Beijing 9th World Salt Symposium

NATURAL COMPRESSED AIR STORAGE: A CATASTROPHE AT A KANSAS SALT MINE

Leo L. Van Sambeek
RESPEC

ABSTRACT

On October 26, 2000, a brick factory in Kanopolis, Kansas, USA, was substantially destroyed by bricks, sand, and water falling from the sky. The bricks and sand were blown skyward by a high-speed jet of air blowing from an underlying salt mine. The jet of air blew from a previously sealed salt mine shaft and through a pile of bricks next to the brick factory. The escaping (high-speed) air carried bricks and sand skyward more than 100 meters before they fell back to earth and demolished the brick factory. The underground salt mine had been closed about 50 years earlier, and its shafts were sealed with salt, sand, and straw. This paper presents facts and observations, hypotheses, and calculations that indicate the air trapped in the salt mine when the shafts were sealed was subsequently compressed by a combination of natural salt-creep closure of the salt mine and groundwater migrating into the mine. On the day of the incident, the shaft seals apparently failed, and the compressed air blasted from the suddenly opened shaft. For several minutes, the speed and volume of the escaping air were enough to accelerate bricks high into the air. Surface sand and water were blown skyward for an even longer period while the air stream's speed slowed as the air pressure was reduced in the mine. The calculations and interpretations that explain this unusual salt mine incident involve rock mechanics and salt creep, two-phase fluid flow, air compression and storage, air velocity through a mine shaft, and calculating the drag and gravitational acceleration of bricks in a high-velocity air stream. The case study is both interesting and technically informative as regard to possible consequences of salt mine abandonment and compressed-air storage.

Keywords: compressed air, abandoned salt mine, creep, shaft seals

INTRODUCTION

On Thursday, October 26, 2000, the Acme Brick factory in Kanopolis, Kansas, was substantially destroyed by falling bricks, sand, and water blown skyward by a plume of compressed air. Eye witness summaries were that bricks were blown more than 100 meters (m) into the air from an abandoned mine shaft next to the factory. Initial opinions were that either the shaft into the abandoned salt mine had collapsed, compressing the air in the mine and causing an expulsion of the compressed air, or the entire salt mine might be progressively collapsing and displacing the air from the mine, causing “bricks to fly.” A critical question by public officials was whether or not the town of Kanopolis (partially located directly above the mine) needed to be immediately evacuated to avoid endangering lives by the subsidence that would inevitably follow a mine collapse. Acme Brick Company, owners of the destroyed brick factory, asked for a rapid assessment of the incident and recommendations for immediate and future actions to avoid endangering the public and to reassure the public about any long-term consequences of the incident.

BACKGROUND

The following descriptive details were gathered during the investigation:

- A few minutes before the event started, brick factory workers noticed a slow rolling (“tinkling”) of bricks on the bat pile (a “bat pile” is a large pile of discarded and broken bricks that had accumulated next to the factory).
- Slumping (downward movement) of bricks on the side of the bat pile occurred a few seconds before anything started to rise.
- The transition from “quiet” to violent occurred in just a few seconds.
- Bricks, sand, and water were blown at least 30 m into the air (judged against the top of a nearby grain elevator) and perhaps higher than 100 m.
- Bricks and sand were blown into the air for longer than 5 minutes but less than 20 minutes; the most common estimate is 8 to 10 minutes. Water may have been blown into the air for as much as 1 hour. The air-blown plume of materials was visible from several kilometers away.
- Some surging of the air-borne plume was noted, particularly toward the end of the event.
- Varying degrees of a “sulfur” odor were mentioned by some witnesses, but the absence of any odor was claimed by others.
- The crater created around the mine shaft was initially “horseshoe-shaped” toward the east-northeast, rather than circular.
- No witness mentioned any strange tumbling noises or thumping sounds before, during, or after the incident. Tumbling or thumping sounds are typically mentioned over mines with failing pillars.
- The interconnected Royal and Crystal salt mines were abandoned in 1948 and the shafts were filled at that time. The top of the Hutchinson salt is at 195-m depth, and the mines were at the bottom of the Hutchinson Salt Member (depth of about 245 m). The rock above the salt is predominantly shale. A near-surface deposit of sand (about 10 m thick) is the groundwater aquifer.
- The brick factory was built in 1954 and was still operating over the mine site.

The photograph in Figure 1 shows an aerial view of the crater and collapsed portion of the brick factory taken within hours after the event. A railroad boxcar is sitting next to the crater; later, the crater extended under the railroad tracks and the boxcar fell in to the crater. The rectangular-shaped pile of material surrounding the crater is the "bat pile," which is a pile of broken or discarded off-color, or experimental, bricks. The material that collapsed the building was primarily bricks and wet sand that blew up and over the railroad car and then fell and landed on the building's roof.

Figure 1. Aerial Photograph of Demolished Brick Factory, Brick Pile, and Blown-Out Shaft.

The fallout pattern for the falling material was quite directed, as most of the material ended up on the building or in the parking lot shown in the lower left corner of the photograph. The vehicles in the parking lot were severely damaged. Fortunately, most of the workers were in the lunchroom (center of the lower part of the photograph) at the time and the lunchroom was outside the major fallout area and the roof was substantial enough to protect the workers. Virtually no flying material was directed toward the areas shown at the sides or top of the photograph. It was later determined that the air stream escaping the shaft was deflected by bricks sliding from the bat pile and into the crater and by partial blockage of the shaft by its timber lining.

A series of displacement and tilt measurements several hours after the event did not detect any ongoing movement. Surveys Inc., a local surveying firm from nearby Ellsworth, Kansas, installed a line of subsidence benchmarks on both sides of the crater. Several measurements around the crater using a portable electronic tiltmeter were made to detect any "rapid" ongoing tilting around the crater. The tilt pads (which were bricks tamped into the soil) were left in place for subsequent measurements of changes in tilt. String extensometers were built between three of the subsidence benchmarks nearest the crater to detect any horizontal soil movement toward and into the crater.

Repeated elevation surveys over the next several days measured no systematic subsidence on either side of the crater. No benchmark had an elevation change greater than ±3 millimeters (mm), which was the resolution of the elevation survey. Remeasurements with the electronic tiltmeter gave readings similar (±0.02 arc degree) to those measured previously. The string extensometers indicated no detectable horizontal movement of the ground surface on the south side of the crater over a 4-day period.

Soon after the event, water was flowing down the sloping sides of the crater. Estimates of the inflow rate were about 1 cubic meter per hour (m^3/hr), although visual inflow-rate estimates are notoriously inaccurate (±100 percent). Additional streams of water were exposed as soil, sand, and brick continued to slump into the shaft.

Inspection of the concrete retaining walls near the crater detected no recent cracks, and the old cracks noted in the wall the day after the event did not increase in number or expand in aperture over the next several days. The old cracks were marked with spray paint, so any unpainted cracks could be identified as new cracks.

During the 24- to 48-hour period after the event, the lack of detectable movement, tilts, surface cracking around the crater, and cracking in the concrete retaining walls pointed toward a conclusion that the event was over—the mine was not progressively collapsing. An alternative hypothesis was put forth that the air in the mine had become compressed and had vented itself through the old mine shaft at a tremendous speed sufficient to carry bricks and sand high into the air. The remainder of this paper describes the analysis undertaken to substantiate the hypothesis and reconcile it with the witness observations. Finally, the replugging of the shaft is described.

ANALYSIS

The observations and the gathered evidence do not support either of the earliest hypotheses that the shaft had collapsed or that the mine was collapsing. The hypothesis to be analyzed was that groundwater had apparently entered the mine through the shafts over a long time and compressed the air within the mine[1]. As water permeated down through the sand, soil, and salt-filled shaft(s), the saturated porous fill prevented air from escaping upward. Alternatively, the shafts into the mine may have only remained filled near the surface but above the water table, which is located about 10 m below ground level. Therefore, despite being "sealed" at the surface, water could have easily entered the mine through any or all of the shafts from both shallow and deep water-bearing strata, but air would have been prevented from escaping.

[1] The mine was abandoned and its shafts were sealed by filling them with sands, clays, and salt.

The incident during October 2000 occurred at the escape shaft for the Crystal/Royal mine. About 30 years earlier, during 1971, a sinkhole developed over the mine's main shaft (about 110 m from the escape shaft), and that sinkhole had maintained a water level in it about 4.5 m below ground surface. Slow water leakage through the main shaft might have occurred ever since (and even before) the sinkhole, and replenishment of water from the near-surface aquifer was adequate to maintain a steady water elevation in the sinkhole, despite leakage into the mine. As well, a third shaft into the mine (a backfilled airshaft) to the northeast of the brick factory could also have contributed to water leakage into the mine.

A Kansas Geological Survey report [Walters, 1978] on the collapse of the production shaft in 1971–1972 does not supply significant details on just how the shafts were plugged and abandoned but does give information on the geological and hydrological setting. The concrete shaft-collar structure was either removed or the top of the shaft was imploded as part of the filling process in 1948 because there was no evidence of a shaft collar after the incident. The shaft fill had apparently washed out of the shaft and into the mine, because no material was found on the buildings or parking lot that was significantly different from the sand, bricks, and shale rock exposed in the crater.

The Independent Salt Mine shaft pilot-hole log from about 2 kilometers (km) away shows indications of water at the seven depths: three depths are near surface (<11 m), consistent with observations in the crater at the brick factory. The four deeper water sources are at 41-, 56-, 100-, and 191-m depths—depths that were well beyond our vision down the shaft. The total shaft-water inflow currently at Independent Salt is 1.1 m^3/hr through their timber-lined shaft.

In an old Royal mine diary, an interesting comment is made that a leak through the timber was "calked" (chalked) to stop a leak that was squirting into the shaft. The timber shaft lining must, therefore, have been snuggly installed with the intention of being watertight.

Based on an old (1939 vintage) mine map provided by Independent Salt, the combined Royal and Crystal mines area was about 90 hectares. The extraction ratio and mined height given by Walters [1978] for the Crystal mine are 70 percent and 2.7 m, respectively[2], which agree with the historical extraction ratio and mined height for the adjacent Independent Salt Mine.

Based on a 1935 excavated area of 223 hectares, an extraction ratio of 70 percent, and a room height of 2.7 m, the as-mined volume of the mine was 1.7 million m^3. As a reality check, this volume corresponds to salt production of 3.7 million metric tons, or an average annual production rate of 127,000 metric tons/year for an assumed production period of 1905–1935. If mining continued beyond 1935 to 1947 (12 more years) at the same rate, the total as-mined volume would have been 2.4 million m^3 (5.2 million tons of

[2] An "11.5-ft" (7.2-m) height is shown on the 1935 mine map, but it probably refers to the height of the shaft station, which is often taller than the rest of the mine to accommodate the loading and unloading of materials at the shaft.

salt). These are very believable numbers for a Kansas salt mine early in the twentieth century.

The volume of a salt mine changes with time, even after mining stops. The salt pillars in the mine undergo continual shortening by the deformation process called creep. As the pillars shorten, the salt in the pillars expands horizontally into the open room and begins to fill the room. Also, as the pillars shorten, the roof and floor come closer together. The net result is that the volume of a salt mine is ever diminishing until it closes completely. Based on Kansas salt mine experience (mines which are remarkably similar) and conversations with colleagues, about 0.25 percent of the mine volume will be lost per year on average. Therefore, an estimated 18 percent of the mine volume (0.44 m^3 of the 2.44 m^3) was lost to closure during an average mine life of 75 years between 1905 and 2000.

Water probably entered the mine throughout its life. Anecdotal evidence suggests that part of the mine volume was flooded even before closure. As stated before, the Independent Salt Mine has a current inflow rate of 1.1 m^3/hr in the form of leakage through the shaft lining. Using a 0.9 m^3/hr combined shaft inflow rate (about 8,000 m^3 per year) as a basis, between 1948 and 1972, about 0.2 million m^3 of water might have entered the mine, further reducing the open volume to 1.9 million m^3. In 1972, a sinkhole developed over the main shaft, and any trapped and compressed air in the mine was possibly vented based on descriptions presented by Walters [1978].

After 1972, air could not escape from the mine, and both the water entering the mine and natural creep closure compressed the air trapped in the sealed mine. When the compressed air was suddenly released from the mine through the shaft, its speed was determined primarily by the pressure in the mine. The duration of the expulsion depended on the pressure and the volume of compressed air. Early on, the air speed out of the shaft orifice was fast enough to carry bricks upward perhaps as high as 100 m. As evermore air escaped, the mine pressure reduced and the escaping air speed subsequently reduced such that the air stream could only carry water and sand, but not bricks. The air stream speed further decreased to where only water could be carried.

An analysis was performed to determine the required volume of air and air pressure to expel bricks and sand from a crater consistent with the observations. The basic model was that of a container of compressed air (the mine) and connected to a 240-m-long tube (the shaft) where the air expands into a plume after exiting the tube (crater and above). The shaft had inside dimensions of about 3.6 m by 5.2 m, was wood timber lined (friction factor = 110), and open (except for the uppermost 10 m of fill material above the water table). This uppermost section of filled shaft acted as an airtight seal that held back an unknown volume of air compressed within the mine at an unknown pressure. Using standard mine ventilation equations, the calculated initial air speeds through the shaft are shown in Figure 2 for a range of mine pressures.

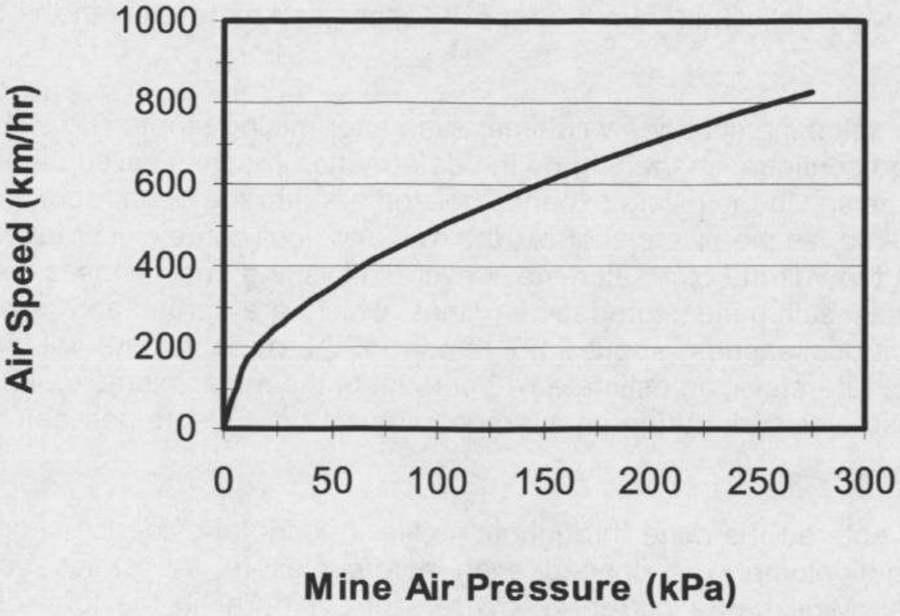

Figure 2. Air Speed in a 3.6- by 5.2-m Rectangular Shaft for a Range of Pressures.

The initial volume of compressed air (at a particular pressure) determines the duration of the expulsion of air. For the 3.6- by 5.2-m timbered shaft described above, the lengths of time for the air speed to drop to 160 kilometers per hour (km/hr) are shown in Figure 3 for ranges of mine volume and mine pressure. From the witness accounts, the shaft blew air vigorously for at least 8 to 10 minutes.

An analysis was also performed of the dynamics of a brick in a high-velocity air stream. Basically, the analysis calculated the upward drag force (lifting) on a rectangular mass compared to the downward gravitational force. The difference between these forces is the acceleration of the mass (net force = mass times acceleration). The drag force is not constant because the air stream expands as it moves away from the orifice, and the air speed is reduced as the area of the air stream increases. For simplicity, assume that the expanding air stream can be approximated by bounding straight sides and an included angle. The air speed leaving the shaft, the brick size and density, and the air stream expansion angle are variables. The calculated result is the height the brick is propelled as a function of time in the air stream, particularly the maximum height before it begins to fall. Other variables in the calculation include the gravitational constant (9.8 m/sec/sec), brick density (1,760 kg/m^3), drag coefficient for cylindrical body at high Reynolds number (2.), and density of air (1.2 kg/m^3).

Figure 4 shows the height that the 3.6- by 5.2-m air stream could theoretically propel 66- by 66- by 230-mm bricks for three air stream expansion angles over a range of air speeds. Witness observations are that bricks were carried to heights perhaps as high as 100 m.

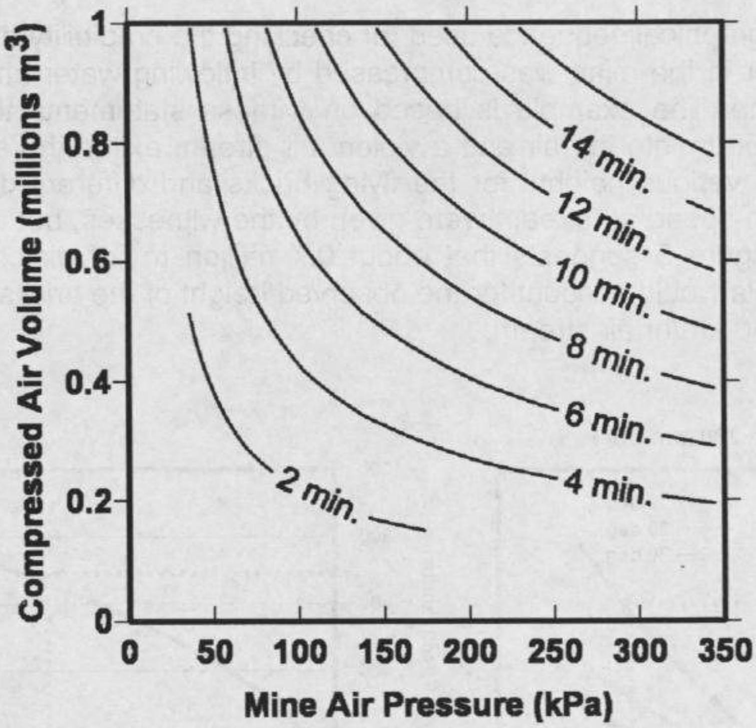

Figure 3. Time Required (Minutes) for Air Speed to Diminish to 160 Kilometers per Hour.

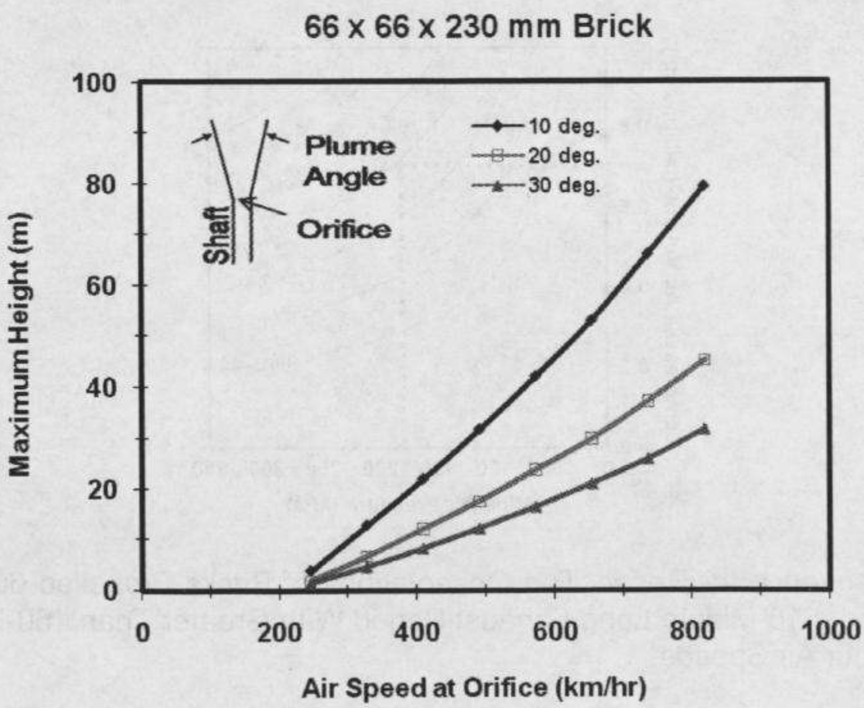

Figure 4. Calculated Height an Air Stream Can Propel Bricks for Three Plume-Expansion Angles to Account for Slowing of the Air Speed.

Figure 5 shows a graphical sequence used for checking the credibility of the hypothesis that the trapped air in the mine was compressed by inflowing water and natural creep closure of the mine. The example is based on witness statements that bricks were propelled at least 50 m into the air and a violent air stream exited the shaft for at least 10 minutes. (Note: various heights for the flying bricks and different durations for the duration of the high-speed air stream were given by the witnesses, but this combination was common.) Figure 5 suggests that about 0.7 million m^3 of air compressed to a pressure of 175 KPa would account for the observed height of the bricks and duration of the greater than 160-km/hr air stream.

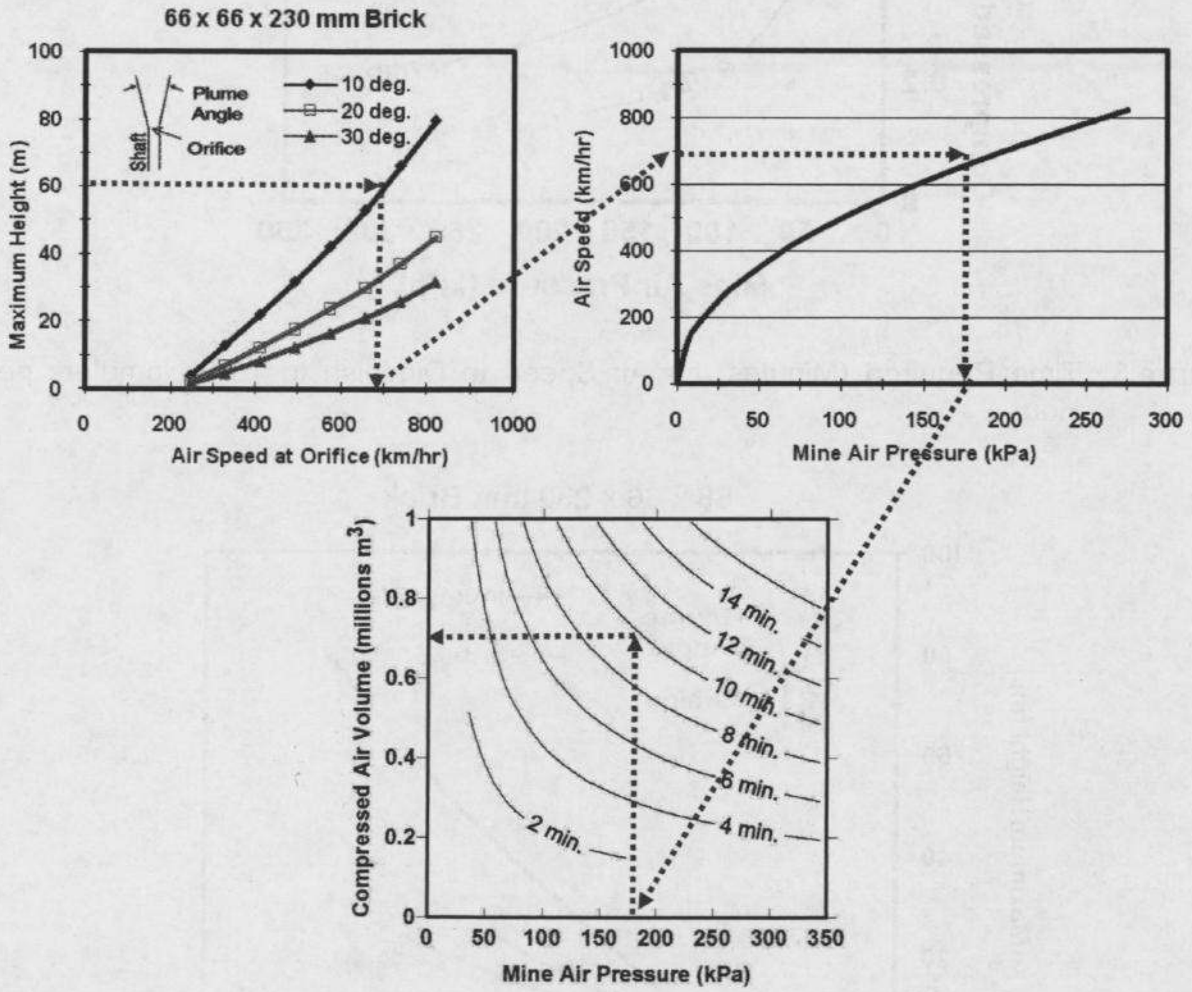

Figure 5. Sequence for Reconciling Observations of Bricks Propelled 60 Meters High and a 10-Minute Long Exhaust Period With Greater Than 160-Kilometer-per-Hour Air Speeds.

Table 1 presents an accounting of the mine, water, and air volumes involved. The original as-mined volume of the mine equals the original air volume. Water leaked into the mine even while the mine was in production, but it is not known if this water was pumped or evaporated into the ventilation. Creep closure is based on current closures in other Kansas salt mines. An assumption is made that any trapped air was vented by the 1972 sinkhole, but that even more water could enter the mine from the sinkhole. The volume accounting substantiates that the 0.7 million m^3 of compressed air at 175 KPa is realistic with a 70 liters per minute (l/min) leakage rate from 1972 to 2000.

Table 1. Calculation of Free Air and Compressed Air Volumes Throughout the Mine History Accounting for Creep Closure, Leakage Into the Mine, and the 1972 Sinkhole

	m^3
Volume of Salt Mined (Mine Volume)	2,440,000
Creep Closure (1905–1948) @ 5 mm/yr	(110,000)
Water Into Mine (1905–1948) @ 7.61 l/min	(180,000)
Free Air Volume in 1948	**2,150,000**
Creep Closure (1948–1972) @ 5 mm/yr	(180,000)
Water Into Mine (1948–1972) @ 15 l/min	(90,000)
Free Air Volume in 1972	**1,880,000**
Creep Closure (1972–2000) @ 5 mm/yr	(140,000)
Water Into Mine (1972–2000) @ 72 l/min	(1,070,000)
Compressed Air Volume in 2000	**670,000**
Compressed Air Pressure in 1972	14 kPa
Compressed Air Pressure in 2000	172 kPa

SHAFT CLOSURE AND SEALING

Closing or resealing the salt mine shaft was required: (1) to prevent anyone or anything from entering the shaft either intentionally or accidentally (shaft closure) and (2) to prevent the ongoing inflow of fresh water to the mine from a location so near the brick factory (shaft sealing). Sealing the shaft was considered mandatory before the factory could be reopened and operated. Basically, unless the mine was intentionally flooded with fresh water or salt-saturated brine, backfilling the shaft with impermeable material (at least partially) was the only viable way of potentially heading off additional (future) damage to the factory site. Without such actions, the risk was too great of continuing deterioration of the shales and siltstones and possibility of a major sinkhole. While slowing the inflow would not alleviate the long-term risk, enough time could be bought to recover the investment required to reopen the factory.

As long as the shaft was unsealed, the fresh water falling down the shaft was unequivocally dissolving salt. This salt would be dissolved either around the shaft from the top-of-salt downward toward the mine or from pillars within the mine, or both. Removal of salt along the shaft would have produced an ever-wider void centered on the shaft. If the void became large enough, the undercut shale above the void would be unsupported and susceptible to failure. Any shale failure into the shaft could initiate a progressive upward stoping of failing rock that could propagate to the surface. The result would then be a sinkhole on surface, the size of which would be determined by the area of undercutting. Conceivably, the diameter of a sinkhole could approach 60 m or more, or about twice the diameter of the crater.

Not withstanding the problems of salt dissolution around the shaft, dissolving salt from pillars within the mine would cause subsidence effects on the surface. The effects could range from an inconsequential acceleration of the surface subsidence, to disruptive differential subsidence within the brick factory area, to the unlikely loss of pillar support over an area wide enough to cause an overburden collapse and sinkhole. Because the mine was filling with fresh water, about one volume of salt was being dissolved for every six volumes of water that entered the mine. Therefore, a large volume of salt was susceptible to being dissolved—a mine volume of 0.7 million m^3 is suggested in Table 1; therefore, an additional 0.1 million m^3 of salt might be dissolved. Little information was available on the exact pillar configuration and the local dip and elevations within the mine. Consequently, it was unknown if the dissolution would be concentrated within the shaft area (and consequently, under the brick factory area) or be diffused over a wide area of the mine.

Inferences of what could happen with continued fresh water entering the mine were based on this author's personal experience at the Retsof salt mine in western New York (e.g., Van Sambeek et al. [2000]) and case histories of sinkholes over solution mines in the Hutchinson, Kansas, area (e.g., Dyni [1986]). At Retsof, a direct correlation was determined between the inflow of fresh water and short-term surface subsidence over the inflow location and downdip along the water flow path. The surface at Retsof subsided 6 m even outside the sinkhole areas, which was directly over the inflow locations. Within a 400-hectare area, the subsidence rapidly diminished from this 6 m, but the subsidence was still as much as 0.6 m up to 1 km away from the inflow location.

Because of these concerns, the shaft had to be filled or plugged to arrest or significantly postpone the effects of dissolution. Sealing the shaft in a watertight manner was a real challenge because of the ongoing water inflow and unstable nature of the ground within the crater and around the shaft throat. Ideally, the shaft would have been inspected, timbers removed at selected locations, alternating layers of engineered sealing and structural materials emplaced, and the shaft capped to preclude any surface settlement. Less ideally, natural sealing materials (bentonite, clays, asphalt) and immobilized structural fill would be emplaced. At a minimum, but with less likelihood of success in completely blocking the water in the long term, the shaft could be backfilled with coarse material (boulders, concrete riprap, or bricks), and grading toward a finer material, with final completion being a layer of contained clay near the surface but below the deepest aquifer.

The shaft was sealed by constructing a slurry wall around the shaft to slow water flow into the shaft followed by placing an immobilized granular fill covered with bentonite as the natural sealing material. The granular material was wetted on the surface and the free-falling material compacted itself at the base of the shaft. After filling the base, additional granular fill and several bentonite layers between layers of granular fill were used to form a water-tight plug within the confines of the shaft. Recognition was given to being unable to effect any plugging or sealing behind the timber lining or in the disturbed rock zone immediately outside the shaft timbers.

Another similar-sized venting of air is not possible. The free air volume in the mine when the shaft was plugged was probably less than 0.7 million m^3. In order for this air to again be displaced by enough water to compress the air to a reasonably great pressure, the resulting compressed air volume will be too small to sustain even a few minutes of high-speed air. The risk for a short-term event remains—but such an event is deemed unlikely.

SUMMARY

The catastrophic event and its analysis indicate a substantial amount of water had flowed into the interconnected Crystal and Royal salt mines through one or more of their inadequately sealed shafts. The inflowing water displaced and compressed the air trapped in the mine. The compressed air was suddenly released on October 26, 2000. The speed at which air exited the mine was fast enough to carry bricks, sand, and water into the air to observed heights greater than 100 m for several minutes. The bricks and wetted sand fell on the brick factory and their accumulating weight collapsed the roof.

This summary is bolstered by reliable statements that the mine shafts were filled from bottom to top with sands, clays, and salt in 1948. Such fill would not have prevented water from permeating down the shafts but, apparently, the combination of saturated, porous fill and downward moving water did prevent air from percolating upward and escaping. A sinkhole during 1971 over another of the mine's shafts may have both vented any compressed air trapped in the mine at that time, but more importantly, opened an even more permeable pathway for water to enter the mine. Despite that the actual pathway or means for water to enter the mine will never be known, a release of trapped air compressed by inflowing water and supplemented by creep closure of the mine seems the most logical explanation for the event and is in technical agreement with witness observations and measurements.

ACKNOWLEDGEMENT

The author acknowledges Acme Brick Company, Fort Worth, Texas, for allowing publication of this case study paper.

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