GROUND FREEZING: THE USE OF LIQUID NITROGEN SYSTEMS CONVERTED TO BRINE

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ABSTRACT

There has been a trend in recent years in performing the initial formation freezing using liquid nitrogen (LIN) and then converting the system to circulating refrigerated brine. While proponents of this method state it decreases freezing time, it can also be considered an alternative to inadequate refrigeration capacity. This method was used on several small projects in the 1980s. Problems such as broken pipes, frozen brine, and unsafe work conditions caused contractors to re-think the method. This paper discusses these problems and also presents work schedules showing no schedule reduction. In fact, this method can lead to longer time as well as significantly higher costs.

Keywords: liquid, nitrogen, ground, freezing, brine

BACKGROUND

Ground freezing as a method to provide groundwater control and temporary earth support for excavations is completed using a relatively simple process: drilling and installing refrigeration pipes around the perimeter of the excavation and introducing a coolant into these pipes. The coolant extracts heat from the ground, converting the pore water to ice and forming a strong, impermeable material. A typical ground freezing system is illustrated in Fig. 1.

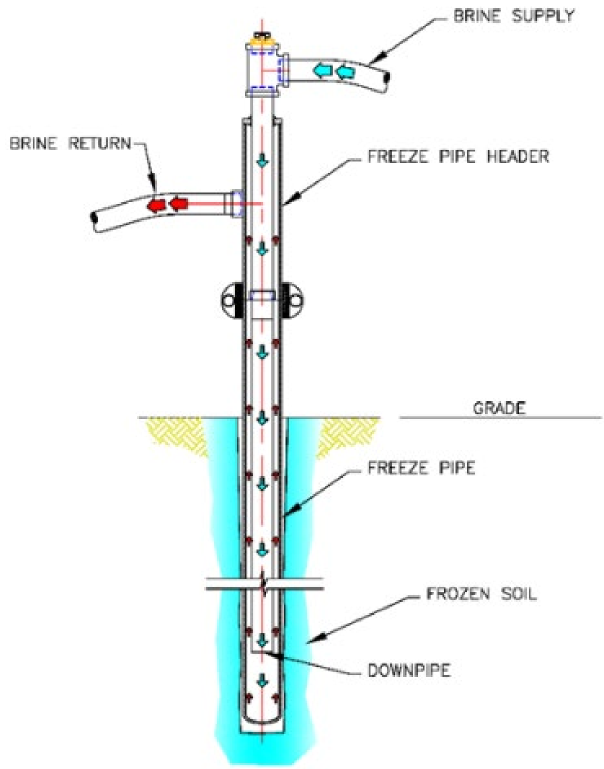

Fig. 1. Typical ground freezing system

SYSTEMS

There are two basic types of coolant systems: circulating and direct expansion. The circulating coolant system is made of two separate, closed systems. The medium circulating is the secondary coolant. It is cooled at a central refrigeration plant, circulated through the pipes, and warms as it extracts heat from the ground. It then circulates back to the plant where it is cooled. This coolant is chilled in a heat exchanger by the primary refrigeration system where a compressor system is charged with a refrigeration gas. The heat is ultimately extracted from the ground and expelled into the atmosphere by an evaporative condenser. Secondary coolants are usually a brine or glycol chemical while the primary refrigeration gas is anhydrous ammonia or another commercially available gas.

Direct expansion systems are much simpler. A cryogenic liquid such as nitrogen or CO_2 flows into the individual pipes and boils when in contact with the warmer soil. The gas then exits the pipe and is discharged into the atmosphere as shown in Fig. 2.

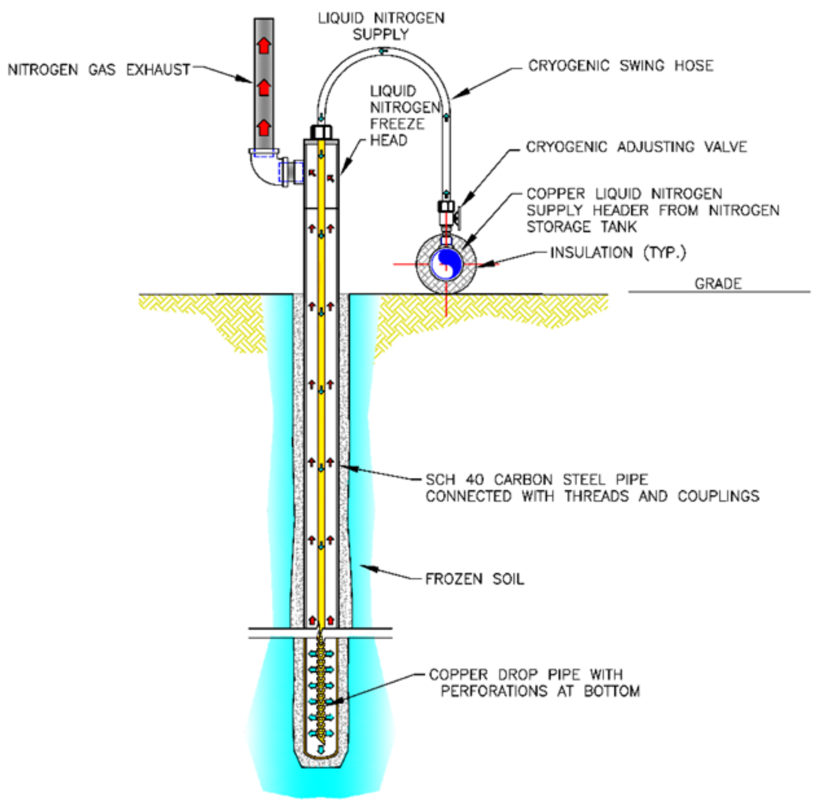

Fig. 2. LIN system

Both systems have a series of advantages and disadvantages, summarized in Tables 1a-b.

Table 1a. Circulating System

Advantages	Disadvantages
Lower cost	Longer freezing time
Location not a factor	Ammonia gas
Components readily available	Circulating calcium chloride
Adaptable for large projects	Electric power required

Table 1b. Direct Expansion

Advantages	Disadvantages
Reduced freezing time	Higher cost
Non-toxic to environment	Not always available in remote locations
Suitable for small project	Requires cryogenic components
Substantially colder and strong frozen soil	Asphyxiant

Technical comparisons

It is important to note the technical difference between the two methods prior to any economic evaluation. Most projects can be quickly evaluated relative to what method should be used. The circulating system is used for most ground freezing applications. The coolant can be pumped for long distances and is used in deep excavations exceeding 600 m. The pipe systems operate under relatively low pressures and present no dangerous situations. The frozen soil strengths range from 3.0 to 10.0+ MPa, which are suitable for most excavation support systems. A circulating system can be drilled and installed in any location that can be accessed and supported with diesel generators for electrical power.

With the direct expansion system, it is difficult to transport the LIN very long distances or flow into deep refrigeration pipes as it will boil off and become a gas. It should be emphasized that while the evaporated gas is very cold, it does not permit efficient heat transfer compared to the nitrogen in a liquid state. It can be very difficult to transport the LIN to remote places and in some cases also difficult to get the quantities necessary to freeze large projects. LIN plant capacity and location are key to considering its use prior to any detailed technical or economic evaluation. With the cryogenic temperature (T) of -196ºC, the frozen soil is considerably colder and stronger than with the circulating systems. While these Ts are usually not required for most excavation support systems, they are sometimes necessary to form a water tight frozen bond against the subsurface structure of a tunnel boring machine.

Economic comparisons

While an economic analysis of each method is beyond the scope of this paper, a few key points are warranted:

1) if the total length of refrigeration pipe for the project is greater than 1500 m, LIN is most likely more expensive than brine;
2) freight often charges due to long distances or traffic congestion through large metropolitan areas, making LIN technically unfeasible;
3) very small projects like sealing a breach in a slurry diaphragm or secant pile wall do not warrant the expense of installing a circulating coolant refrigeration plant and power supply, making LIN the primary choice;
4) if someone gives you an exact estimate of how much nitrogen is required to freeze a project, they are mistaken as it is very difficult to estimate LIN consumption as described in subsequent sections.

Refrigeration requirements

Initial steps in designing a frozen structure include evaluating the frozen soil's mechanical properties and then determining the frozen earth structure's size or thickness. A structural thickness also generally specifies the required T regime. Most specifications require either an average T of -10ºC or the frozen zone to be considered at the zone between -2ºC intrados and -2ºC extrados; the latter is much easier to define. To determine the length of time required to form this frozen zone as well as the refrigeration load required, a thermal analysis is completed. A time-dependent heat transfer finite element model can be used to conduct such an analysis. In addition to the project geometry, using a simple tunnel or cross passage as illustrated in Fig. 3 is recommended for simplicity. The following parameters are required: unfrozen and frozen heat capacity, unfrozen and frozen thermal conductivity, volumetric water content, initial ground T, and coolant T.

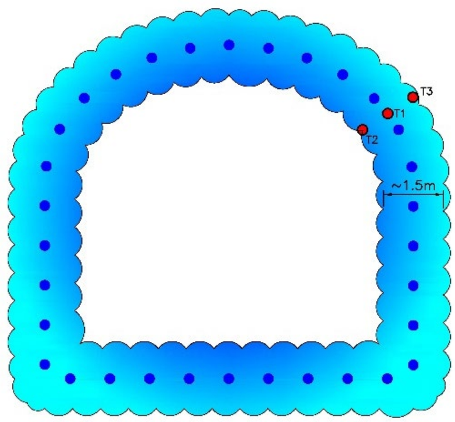

Fig. 3. Tunnel cross section

Using the geometry in Fig. 3 as the basis of the model, Ts at T_1, T_2, and T_3 are evaluated against time. Fig. 4a presents the time versus T plot when using a -25ºC circulating brine while Fig. 4b sows the same plot but with -196ºC expendable LIN.

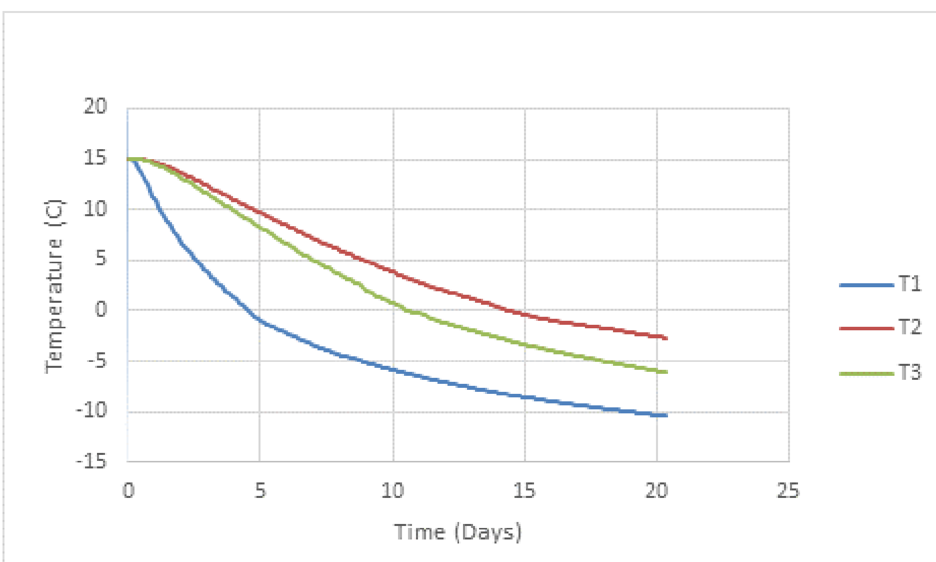

Fig. 4a. Time vs. T for circulating brine

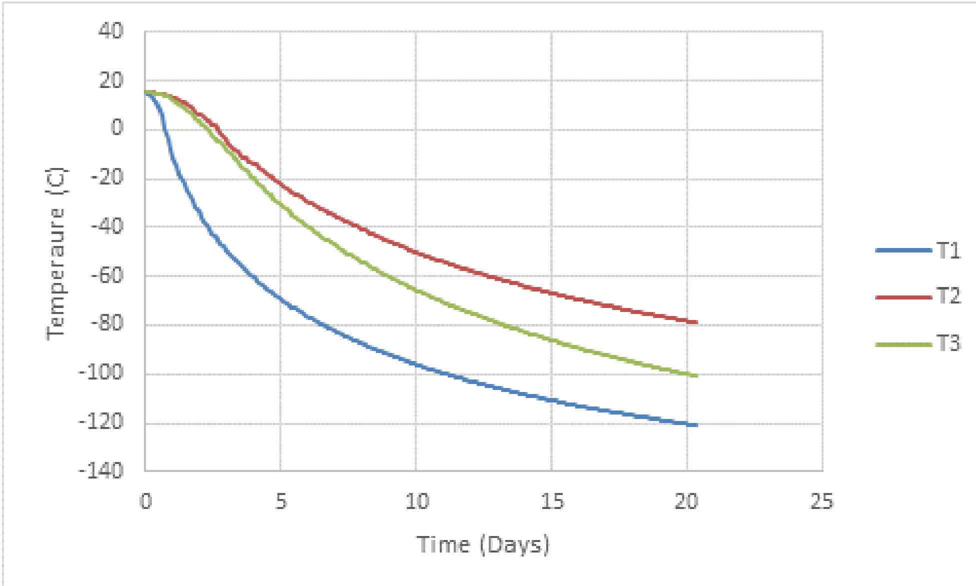

Fig. 4b. Time vs. T for expendable LIN

Interpretation of these two graphs is straightforward; T2 and T3 are both located 0.75 m off the centerline of refrigeration pipes, consistent with the 1.5-m-thick frozen zone determined in the structural analysis. With the brine system, the frozen structure is formed in 17 days, but only four days are required when using LIN. Before reaching the conclusion that faster is better, there are additional considerations.

Figs. 5a-b present the actual heat extracted (for one m of pipe) from an individual refrigeration pipe using each method.

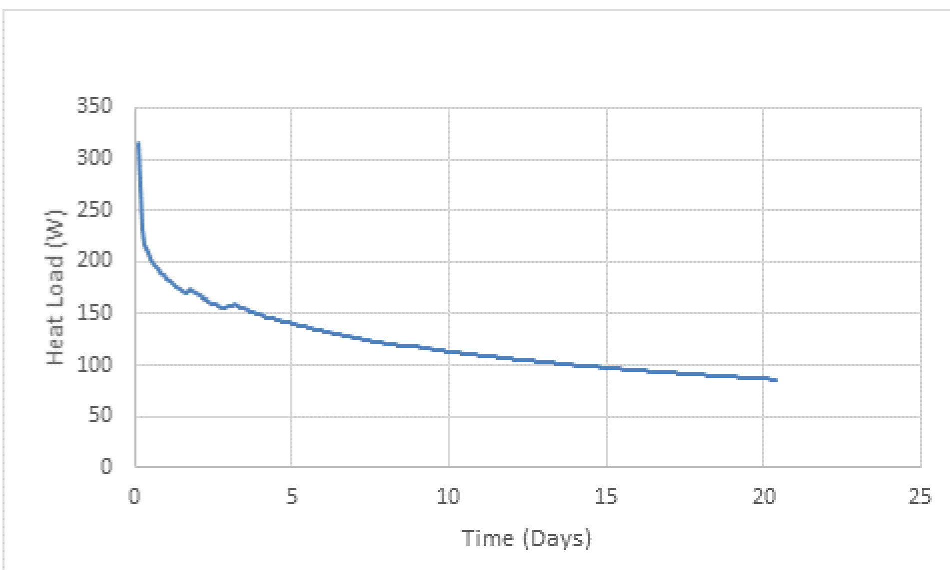

Fig. 5a. Time vs. heat load (per meter of pipe) for -25°c brine

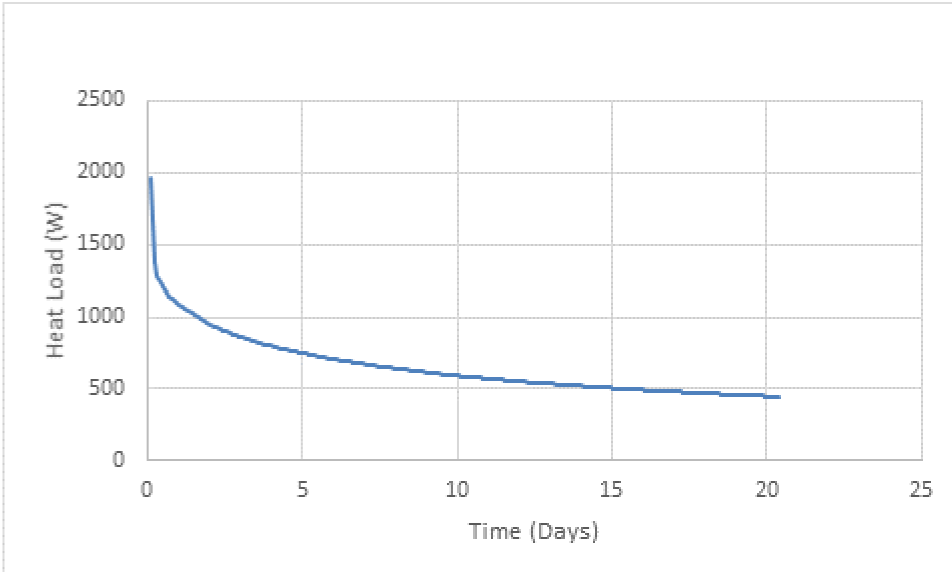

Fig. 5b. Time vs. heat load (per meter of pipe) for -196ºc LIN

Using these graphs, it is possible to evaluate the total amount of heat removed during the formation freezing times. With the brine system, 1.82E+8 joules are extracted simultaneously with 3.26E+8 joules. Almost twice as much heat is extracted with LIN in about 25 percent of the time. This leads to considerable inefficiencies and additional costs.

LINDE, a producer of LIN, notes on its website that 1 kg of LIN has the capacity to extract approximately 200 kJ of heat from soil. This relationship has been used in the industry (including by the author) to evaluate the amount of LIN required to freeze the ground. Obviously, the computations are more complex and require the designer to evaluate the amount of soil to be frozen (obtained by the structural analysis) and soil T required. The soil T is the variable that can lead to inaccurate and underestimation of the quantity of LIN required.

As previously noted, it is necessary to evaluate the average T to be attained during freezing. Typically, -10ºC is used. A simple way of evaluating this is to assume you have one m^3 of soil that you want to lower from 15ºC to -10ºC. Using the volume and a delta T of 25ºC, one can compute the amount of heat extracted from the soil. However, referring to Fig. 6a, it can be readily observed that the delta T is significantly higher than 25ºC.

Contrasting the contours in Fig. 6a with those in 6b, it can readily be observed that substantially more heat is extracted from the ground to form the required structural thickness of the frozen wall. At first glance, this may be seen as no consequence and perhaps even advantageous. The wall has been formed in less time and the lower Ts result in a significantly stronger (even though unnecessary) frozen mass. The problem with this is more logistic and economic.

Most engineers and contractors (including the author) have relied on 1 kg to extract 200 k estimate previously noted. As stated, this is based on a delta T of 25ºC. Since the delta T is higher than 25ºC, more LIN is required than estimated. Because of this, the author can state with confidence more LIN is always used than estimated using this relationship.

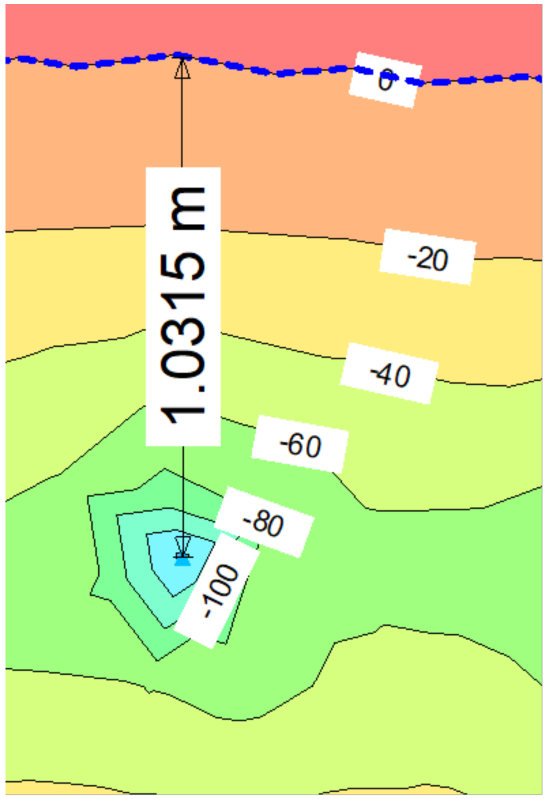

Fig. 6a. T contours (LIN)

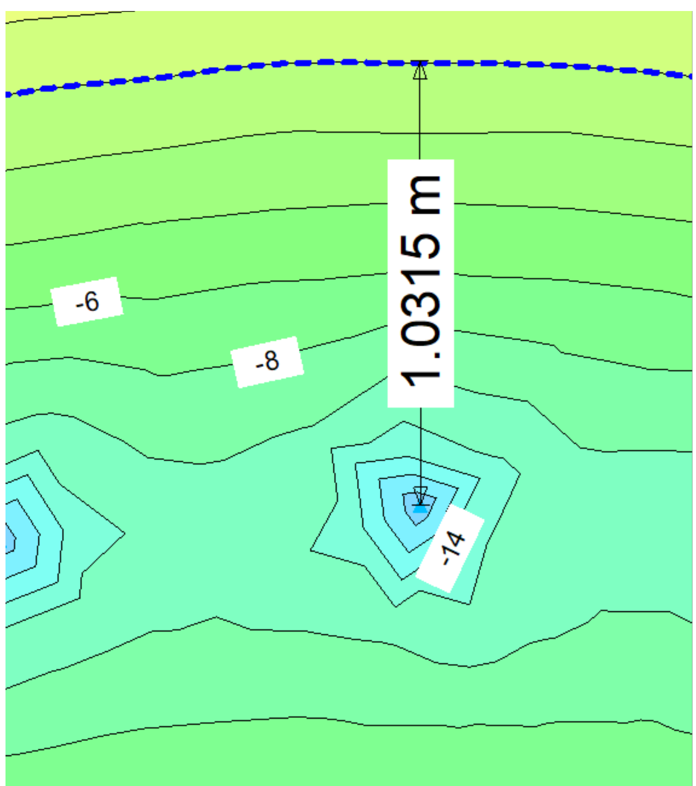

Fig. 6b. T contours (brine)

Experienced contractors have historical and proprietary methods of estimating LIN usage. Even with this knowledge, the fact remains that LIN is extremely inefficient compared with a brine system when evaluating the amount of heat to be extracted.

So why use LIN in place of brine in those cases where cryogenic Ts are not required? In these cases, the contractor does not have the appropriate refrigeration plants available and opts for a simpler and much more expensive approach with the LIN.

The heat load of approximately 300 w per m of freeze shown in Fig. 5a can be used to compute the required refrigeration plant size for a relatively short tunnel adit or cross passage. For example, a current tunnel adit has a length of 30 m. Multiplying 32 pipes by 30 m by 300 w indicates a refrigeration plant capacity of 288 kw is required. This is a refrigeration unit that does not indicate the electric power required. It should be noted this is the peak capacity required to form the frozen earth structure. Once formation has occurred (approximately 17 days), the required refrigeration load is decreased to approximately 100 w per m of refrigeration pipe.

There are two types of refrigeration plants used in civil tunnel projects, as shown in Figs. 7a and 7b. Fig. 7a shows a truck-mounted unit capable of producing 310 kw of refrigeration at -30°C. It uses ammonia as a primary refrigerant and calcium chloride brine as the secondary circulating refrigerant. The unit shown in Fig. 7b is a smaller, portable unit capable of producing 100 kw of refrigeration at -30oC. Small units like this are used inside tunnels as they also offer the safety advantage of using refrigerant instead of ammonia.

Fig. 7a. 310 kw at -30°C refrigeration plant

Fig. 7b. 100 kw at -30ºC

It should be noted that a kilowatt of refrigeration does not indicate the amount of electric power required for the freezing. Additionally, a refrigeration plant's power rating is evaluated at specific coolant T. The 310 kw (at -30ºC) has higher kw capacity at -20ºC. Selection of refrigeration units also requires close evaluation of the coolant flow capacity through the system. A flow rate of at least 110 m^3 per day is required for efficient heat transfer.

COMBINING METHODS

Referring to the previous example cited, a recent project required 288 kw of refrigeration capacity during the initial formation freezing. A plant similar to the one shown in Fig. 7a would be used for that project. Referring to Fig. 5a, it can be observed the required load will decrease during maintenance freezing. This type of refrigeration plant is custom-made, often very expensive, and not readily available. As an alternative to using the appropriate equipment, attempts have been made to use LIN for the initially high load freezing and then convert to a circulating system for maintenance with a lower powered plant. This system is justified because it can get the initial freezing done in less time.

When referring to Fig. 4, it is readily apparent that LIN will freeze the ground faster, but in the scheme of the entire project, it will not necessarily save time or compress the schedule. Reasons for this include but are not limited to: two separate coolant distribution manifolds will have to be fabricated and installed; time will be required to change over from the LIN to the circulating coolant system; refrigeration pipes have a high probability of developing leaks during the LIN freezing and will require repair; the Ts resulting from the LIN freezing could result in freezing the brine after conversion; and two separate health, safety, and environmental protocols are required.

Using the two separate systems is certainly possible, but one must question the economic logic of doing this. As demonstrated, the LIN extracts more heat than required. The T will be lowered more than necessary and then heated when the circulating system is implemented. As previously explained, estimates of LIN are frequently lower than estimated and more product is required; sometimes, more than twice as much. LIN can be very expensive depending on availability and transportation costs.

CONCLUSIONS

The author acknowledges any individual project is suited for either a circulating system or LIN for reasons cited. There may even be applications where a combination of the two methods is appropriate. However, combining methods because a contractor does not have the appropriate equipment will most likely have complications, require more time, and certainly cost more.