpeng, Tongbai County. These saline breakouts have cause severe salinization of the land, which currently has an area of over 300,000 m^2. Water from some drinking wells has also become contaminated and nonpotable.

A systematic study of the geological conditions, operation of the mines, the hydrogeochemistry of groundwater bursts shows leaked solution waters are the source of the groundwater bursts (Shi et al., 2013). Over the 40 years of mine operations, natural and induced fractures, cracks, faults, and leaking brine wells have formed connections with one another. Previously un recognised water leakages of saline mine waters have welled up and recharged shallow aquifers, before finally reaching the ground surface as groundwater bursts, where pressurised escaping waters can form fountains up to a metre tall.

Case Histories: Storage cavern problems

The world's demand for fuel means it must be held in sufficient quantities near centres of distribution so as to insure security of supply. Deciding where and how mankind stores substantial volumes of hydrocarbons (or in the future the much more volatile hydrogen) in or near populated areas will always be a problem. There have been a few accidents in below ground storage facilities and some are described in this section. However, when the environmental and safety records of above and below ground fuel storage facilities are compared, the below ground facilities are an order of magnitude safer and less environmentally hazardous. Problems with storage caverns in salt hosts are related either to the utilisation of non-purpose built caverns or to human error and poor management practices (Figure 13.7).

Weeks Island, Louisiana

The Weeks Island Strategic Petroleum Reserve (SPR) facility on Weeks Island, Louisiana, is some 30 km SE of Jefferson Island. Like other salt-cored islands, the landscape shows a variety of surface features indicative of ongoing salt dissolution such as dolines and linear valleys atop shear zones (Figure 13.48a). It utilized abandoned room and pillar caverns of the Morton Salt Company mine and so was unusual compared to other purpose-built storage caverns of the Strategic Petroleum Reserve (SPR). It was purchased in the 1970s, a time that was early in the annals of the SPR and at the height of the 1970s oil crisis. Occupying a former salt mine it was the shallowest of all the SPR facilities across the USA (150-220 metres below the land surface). It was not a custom built facility, nor was it constructed by solution mining technologies.

Following oil fill in 1980-1982, the facility stored some 72.5 million BBL of crude oil in abandoned mine chambers. Then in November 1995, the Department of Energy (DOE) initiated oil drawdown procedures, along with brine refill and oil skimming, plus numerous plugging and sealing activities. In 1999, at the end of this recovery operation, about 98% of the crude oil had been recovered and transferred to other SPR facilities in Louisiana and Texas; approximately 1.47 MMBL still lies in the now plugged and abandoned cavern system.

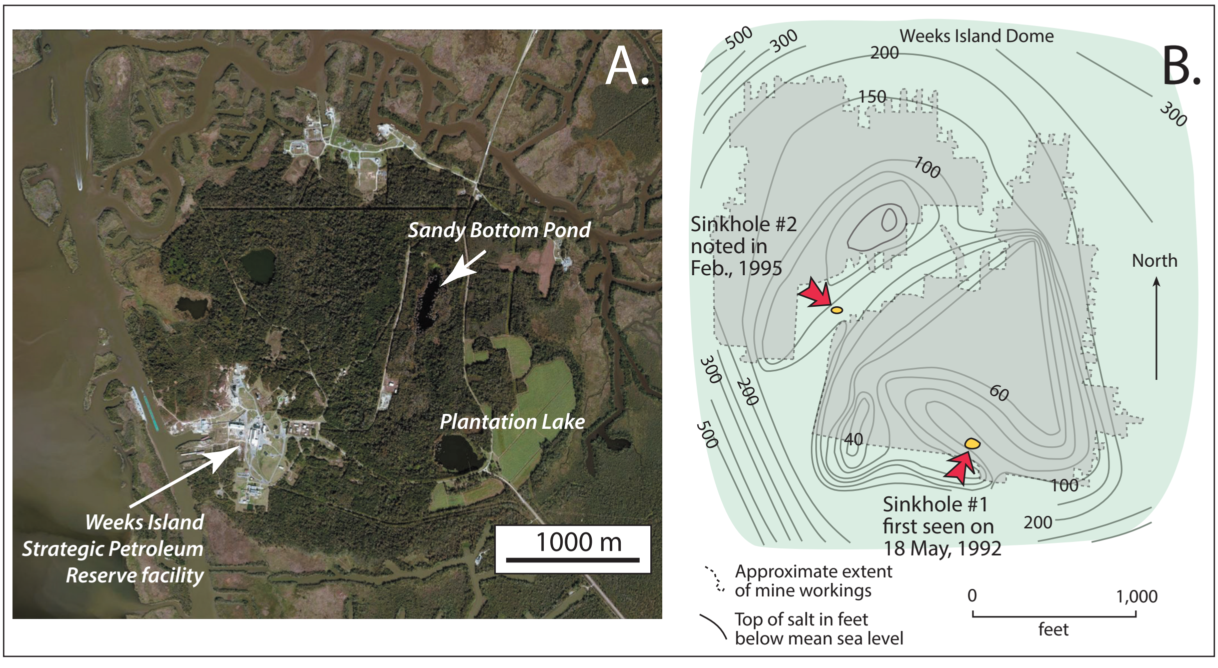

Figure 13.48. Strategic Petroleum Reserve facility, Weeks Island, Louisiana. A) Location of SPR facility and the presence of natural water-filled collapse dolines. B) Top of salt contours showing how sinkholes developed in depressions atop the upper part of the salt. The sinkholes occur in regions near the edge of the cavern, with the potential for foundering of the cavern roof into the chambers of the former Morton Salt mine.

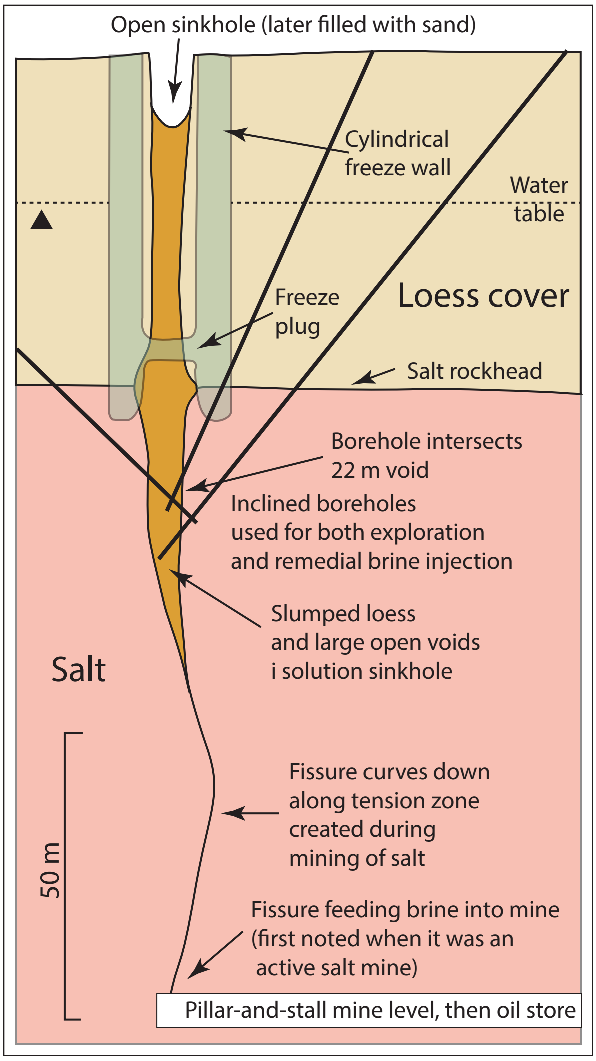

Figure 13.49. Schematic section through the main Weeks Island sinkhole and its remedial freeze curtain (after Waltham et al., 2005).

The cause of this drainage and abandonment was an active sinkhole some 10 metres across and 10 metres deep, first noted near the edge of the SPR facility in May 1992 and perhaps reaching the surface about a year earlier. However, the growing depression was located on the south-central portion of the island, directly over a subsurface trough, which is obvious in the top-of-salt contour based on mine records (Figure 13.48b; Neal and Myers, 1995). Earlier shallow exploratory drilling around the Department of Energy service and production shafts in 1986 had identified the presence of irregularities and brine-filled voids along the top of salt in this region. A second, much smaller sinkhole was noticed in early February 1995, but it did not constitute a serious threat as it lay outside the area of cavern storage.

Neal (1994) pointed out that Kupfer's 1976 map of that part of the mine located beneath the first sinkhole showed black salt. Regionally, black salt in Gulf Coast salt mines is often associated with anomalous leach-zones, indicating zones where salt was subject to unpredictable movement and sometimes to collapse. The volume of this sinkhole (estimated as 650 m^3 when first noted), its occurrence over a trough in the top of salt, and its position directly above the oil-filled mine caverns, meant it was of concern to the SPR authorities, especially in terms of the stability of the roof of the storage cavern. This feature did not form overnight, it lies atop a shear zone that formed during the diapiric rise of the salt and capped by a rockhead valley containing Pleistocene sediment fill. Salt extraction probably created tension across the shear zone, thereby favouring fracture enlargement, as early perhaps as 1970 (Figure 13.49; Waltham et al., 2005). Eventually, an incursion of undersaturated groundwater traversed the fracture zone across some 107 m, from a level equivalent to the rockhead down to the mine where it emerged. Over time, ongoing dissolution enlarged a void at the top of the salt, creating the collapse environment for the sinkhole that was noted at the land surface in 1991. Investigations undertaken in 1994 and 1995 into the cause of active at-surface sinkholes verified that water from the aquifer above the Weeks Island salt dome was seeping into the underground oil storage chamber at the first sinkhole site (Figures 13.48, 13.49; Neal and Myers, 1995; Neal et al., 1995, 1997). Drainage and decommissioning of the Weeks Island facility followed.

Beginning in 1994, and continuing until abandonment of the facility, saturated brine was injected directly into the throat of first sinkhole, which lay some 75 metres beneath the surface. This essentially arrested further dissolution and bought time for DOE to prepare for the safe and orderly transfer of crude oil to another storage facility. To provide added insurance during the oil transfer stage, a "freeze curtain" was constructed in 1995. It consisted of a 54 well installation around the principal sinkhole, which froze the overburden and uppermost salt to a depth of 67 metres (Figure 13.49; Martinez et al., 1998). Until the mine was completely filled with brine and its hydrocarbons removed, this freeze wall prevented groundwater flow into the mine via the region of black salt around the sinkhole. Dealing with this sinkhole was costly. Mitigation and the removal and transfer of oil, including dismantling of infrastructure (pipelines, pumps etc.), cost a total of nearly US$100 million; the freeze curtain itself cost nearly $10 million.

In hindsight, based on an earlier leak into the mine, while it was an operational mine, and the noted presence of black salt in a shear zone in the mined salt, one might fault the initial DOE decision to select this mine for oil storage. In 1978 groundwater had already leaked into a part of the mine adjacent to the sinkhole and this was forewarning of events to come (Martinez et al., 1998). Injection of cement grout into the flow path controlled the leak at that time, but it could just as easily have become uncontrollable and formed a sinkhole then. But in 1978 the technology needed to understand the salt physics, salt solution and mine conditions and so predict future events had not been developed. The world, and the United States, was in the middle of an oil crisis and as a former US President once observed, "It's hard to drain the swamp when you're up to your arse in alligators!"

Gas escape, explosions and fires from cavern leaks

Almost all the explosions and fires described in this section are caused either by human error, poor forward planning, a lack of due diligence by the storage company or operator or a combination of these factors (Table 13.7; Yang et al., 2013). In all cases the salt caverns themselves did not fail. In spite of these accidents, cavern storage is still one of the safest ways to store what are very large volumes of highly explosive materials. Consequences are far graver, and death rates orders of magnitude higher, when explosions and fires have occurred in above ground fuel storage tanks and facilities (Evans, 2009).

The West Hackberry explosion

On September 21, 1978 a blowout and explosion occurred at the West Hackberry salt dome storage facility in southern Louisiana (USA). It killed one worker, released 10,000 m^3 of oil to the surface and cost US $14-20 million (1980 dollars) in cleanup and remediation. The incident occurred during workover operations on one of the access wells to the No. 6 cavity.

Understanding the causes of the explosion requires a few background comments on casing strings in the well and the workover specifications (Figure 13.50). The well completion was made up of an outer 12.75-in (32.4 cm) casing string cemented to a depth of 2632 ft (816m). Cemented inside was another 9.62-in (24.4 cm) diameter casing string some 2603 ft (807 m) long. This was probably added after the "initial" completion to improve oil tightness when the cavity was converted to oil storage. An innermost 5.5-in (14 cm) diameter pipe string was used to withdraw brine whenever oil was pumped in to the cavity (see Figure 13.50).

On the day of the explosion the workover consisted of withdrawing the 5.5-in innermost tubing string, repairing a leak on the 12.75-in casing, and reinforcing the wellhead equipment. To accomplish this, the annular space between the innermost pipe string and the 9.62-in casing had been filled with high-viscosity mud. This was designed to bring wellhead pressure in the oil string to zero. Once the annular space was filled, a packer was set at the bottom of the 5.5-in brine pipe to seal it off from the cavity. Work then commenced on pulling the innermost 5.5-in pipe; however, after 14 pipe lengths had been stacked, the packer slipped as increasing differential pressure started to push it up to the surface. As the packer rose, the pressure (brine to oil differential) on it increased. Soon the packer shot up and out on to the surface, forming an oil geyser (blowout) that continued until the pressure differential had dissipated. By that time an estimated 72,000 barrels (10,000 m^3) had shot up into the air, caught fire and killed one of the drilling crew.

A poor understanding of the pressure distribution in the fluid columns when the workover was designed is the main reason for the incident. As planned, the workover was extremely delicate, it was attempted without drawing down the oil pressure in the cavern. As the oil was under high pressure (sealed in by viscous mud in oil feeder casing) as the workover began it was liable to expand violently if any mishap upset the status quo. Injecting the viscous mud at the top of the well was a good precaution against any failure of the topside valve on the oil-filled annular space, but it had absolutely no effect on the dangerous situation at the bottom of the cavity and if the packer failed, which it did, there was no way of preventing a blowout.

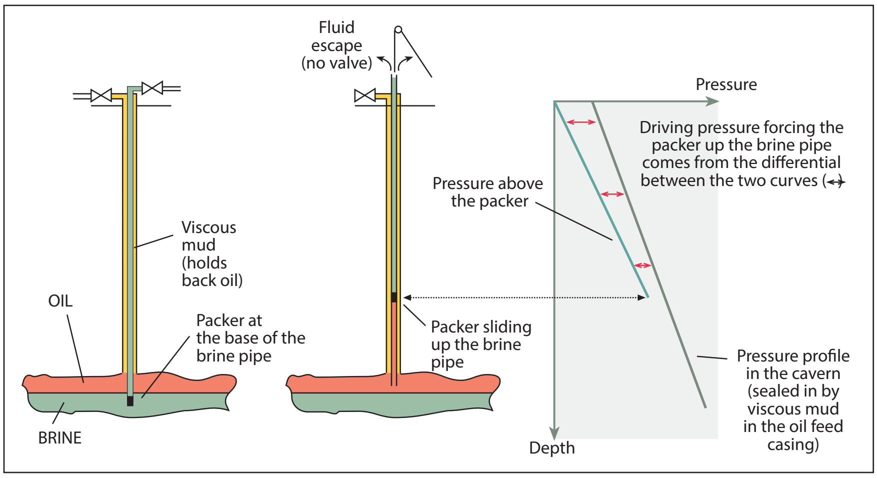

Figure 13.50. Schematic of the pressure differentials that caused the West Hackberry blow out and explosion (see also Figure 13.11).

A comprehensive but simple precaution would have been to release the pressure on the oil in the cavity by drawing down the top surface of the brine in the access well to about one-quarter of its total original height. The volume of oil needed to be withdrawn was, of course, exactly equal to the volume that was expelled in the blowout. This relatively small volume of oil could easily have been stored temporarily in another cavity on the site. So doing would have rendered the workover situation entirely safe.

The Brenham explosion

A disastrous explosion occurred on April 7, 1992, following the outflow of LPG onto the surface from a well atop a storage cavern in the Brenham Salt Dome. The blast occurred some 110 km northwest of Houston. It killed a 6-year old boy and two adults, injured 21 persons, damaged more than 40 homes and snapped trees like matchsticks, while denuding acres of rolling farmland. In all it caused an estimated US$ 9 million in damage to property within a 5 km radius. Seismographs at three Texas universities within 120 km of the scene recorded surface tremors ranging from 3.5 to 4.0 on the Richter scale. Windows were rattled in homes more than 200 km away.

The Brenham storage facility consisted of a 380,000-bbl (60,000-m^3) cavern filled with LPG (a mixture of propane, ethane, n-butane and other gases). The cavern was linked to ground level by a 13-3/8-in diameter, 2,702-ft long cemented casing (Figure 13.51). A central brine pipe (2,871-ft long) allowed injection and withdrawal of brine. LPG was injected into, or withdrawn from, three distinct pipelines. Brine was provided by two above-ground brine ponds. The wellhead was

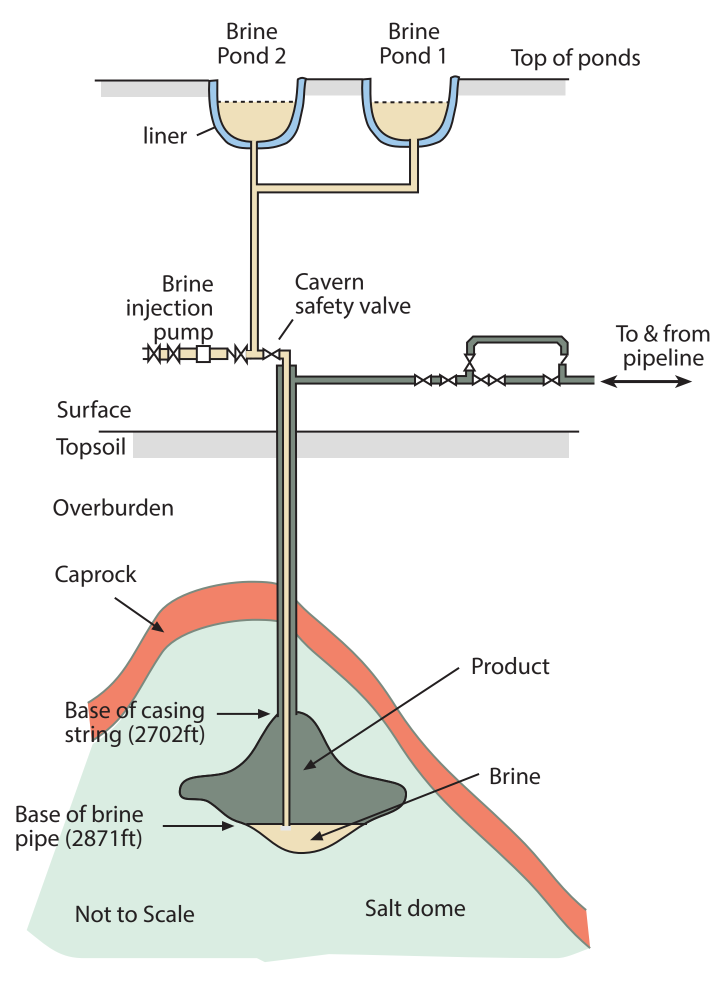

Figure 13.51. Schematic of the situation at the time of the Brenham explosion.

equipped with a shutdown valve. The Brenham station was operated remotely by a dispatcher in Tulsa, Oklahoma (Bérest and Brouard, 2003).

At 5:43 am on April 7, 1992, additional LPG was injected in the cavern. The brine/LPG interface unexpectedly reached the 1-in diameter weep hole located in the lower part of the central tubing, some 1 ft above the tubing base. The weep hole was supposed to provide warning in case of imminent overfilling. LPG flowed into the central brine tubing, leading to lower density in the fluid in the central column, partial vaporization and expansion of the lighter gases, a pressure drop in the cavern and, ultimately, a large flow of gas through the weep hole and the tubing base alike.

Brine, followed by liquefied gas, daylighted at the brine pond surface. Back-calculation proved that 3,000 to 10,000 bbl (500 to 1,600 m^3) of liquefied gases were expelled via the ponds. The release of gas into the atmosphere activated gas detectors at ground level. (Such activation was apparently a relatively frequent event at this station, and alarms were often unrelated to an actual gas leak). The dispatcher in Tulsa was not able to interpret correctly the somewhat confusing information delivered by the telemetric system - a unique signal was sent, whatever had activated a number of detectors. The shutdown valve (or cavern safety valve) was assumed to have immediately reacted to the high pressure level (100 psi) in the brine tubing at the wellhead, but the system failed.

A subsequent National Transport Safety Board (NTSB) investigation confirmed the local operator had overfilled the storage cavern to where LPG had escaped into an adjoining brine storage pit through the brine injection system via an open valve. Product had then evaporated and, being heavier than air, formed a low-lying cloud 30 feet high and several hundred yards long. At 7:08 am the "mushroom-shaped" vapour cloud was ignited by an automobile driving into the foggy cloud near the storage facility.

According to the NTSB report, Mapco (the operator of the facility) was not aware of the volume of product in storage at the site. Some 338,995 barrels were actually stored instead of the 288,000 bbl estimated by Mapco. NTSB concluded that the management procedures had lacked oversight adequate to confirm employee measurements. Nor did the company have the ability to balance cavern receipts against withdrawals. In addition, employee measurement procedures did not adequately take into account specific gravity variations of the NGLs in storage.

Aside from the computation errors, NTSB said other contributing factors included:

a) Inadequate positioning of the brine pipe weep hole - in a post accident redesign it was moved to 6 feet above the base of the brine pipe,
b) A lack of several fail-safe features on the cavern's shutdown system - this system had included a brine pressure-sensing line designed so that when a large pressure build-up was sensed in the brine line it switched a spring that, when triggered, sent an electrical signal in a chain containing a fusible link whose fusion should have closed the brine safety valve and so prevented product leakage back up the brine pipe. It is extremely likely than one or two manual valves were closed on this sensing line at the time of the explosion, isolating it from the main body of the brine pipe, so making the emergency shutdown system ineffective. Ironically, the shutdown valve was activated when heat from the explosion burned the fuse and triggered valve closure (it shut the barn door after the horse had bolted).
c) Inadequate emergency response training and procedures, along with poor communication among Mapco employees responding to the alarms and to the obvious surface emergency.

Early media coverage sensationally reported that "A Salt Dome Has Blown Up". However the cavern storing the leaked liquids later passed a mechanical integrity test and is still in use today. It was operational supervision and safety procedures that failed dismally, not the cavern. After this accident, the Railroad Commission of Texas issued new regulations (effective in 1994) mandating that LPG storage caverns be protected by at least two overfill detection and automatic shut-in methods.

Barber's Hill explosion and collapse

On October 3, 1980 a gas-fed explosion occurred in a residence in Mont Belvieu, a Texan town that sits atop the Barbers Hill diapir, some 60 km west of Houston. Barbers Hill dome is the largest subsurface LPG storage facility in the U.S. with over 126 active solution-mined caverns storing between 75 and 300 million barrels of light hydrocarbon products. The explosion was ignited by a woman who sustained burns when turning on her dishwasher. A spark from the dishwasher had ignited gas that had accumulated in the foundation of the house.

Two weeks earlier, on September 17, 1980, a drop in pressure had been recorded in one of the nearby cavities storing liquefied petroleum gas (70% ethane, 30% propane). The cavern was emptied of product and filled with brine. Subsequent investigation showed a leak had occurred through a corroded casing joint in the access well in the vicinity of the porous anhydrite caprock (Figure 13.52). The well in question had originally been drilled in 1958. Leaking gas seeped through the surrounding soil to accumulate in the foundations of the residence where the explosion occurred. In the days that followed, gas daylighted haphazardly in residential areas around the site of the original explosion. Holes were drilled into the watertable to find and vent pockets of gas. Residual gas saturations in the soils forced the evacuation of 73 families for nearly seven months and a drastic fall in property values.

Because of its low density, propane tends to rise to the surface, either through the cement along the outside of the casing or by dispersing in the overlying ground surrounding a breach (Bérest et al., 2003). This happens, for example, if escaping gas intersects a sufficiently pervious water-bearing layer just below the surface. The gas can accumulate in building foundations, emerge at streams and similar low-lying ground or come up through faults and joints, daylighting at the surface several hundred meters from the well head. To minimise this potential problem, the architecture of the access well is of utmost importance. In the Mount Belvieu situation, if the two last cemented casings been anchored in the salt formation and not into the anhydrite cap, the propane leak would have been channeled in the cemented annular space between the two casings, with considerably lesser consequences (Thoms and Kiddoo, 1998).

A few years later, on July 30,1993, there was another event that further lowered Mont Belvieu property values. In a few hours a sinkhole crater formed between two brine wells in the EGP Fuel Storage facility (Cartwright et al., 2000). The crater stabilized with a diameter of 12 metres and a depth of 6 metres. A well that was near the problem site had to be abandoned after the sinkhole formed. It was not a hydrocarbon storage well so the environmental implications of a collapse-induced abandonment were not as significant it would have been for a failed hydrocarbon cycling well. The cause of the sinkhole is contentious but it is thought that brine cycling in the two wells may have contributed to the collapse. Detailed subsidence work in the cone of subsidence about the sinkhole suggest that it was probably there prior to the collapse and, if it had been monitored, the data could have been used as an indicator of the likelihood of collapse (Cartwright et al., 2000).

Brine injection that drives brine compensated withdrawal of the stored hydrocarbons periodically requires large volumes of brine in short time frames. But in Mont Belvieu there was not sufficient above ground infrastructure to store the large volumes of brine needed for product cycling. To give access to large volumes of brines quickly, brines were pumped down dedicated brine storage wells with bases in shallow caprock caverns. Wells adjacent to 1993 Mont Belvieu sinkhole were two such wells that had stoped toward the landsurface, perhaps facilitated by ongoing brine cycling.

Mineola propane fire

In 1995 there was an underground fire that burned for several days at a salt dome storage cavern operated by Suburban Propane near Mineola in East Texas, some 145 km east of Dallas. The cavern in which the blow-out occurred extended from 1200 ft to 2500 ft (350-750 m) subsurface. The blowout occurred when a salt wall separating two storage caverns had become so thin from the enlargement associated with brine compensation (product cycling) that it cracked (Gebhardt et al., 2001). This allowed stored propane product to flow from one cavern to an adjacent cavern that was empty of product and undergoing testing. Pressurised nitrogen was being injected into the adjacent brine filled cavern as part of a standard mechanical integrity test. The testing may have contributed to the penultimate pressure buildup that allowed propane product to leak

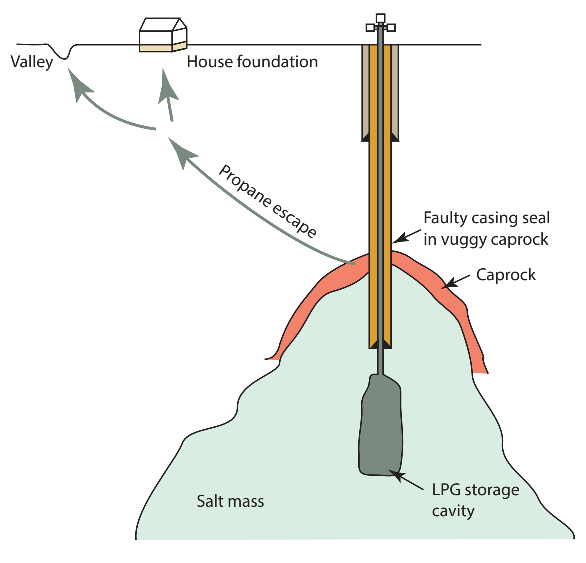

Figure 13.52. The Mont Belvieu (Texas) 1980 accident. After 22 years of operation, the last cemented casing became leaky. In Texas, more recent wells must be equipped with two casing strings into the salt (after Bérest et al., 2003).

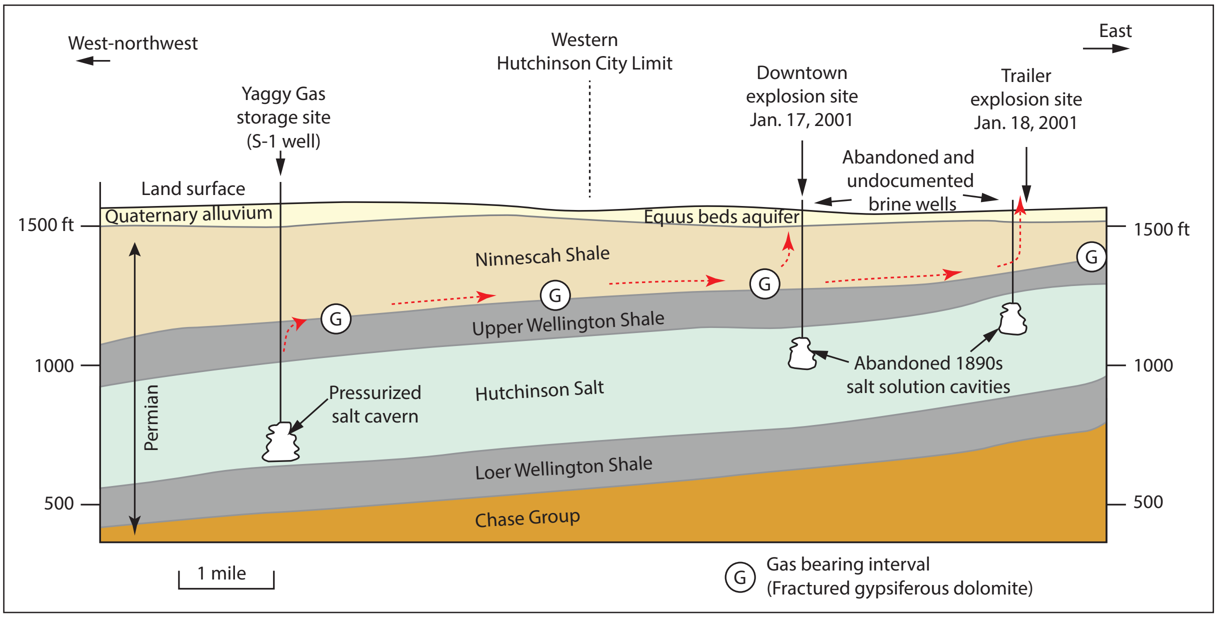

Figure 13.53. Hutchinson, Kansas January 2001 gas explosion, explanatory cross section (redrafted and modified from image downloaded on June 4, 2013 at <http://www.kgs.ku.edu/Hydro/Hutch/GeneralGeology/index.html>)

into shallow depths via a casing leak (Bérest and Brouard, 2003). The leaking well had originally been drilled as an oil producer in the late 1950s, four decades before the accident. Liquified gas escaped through the soil in a halo that extended as far as 100 feet from the well. The escaping gas ignited and burned releasing heavy black smoke. Extinction of the fire was not a viable option, as dangerous re-ignition and flash back was likely. The innovative kill techniques applied to this well are described in Gebhardt et al. (2001).

There are potential problems with longterm intercavern integrity as all salt caverns will enlarge during product cycling, so the Texas Railroad Commission now legislates what is an acceptable degree of enlargement before a storage cavern must be plugged and abandoned.

Hutchinson explosion

On January 17, 2001, a gas explosion and fire destroyed two businesses in downtown Hutchinson in central Kansas (Allison, 2001). The next day in the Big Chief mobile home park 3 miles away another explosion occurred and 2 residents died of injuries received. The explosions were tied to geysers spewing gas and water, and their appearance caused the excavation of hundreds of Hutchinson residents. Pathways to the landsurface at both explosion sites and to the various active geysers across town were directly tied to undocumented and abandoned wells that were once used to solution mine the Hutchinson Salt.

The January 17-18, 2001 eruptions of gas and brine, driving 30-ft (10m) geysers in the town, resulted from the loss of 143 MMcf of gas from the Yaggy natural gas storage facility located 7 miles down the road from the town community of 40,000 people (Figure 13.53). Oneok Inc., owned and operated the Yaggy field through a subsidiary company called KGas. Upon review of pressure records, KGas officials realized that the S-1 cavern had probably been leaking at a low level, at least since the pod of caverns had been refilled with natural gas on January 14, and perhaps much longer, perhaps since the initial well workover in the 1990s. At the time of the refilling, technicians did not think much of a minor pressure drop, as it was a routine situation associated with filling the cavern. When the caverns are pressurized, the natural gas is compressed, raising its temperature. Once in the caverns, the pressurised gas begins to cool and condense, resulting in a slight pressure decrease. It was common practice to then "top off" the cooled caverns with additional gas to fill the caverns to the final storage pressure.

The Yaggy field of salt caverns was originally developed in the early 1980s to hold propane. Wells were drilled to depths of about 650-900 feet (200-300 m), into the lower parts of the Hutchinson Salt Member and cased with steel. The roof of each cavern was about 40 feet (12m) below the top of the salt layer. The company had difficulty making a financial success of the operation and eventually ceased operations. All of the storage wells were filled with brine and then plugged by partially filling them with concrete. KGas acquired the facility in the early 1990s and converted it to natural gas storage (by definition this is a pressurized storage system). Plugged wells were drilled out to return the feeder wells and caverns to use. At the surface the wells in the Yaggy facility are 300 feet (90m) apart. At the time of the crisis, Yaggy had about 70 wells, of which 62 were feeders to active natural gas storage caverns. More than 20 new wells had been drilled and were being used to create new caverns for expansion of the field storage capacity.

At full capacity, the field could hold 3.5 billion cubic feet (Bcf) of gas at pressures of about 600 pounds per square inch and at the time of the accident it was supplying up to 150 MMcf (million cubic feet) of gas per day. Yaggy is the only natural gas storage field in salt caverns in the state of Kansas. Other salt caverns in Kansas are used for brine-cycled storage of liquid hydrocarbons, such as propane, at much lower pressures than the natural gas at Yaggy.

Records show that when KGas drilled the concrete out from the well casing in S-1 well to return the well to operation, they encountered a steel casing coupler that was dropped into the concrete in the well during the plugging operations (Allison, 2001). During the workover this object may have deflected the drill bit against the side of the well casing damaging and weakening it. A post accident down-hole video in S-1 shows a large curved slice in the casing at that depth. The city's geological consultant described it as looking "like a kitchen knife cutting into a can." Prior to the Yaggy facility approval by state authorities the S-1 had a satisfactory casing pressure test, as required by the Kansas Department of Health and Environment. The test was though to demonstrate the integrity of the casing at that time. However, the well at the depth of the leak was never tested to the maximum pressure that would be experienced in service.

The route followed to the surface by the escaping gas is not completely documented. Initial seismic surveys in early February 2001 at first indicated a possible subsurface sand channel through which the escaping gas flowed up from the storage facility. But that was not borne out by a study of regional well logs or the 22% success rate in drilling for suspected gas pockets (Watney et al., 2003) or subsequent seismic interpretation (Nissen et al., 2004). The most likely candidate carrier is thought to be a fractured intrasalt gypsiferous dolomite layers that pinched out northwest against the tight shales, and so facilitated drainage to the crest of the anticlinal culmination that underlies the town of Hutchinson (Figure 13.53).

There are more than 600 NGL-LPG salt storage caverns in bedded Hutchinson salt in the state of Kansas, the most of any state in the USA. Kansas also has plans for more natural gas storage caverns, although Gulf Coast salt dome caverns are 10-20 times larger. The mix of bedded salt and permeable rock formations (perhaps even intrasalt) around Hutchinson region, the presence of natural dissolution irregularities and the fact that Hutchinson has been an area of solution mining since the late 1800s is a real problem for storage of high-pressure fluids. Once the S-1 well was breached, numerous unplugged brine wells that were long ago drilled within the Hutchinson Salt and abandoned, without appropriate documentation, routed the escaping gas to the surface. Such wells are directly tied to the downtown fire that first heralded the problem, and to the two deaths that occurred in the explosion in the mobile home park a few days later. Work since the explosion has pointed out numerous problems to be addressed in a region of bedded salt that appears in many ways not to be a suitable site for future natural gas storage projects. Even so, the salt storage cavern itself did not leak, the access piping was the problem due to well workover damage.

After the accident, poor regulation and the small inspection staff numbers in the state of Kansas (compared to neighboring states) were incriminated by several experts (Bérest et al., 2003). New sets of regulations were discussed and legislated, including mandatory double casing in wells, corrosion control, well conversion restrictions (salt caverns designed to store LPG should not be converted to store natural gas, and cavern wells that have been plugged cannot be reopened and used again), maximum pressure limit of 0.76 psi/ft (1.73 10^{-2} MPa/m) and new testing requirements, such as a leak test should be performed every 5 years.

CO_2 outburst, Menzengraben Potash Mine, E. Germany

An intense outburst of carbon dioxide took place on 7 July 1953 in the vicinity of the Menzengraben potash mine of the former East Germany (Hedlund, 2012). This disaster occurred in a salt mining region known to be gassy, and prone to CO_2 rock-burst problems (Table 13.8). The gas escaped from the #2 Shaft House immediately after a scheduled underground blast at 11:35 pm on the evening of July 7,1953. As a result of the gas escape some 12 people died above ground from CO_2-induced asphyxiation, many died in their sleep. No-one died underground as, due to the gassy nature of the extracted salt, it was standard practice to bring all staff above ground prior to a blast. For 25 minutes after the scheduled blast, a large amount of CO_2 blew with great force out of the mine shaft. Outside, it was a still night with no wind, allowing concentrated CO_2 to accumulate in a nearby valley, leading to multiple asphyxiation casualties.

Based on a review of concentration-response relationships, the location of victims, and other information, Hedlund (2012) concluded that concentrations of 10-30% carbon dioxide occurred up to 450 metres from the point of release at the shaft house, for at least 45 minutes, with some 1100-3900 tonnes of CO_2 blown out of the mine, at "blow-out" intensities estimated to be 4 tonnes per second. The majority of the gas escaped via a near-vertical high-velocity jet, with only little loss of momentum due to impingement. The nature of the escape and the ability of the gas to pond is relevant to planned CO_2 sequestration facilities, worldwide. The largest natural CO_2 induced disaster occurred in 1986 in the vicinity of Lake Nyos (Cameroon), when a CO_2 plume was released from lake bottom sediments. The gas plume had a likely volume of 1.5 million tonnes and spread up to 25km from the release point, hugging the lower parts of the landscape and killing an estimated 1700 people,

Date	Mine	Salt burst (tonnes)	$C0_2$ released (m^3)
27 November, 1908	Dietlas	2700	18,000
15 April, 1938.	Marx-Engels	7000	Not stated
31 November, 1938	Ernst Thalmann	15,000	200,000
29 January, 1942	Menzengraben	5000	75,000
3 June, 1943	Menzengraben	18,000	450,000
10 May, 1950	Marx-Engels	20,000	Not stated
13 October, 1951	Menzengraben	13,000	200,000
7 July, 1953	Menzengraben	65,000	700,000
15 October, 1957	Menzengraben	22,000	400,000
21 August, 1981	Not stated	6000	1,000,000
25 May, 1984	Not stated	110,000	2,300,000

Table 13.8. Reported salt burst and CO_2 release volumes resulting from CO_2 outbursts in the Werra District (after Hedlund, 2012)

Storage cavern	Time and place of accident	Reserve resource	Accident description	Accident cause	Economic loss	Influence scope
Kiel	1967, Germany	Natural gas & hydrogen	Volume lost 12.3% after 45 days	Excessive creep of salt, operating at too low pressure	Cavern failure (reduced capacity)	The cavern
Eminence	1970-1972, Mississippi, USA	Natural gas	Volume lost more than 40%	Excessive creep of salt, operating at too low pressure	Cavern failure (reduced capacity)	The cavern
Stratton Ridge	1990s, Texas, USA	Natural gas	Cavern abandoned, ground subsidence, settlement rate 40 mm/a	Excessive creep of salt and in wet condition	Cavern failure	Ground above the caverns
Bayou Choctaw	1954, Louisiana, USA		Cap rock collapsed, ≈245 m diameter lake formed on the surface	Human error	Cavern failure	Ground above the caverns
Clovelly	Louisiana, USA	Oil storage	Cavern in salt overhang dissolved into cap rock	Thin cap rock, inadequate salt buffer	Cavern abandonment	The cavern
Napoleonville Bayou Corne	2012-ongoing, Louisiana, USA	Brine cycling	Cap rock with large voids, unexpected shale layers in salt edge leading to collapse	Cap rock failure, inadequate salt buffer	Cavern abandonment, loss of brine storage	The cavern and ground above

Table 13.9. Problems in pressurized storage caverns (see text).

along with large numbers of livestock.

Recognising and preventing potential cavern problems

Three factors can contribute to the breaching and collapse of solution-mined cavities, namely creep, uncontrolled leaching, and the presence of anomalous zones in what had been assumed to be homogenous salt (Table 13.9). Anomalous zones may be unexpected regions of highly soluble salts (potash salts), of fractured intrasalt beds, or zones of much older natural leaching (e.g. black salt), which may contain pressurized brine or gas (methane or nitrogen). In brinefields and some salt mines the anomalous zones tend to occur near intersections with poorly documented older well bores. The same set of factors generates many of the operational problems in conventional salt mines (Chapter 11 and 12).

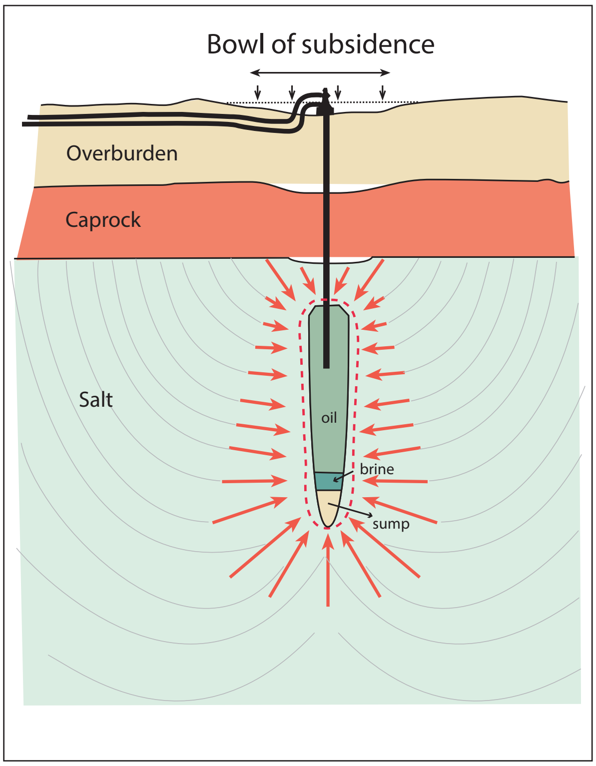

Figure 13.54. After the cavern has formed and is filled, salt creep causes the cavern to shrink from its original size (dashed shape) into a somewhat smaller configuration. This induces subsidence and possible collapse in the zone above the cavern. At the surface this process forms a "bowl of subsidence" (in part after Thoms, 2000).

Salt Creep

The principal factors influencing the rate of salt creep are; a) cavern depth and overburden characteristics; pressure and temperature gradients, b) internal cavity pressure, c) cavern shape, d) salt properties (e.g., variations in halite crystal size, moisture content). Left alone, and not subject to fresh water incursion, salt (especially carnallite and bischofite salt) will creep into an unbreached storage cavern until differential pressures are equalised. Salt cavities in homogenous halite hosts are generally stable at depths between a few hundred metres and about 2000 metres depth (Figures 13.1; 13.54). Below that depth there is an elastic-plastic transition zone for salt behaviour somewhere below 1000 to 2000 metres. Cavities below this can be relatively unstable and show large volume decreases through rock creep; with the transition depth depending on the composition of the salt, the geothermal gradient and the overburden pressure. Effects of salt cavity creep, due to inadequate internal pressuring, were first noted in the 1970s by the operators of some large purpose-built storage caverns. The Eminence cavern in Mississippi, built at 1700-2000m, lost 40% of its volume in just two years post-construction, while Tersanne in France lost 30% to salt creep (Figure 13.55). Such losses in storage capacity were potentially expensive, but when adjustments were made to cavern depths and minimum gas storage pressures, the volume loss stopped. Today both facilities are still operational and have recovered much of their initial volume loss (Thoms and Gehle, 2000a). Salt creep occurs at slower rates above the