the outside pipe. With the first circulation of the refrigerant, temperatures drop very rapidly; but as the freezing point of the material is approached, the rate of change of temperature slows down considerably. Wet or moist sand often freezes as hard as many types of rock and has a compressive strength of a dependable and determinable value in the frozen arch ring. Silts are somewhat slower to freeze, and clays even slower; but once frozen, all have a structural value.

GORGE HIGH DAM—SKAGIT RIVER PROJECT

One of the largest applications of refrigeration for stopping the flow of underground water was on the Gorge High Dam on the Skagit River in the State of Washington.

The problem was how to excavate the gravel through which the water was flowing and provide a foundation to build the dam up to what would normally be considered the bottom of the river level. To accomplish this, two cut-off walls were provided; one by cement grouting and the use of well points to pump the water out; the other by freezing the gravel itself to make a double wall of ice.

To make a freeze wall, a line of vertical pipes was sunk into the canyon floor from wall to wall, a distance of about 475 ft. The line roughly paralleled the axis of the future dam and was placed about half way upstream above the new dam site and an existing diversion dam. On 4 ft centers the pipes went down to bedrock, the longest 240 ft deep. The refrigeration made a solid wall of ice 4 to 5 ft thick.

Each vertical unit consisted of 3 pipes. On the outside was a 6 in. casing pipe whose main function was the protection of the freezing pipes. Inside that was a 3 in. pipe that carries brine up from the bottom of the hole. Inside the 3 in. pipe was a 1½ in. pipe that carried the brine to the ground from the header pipes.

The header pipes ran horizontally above the line of freeze

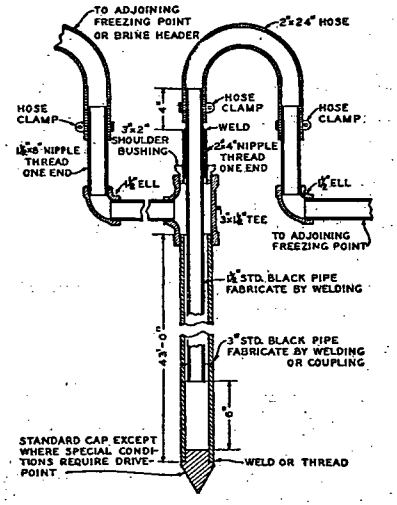

Fig. 2 .... Freezing Points Used at Grand Coulee Dam

holes, taking the brine from the refrigeration units out to the line and then back to the refrigeration units again. Capacity of the units was 250 tons per day. The brine was pumped in at −10 F.

The refrigerating equipment consisted of 6 self-contained brine, or water cooling systems. Two of these units were equipped with larger condensers and chillers for handling the maximum high temperature water cooling load (for concrete).

All units were operated on maximum brine cooling load (250 tons) when freezing each cut-off wall. Capacity of each unit, cooling 167 gpm calcium chloride brine to −10 F, was 42 tons. Total brine flow was 1000 gpm. Three units, totaling 126 tons, were used for holding duty on each frozen cut-off wall. The two units with the larger condensers and chillers were then operated on water or high temperature brine for the concrete cooling load. Total capacity was 150 tons, 750 gpm, at +25 F.

The brine supply and return headers were 8 in. steel pipes. All freezing coils were connected in parallel and each coil was single pass with immediate return of the brine to the chiller. Because of the varying depth of the freeze holes, each required a throttling valve to regulate the quantity of brine and the freezing rate. Each coil also required cut-off valves for isolation in case of a coil rupture.

Between the grout curtain and the freeze line, a series of wells were sunk. Pumps ran constantly to keep the water in the intervening basin under a minimum head and in a static condition so that freezing would be aided by absence of flow between the refrigeration pipes.

During the freezing process, temperature of the brine was checked constantly at inlet and outlet as a means of determining the condition of the ice wall. The differential in temperatures indicated the progress of heat extraction from the ground around the pipes.

GRAND COULEE DAM

An earlier application along similar lines was put into effect on the Grand Coulee Dam, when a flow of water through glacial silt in the materials underneath the cofferdam threatened to imperil the excavation within the cofferdam.

A flow of water through flour-fine glacial silt in a 120 ft wide crevice in the rock at Grand Coulee Dam was stopped by freezing an arch shaped berm of the saturated silt across the mouth of the channel. The berm was made 20 ft thick along a 105 ft radius of the arch to provide an adequate dam, to resist the thrust from a head of 40 ft of material weighting 90 lb per cu ft, computed as having a thust of 75 percent full liquid pressure.

To make the dam effective in 3 weeks time a spacing of 30 in. between freezing pipes was used. This spacing was determined by assuming that, with 10 F brine, 6 in. of material would be frozen in 2 days, 12 in. in 8 days and 15 in. in 20 days. Apparently, however, the actual freezing was effected at a somewhat greater speed.

The arch was formed by 8 parallel rows of points with 16 points in a header group. Some 25 extra points were installed on each buttress haunch to increase the bonded area and lessen the tendency toward sliding. All of the 377 points used were 43 ft long, formed as shown in Fig. 2. The brine was forced down the 1½ in. pipe, returned in the annular space between the 1½ and 3 in. pipes, and was expelled at the tee. The 3 in. pipes were driven with a 300 lb drop hammer striking against a heavy drive-coupling.

SHAFT SINKING BY SOIL FREEZING

This method was invented by F. H. Poetsch in 1883 and introduced into this country by Charles Sooysmith. Its essential feature is solidifying by freezing, the water-bearing ground in which the shaft is sunk. Sometimes the freezing is continued into water-bearing rock. The method has been used considerably in England and on the Continent for shafts 200 to more than 2000 ft deep. Vertical holes, 2 to 4 ft apart, are first bored on the circumference of a circle outside the periphery of the proposed shaft. Into each hole are lowered pairs of concentric pipes, through which brine, cooled to low temperature, is circulated. The brine passes down through the inner pipes and up through the space between the two, the outer pipe being closed at the bottom (Fig. 3).

Freezing Pipes

The holes for these are bored by the usual methods and, in soft ground, are cased. They must be vertical, or nearly so; otherwise the distances between them, at the bottom, may be too great to permit the formation of a complete ice wall. In very deep shafts, due to the difficulty of keeping the borings vertical and properly spaced, the freezing is sometimes done in stages, each 200 to 300 ft deep.

The stages of forming the ice wall are shown by Fig. 3. It must be thick enough to withstand the pressure to which it will be subjected, and the freezing pipes are located accordingly. Frozen sand is stronger than clear ice. Experiments have shown that frozen saturated sand crushes at about 2500 lb per sq in. at −25 C and at about 1700 lb at −12 C. It should, therefore, carry safely 300 lb per sq in. Assuming full hydrostatic pressure on the outside of the ice cylinder, the thickness of the wall for a shaft 300 ft deep and 20 ft diameter should be about 7.5 ft.

Freezing Plant

Ammonia is generally used as the basic refrigerating medium. Carbon dioxide is also occasionally used. Then brine, chilled by the ammonia is circulated through the freezing pipes. The brine is commonly $CaCl_2$ but $MgCl_2$ is recommended, as it has less tendency to precipitate at low temperatures and clog the piping.

Typical examples, as applied in Europe, include Shaft 6, Anhalt government salt mine, Leopoldshall, Stassfurt, Germany. Twenty-six five inch holes were bored in a circle, 26.25 ft diameter and cased to depth of 325 ft. The boring was difficult and consumed 17 months. Freezing was continued for 3 months before sinking was begun. After only 30 ft had been sunk, a small leak broke through in shaft bottom

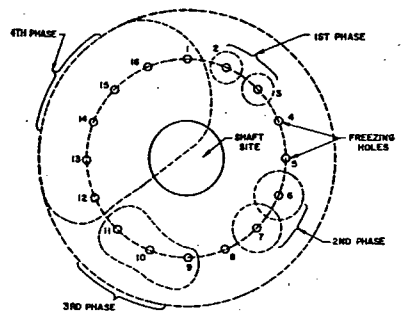

Fig. 3 .... Formation of Ice Wall

and flooded the shaft. Sinking was stopped and freezing continued for 75 more days, after which a progress of over 60 ft per month was maintained to a depth of 202 ft. The shaft was lined with iron tubbing (cast iron rings); the space behind being filled with concrete mixed with water containing calcined soda. Sinking and lining were prosecuted alternately until tubbing was sealed to the rock at a depth of 325 ft. Aside from the difficulty of boring the holes, this sinking was entirely successful.

THE OBIJWAY SALT MINE

The Poetsch method was further developed by Winston Bros. Company and used successfully by them on several projects. At the Obijway salt-mine shaft site in Windsor, Ontario, exploratory drilling disclosed mixed overburden from grade to 90 ft below, limestone to −365, sandstone to −445 and mixed limestone, shale and sandstone below that.

At −210, in porous strata of limestone, water under pressure was encountered. It gushed from the surface at 1200 gpm under a 16 ft artesian head and released dissolved hydrogen sulfide and methane gases. Additional, though smaller, water sources were found at other depths. Winston's method was to seal off all this water with a circular wall of ice down to the 720 ft depth.

First step was to drill a relief well in the center of the shaft site. This was pumped to lower the head while the rest of the holes were put down around it. Later, while the wall was being frozen, it relieved squeezing pressure in the core and prevented heaving.

The 28 freeze holes were drilled in a 32 ft diameter circle around the relief well. This put them on about 3½ ft centers which was close enough so that their freeze patterns overlapped to make a solid ring. Drilled by five ordinary well rigs, freeze holes went to a depth of 720 ft, which was below the known waterbearing strata.

Through the 90 ft of unstable overburden to rock, 12 in. holes were cased with 10 in. pipe. Below that 10 in. holes were drilled and left uncased. Careful drilling and frequent checking was necessary to insure that a proper freeze pattern resulted.

When all holes were completed, 6 in. seamless pipe, closed at the lower end, was inserted full depth. A 2 in. pipe extended almost to the bottom inside the 6 in. tube, and brine chilled to −20 F by a 200 ton refrigeration plant at the site was pumped down. Then, flowing up between the two pipes, the brine froze a circular ice wall.

Thermocouples placed at various points indicated the rates and locations of freezing as the ice wall formed. To insure that the wall froze uniformly all around, the 28 freeze pipes were fitted with valves to control the rate of brine flow. When the wall had been frozen to a thickness sufficient to withstand the subterranean hydrostatic pressures, the shaft was sunk in the center.

Besides functioning as an exploratory hole, the center hole served a number of other purposes. A pump was installed in it with the bowl down about 47 ft, which prevented the drill holes from overflowing during the drilling operations. After the freeze holes were drilled and the freeze pipes installed, the center hole was capped.

After the installation of the freeze piping in the freeze holes, the holes were left filled with fresh water. Then, as each hole was opened to the brine circuit, the fresh water was purged and the brine balanced with fresh water until the proper specific gravity was obtained. At the start of the freezing operation, the brine temperature out of the coolers was several degrees above zero. This temperature fell as the freezing progressed so that, at the end of the freezing period, the brine