The link between artificial ground freezing and the mining industry stretches back more than 140 years, and across an ocean. Patented by the German scientist F.H. Poetsch in 1863, the technique is reported to have first been used circa 1862 in the coal mining valleys of South Wales.

In the United States, the first ground freezing application, to a depth of 30 m (100 ft), occurred in 1888 for the Chapin Mine Co. in Iron Mountain, MO.

In England in 1901, the Poetsch method was used for the first time to successfully sink two shafts through 24 to 27 m (80 to 90 ft) of wet sand and boulder clay at the Washington Glebe Colliery, near Sunderland. British mining engineer T.H. Cockin, in his 1905 *Class-Book of Practical Coal-Mining*, noted that, “This method of sinking through thick beds of very wet quicksand has met with great success; it is one of the recognized methods of sinking on the Continent.”

Mine shaft freezing soon became relatively common in Europe where the project could bear the cost of a major refrigeration plant construction. However, it was not until 1952 that the second North American ground freezing project was completed to facilitate the sinking of a 4.5-m- (15-ft-) diameter, 233-m- (765-ft-) deep shaft at a Potash Company of America (PCA) mine in Carlsbad, NM.

Nowadays, ground freezing is used worldwide for both mining and civil applications. In small mine shafts of 3 to 6 m (10 to 20 ft) in diameter, excavations have been carried out to depths of more than 820 m (2,700 ft) within the protection of unbraced or unlined frozen walls. In fact, for deep mines, no better method has yet been established for sinking production shafts through deep, water-bearing ground. Major deposits of coal, potash and salt would still be inaccessible if not for artificial ground freezing.

There are several advantages of ground freezing unique to the construction of shafts. Proper instrumentation can provide complete assurance of the integrity of the freeze to full depth prior to excavation. The frozen wall allows construction to be scheduled without evaluating the in-shaft time necessary to probe ahead, place additional supports or deal with ground water. The freeze can be implemented perfectly through the soil/rock interface, which is often the most difficult geology in which to create a ground water cutoff by other methods. At increasing depths, any discontinuity...
in a temporary support system can be difficult to rectify unless the hydrostatic head is externally relieved, a task that cannot practically be achieved at depth. A frozen wall, by design, is continuous into the underlying cutoff and resists the loads imposed by full ground water and soil pressures.

If there is a disadvantage to ground freezing for the construction of shafts it is that specialized equipment must be used for the excavation of the frozen ground. With continued operation of the freezing system, the frozen ground will encroach further within the shaft excavation at greater depths. In deep shafts, it is common for the entire cylinder to freeze solid. Excavation is either by roadheader or by careful drilling and blasting.

**Basic concepts still valid**

The basic concept behind 21st century ground freezing is the same as that developed by Poetsch. When in situ pore water is frozen, it acts as a bonding agent, fusing together particles of soil or rock to create a frozen soil mass with markedly improved compressive strength and impermeability.

While advanced refrigeration technology has refined modern efforts, the core method of achieving the freeze still dates back to Poetsch. Small-diameter, closed-end freeze pipes are inserted into vertical drilled holes in a pattern consistent with the shape of the area to be improved and the required thickness of the wall or mass. As the cooling agent, typically chilled brine, is circulated through the pipes, heat is extracted from the soil, causing the ground to freeze around the pipes. The brine is returned to the refrigeration plant where it is again cooled. The frozen earth forms around the freeze pipes in the shape of vertical, elliptical cylinders. As the cylinders gradually enlarge, they intersect to form a continuous wall. With heat extraction continued at a rate greater than the heat replenishment, the thickness of the frozen wall will expand with time. Once the frozen wall has achieved its design thickness, the freeze plant may be operated at a reduced rate to maintain the condition during shaft excavation and liner placement. Monitoring of conditions during formation and maintenance is accomplished by temperature sensors installed at various levels in monitor pipes located strategically along the frozen wall. Following excavation and completion of the construction, refrigeration is discontinued, allowing the ground to return to its normal state.

While the principle behind the ground freezing process may appear simple, proper execution of the work, particularly at depth, is complex. Successful freezing operations require a specialist who must be skilled in refrigeration and in analysis of thermal problems. And this specialist must be experienced in ground water flow and geotechnical engineering. Understanding of the strength and behavior of frozen earth is vital.

The alignment of freeze pipes is critical to the satisfactory performance of the ground freezing system. The design, both as to strength and time of forma-
tion, is directly related to the spacing between pipes. If the pipes are permitted to deviate too much, unexpected windows or zones of less than design thickness can occur.

Borehole deviation is more significant for deeper work. For deep mine shafts, specialized guided drilling techniques can be employed, using locating and steering techniques similar to those used for directional drilling. A down-hole mud motor, mounted on a slightly angled flange at the end of a drill string that does not rotate, uses the drilling fluid to power the bit. The hole is surveyed concurrent with the drilling. As the drift is observed, the direction is changed by an angular adjustment of the drill string. In effect, a series of small deviations occurs within the target radius. With this method, holes as deep as 790 m (2,600 ft) have been kept within a tolerance of several feet.

Along with borehole surveying for deviation, there are other quality control measures essential to successful shaft freezing. Instrumentation, including temperature monitoring points such as borehole thermocouples or resistance temperature detectors, must be installed to confirm adequate frozen ground propagation.

The system must be leak-free. The loss of brine into the formation being frozen can result in “windows” that cannot be located by temperature monitors. The water pressure within the unfrozen core of the shaft must be relieved by a pressure relief well as the freeze continues to grow inward and the encapsulated water expands with the phase change. The relief hole also will indicate when closure of the frozen wall is achieved.

Piezometers must be installed to measure ground water gradients. Brine temperatures must be monitored to confirm proper output from the plant and heat extraction from the ground. All of these measures together are essential to confirming the single, overriding project criterion — that the ground water on the inside of the shaft is isolated from the ground water on the outside.

Concreting against frozen ground

For shafts, the lining may be placed concurrent with the advance of the shaft sinking (top down) or once the excavation is complete (bottom up). Concrete walls have traditionally been cast against frozen strata. A rule of thumb used for many years was to increase the design thickness of the concrete by several inches. A proper balance will be achieved between the heat generated by the concrete and the heat extracted by the freezing process with the placement of a minimum thickness of concrete. The heat balance will be such that the heat of hydration of newly placed concrete will thaw, to some depth, the adjoining frozen ground.

**FIG. 3**

Roadheader commonly used for excavation of frozen ground.

**FIG. 4**

As ground freezing technology advanced, portable brine refrigeration units, such as this, were developed, allowing ground freezing even in restricted areas.
earth. Depending on the rate of release of the cement’s heat of hydration, a thermal equilibrium will eventually be reached after which the ground will slowly refreeze, followed by a progressive freeze of the concrete itself. But, before the freezing temperatures propagate through the new concrete, the designed thickness of the concrete wall will have hydrated sufficiently to achieve its initial set. The concrete will continue to cure at a reduced rate when frozen.

**Noteworthy projects**

While a discussion of the principals behind, and execution of, the freezing process is undoubtedly useful to mining engineers and mine owners, the following projects, which represent just a handful of the many successful applications of the technique, provide the best testimonial.

**Strategic Petroleum Reserve, Weeks Island, L.A.** More than 7.6 GL (2 billion gal) of crude oil has been stored at the U.S. Department of Energy’s Strategic Petroleum Reserve in Weeks Island, L.A. The oil has been stored in an abandoned salt mine cavern 175 m (575 ft) below the surface for more than 20 years.

During routine inspection, a 9-m (30-ft-) diameter surface sinkhole was discovered above the cavern, indicating erosion to the protective salt dome approximately 60 m (200 ft) below the surface. This was determined to result from leakage of the overlying fresh water aquifer through mine-induced fractures in the salt. Additional investigations indicated that the ongoing leakage flow of 11 L/min (3 gpm) was displacing approximately 3 m³/d (4 cu yd/day) of material.

Since similar fresh water leaks in other salt mines had resulted in rapid erosion and subsequent mine failure, concern about the preservation of both the environment and the oil reserve led to decommissioning of the site. During the five-year period required to pump out the oil and close the site, it was essential to halt further deterioration. Ground freezing was selected over permeation grouting for this operation since it was suited to the highly disturbed ground conditions, variable geology, complex ground water chemistry and access limitations at the sinkhole.

The intent of the ground freezing program was to form two protective structures. The first was a cylinder of frozen soil seated down into solid salt. It was designed to prevent further ground water inflow into the sinkhole area and afford emergency structural support to the surrounding soils in the event of further significant ground subsidence. The second, and ultimate, objective was to create a more energy-efficient massive frozen soil cap about 20 m (70 ft) in diameter and 10 m (32 ft) thick over the entire sinkhole/salt interface to prevent further erosion for the duration of the oil removal.

Thermal analyses were performed using a finite element ground freezing model to arrive at the optimum freeze pipe configuration, evaluate freeze wall growth and estimate thermal loads to meet project schedule demands. From these analyses, a final design was arrived at. It consisted of:

- An outer ring of 22 pipes installed on a 16-m (54-ft-) diameter circle and drilled and socketed into the salt to ensure a positive freeze/salt seal.
- A middle ring of 22 pipes installed to the top of salt on a 14.5-m (48-ft-) diameter circle. Together with the outer ring, it provided the formation of the cylindrical freeze with adequate thickness to temporarily support full-depth soil loading in the event of complete collapse of the interior sinkhole backfill material.
- An inner ring of 10 freeze pipes on a 12-m (40-ft-) diameter circle installed into the backfill of the sinkhole itself to propagate growth of the freeze inward and form the solid plug of frozen material inside the frozen cylinder over the sinkhole throat.

Seven monitor holes were also installed within the frozen soil limits to gather piezometric and temperature...
data to demonstrate the rate of growth and final integrity of the frozen structures. The formation of the full depth cylindrical freeze and the “ice cap” required 3.5 and 10 months, respectively, very close to the model values.

Cote Blanche salt mine, Cote Blanche, LA. A niche for ground freezing has long existed in southern Louisiana. This is where massive salt deposits, known as salt domes, are overlain by the loose, wet silts and sands of the Mississippi Delta. For vertical shaft construction, ground freezing is the preferred method of ground support, promoting ideal conditions to construct the shaft “in the dry.” However, before the thaw, absolute water tightness must be established in the concrete liner. Otherwise, any seepage will dissolve salt from behind the shaft lining, increasing the leakage path and ultimately flooding the mine. Salt mines have been lost this way.

Cote Blanche, on the Gulf of Mexico, is one of the prominent salt domes known as the Five Islands and is one of only three remaining active salt mines. Ground freezing was used to sink a new 5-m-(16 ft-) inside diameter production shaft 138 m (455 ft) below the surface. Subsurface soils consisted of sands and gravels saturated with brackish water to a depth of 106 m (350 ft), overlaying a 21-m (70-ft) thick stratum of sandy clay. Variable disturbed soils were present from 128 m (420 ft) to top of salt. There, the granular soils contained a saturated salt solution with a freezing point of -21° C (-6° F).

A freeze wall 3.6 m (11.8 ft) thick was required to resist soil and ground water pressures in the salt contact zone. To achieve this, 35 freeze pipes and monitors were drilled to a depth of 150 m (500 ft) on a 10-m- (33-ft-) diameter circular pattern. To freeze the salt-saturated sand, it was necessary to chill the calcium chloride brine coolant to a relatively cold -37° C (-36° F). A freeze plant with 50 percent greater capacity than normal was employed and maximum power maintained until the permanent concrete lining had been constructed to a depth of 167 m (550 ft), 29 m (95 ft) into solid salt.

White County Coal, Carmi, IL. White County Coal has been a leading producer in the Illinois Coal Basin since 1983. When the company initiated construction of a new facility to access additional recoverable reserves about 245 m (800 ft) below the surface, it was important to maintain a stable, dry excavation for the sinking of a service shaft 11 m (37 ft) in diameter.

The subsurface profile at the shaft location consisted of 36 m (120 ft) of loose, saturated sandy soils overlying an approximately 40-m- (140-ft-) thick layer of Mount Carmel sandstone, a major regional aquifer. Beneath this was an impervious shale stratum. Ground water was just 2.4 m (8 ft) below grade. Ground freezing was the method of choice to ensure the stability in the overburden soils during excavation and to control ground water inflow through the overburden and the underlying sandstone.

The ground freezing program called for more than 40 freeze pipes to be installed around the circumference of the proposed shaft to a depth of 90 m (300 ft), terminating in the shale stratum that acted as a lower ground water cutoff. Less than four months after freezing was initiated, a 2-m- (7-ft-) thick frozen perimeter wall had been created, allowing excavation to begin.

Kansas Underground Salt Museum, Hutchinson, KS. Carey Salt is no stranger to the innovative uses of abandoned portions of its active Hutchinson Mine in Reno County, KS. Under a lease agreement, converted caverns deep below the surface have provided safe, environmentally stable, underground storage facilities for sensitive information and assets since 1959. Now the Reno County Historical Society is poised to unveil another novel Hutchinson Mine attraction — the Kansas Underground Salt Museum. Visitors will be transported 200 m (650 ft) underground by a double-deck elevator. Ground freezing was the method of choice to stabilize more than 40 m (135 ft) of sand and wet mudstone overburden to ensure completely dry and stable elevator shaft excavation.

The 115-mm- (4.5-in.-) diameter steel freeze pipes were installed through the overburden to a depth of 40 m (135 ft) around the proposed shaft perimeter and passed through weathered mudstone into the underlying shale to

FIG. 6
Excavation of the White County shaft by a muck chute.
ensure that the freeze continued through the critical soil/rock interface. The temporary frozen wall, a minimum of 1.8 m (6 ft) in thickness, was formed by circulating calcium chloride brine chilled to -31° C (-25º F). The freeze was formed in 28 days. The nominal 4-m- (14-ft-) diameter shaft was excavated by Thyssen Mining and the 0.6-m- (2-ft-) thick permanent concrete liner was placed.

Underground excavations in salt must always be completely isolated from ground water or catastrophic failure can occur. In the shallow rock, special water seals were, therefore, placed in and behind the concrete shaft lining so that once freezing was discontinued and the ground had thawed, ground water could not seep down into the soluble formation below.

**Gibson County coal mine, Princeton, IN.** Gibson County Coal is expanding its mining operations near Princeton to access additional coal reserves. Construction operations include the sinking of the North Portal No. 2 shaft. This 8.5-m- (28-ft-) inside diameter vertical service shaft will end about 170 m (550 ft) below ground. However, more than 30 m (100 ft) of saturated soils, (most of them sands lying within the flood plain of the Patoka River) overlie competent coal-bearing rocks at a depth of 35 m (115 ft). The mine owner specified ground freezing to stabilize the overburden soils during shaft excavation and liner placement.

Piezometer readings taken during a pre-freeze 40-day period revealed abrupt changes in water levels within the sand aquifer, corresponding to water level fluctuations in the volatile Patoka River, a half-mile away. To protect the project from seasonal flooding, the owner specified the construction of a raised collar to prevent inundation of the shaft with a flood. This work was completed before the freezing installation. The prime supply and return pipelines were located in a gallery built around the shaft collar and safely above the natural ground surface, which was, in fact, inundated for a brief period during the formation of the frozen wall. The freezing design called for approximately 40 freeze pipes, plus an array of piezometers and temperature monitors, installed through the overburden soils and extending 4.5 m (15 ft) into the underlying sound rock.

Ground freezing began in November 2006 and closure was confirmed in December. Shaft sinking by Frontier-Kemper, the prime contractor, is now well into the rock, having penetrated the frozen section without incident.

From the first applications up to the present day, ground freezing has consistently proved to be the best, if not the only, solution for deep shaft sinking through saturated or otherwise challenging subsurface conditions. This has been borne out through numerous successful projects worldwide, both in the mining and civil engineering industries.